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How can emerging economies meet development and climate goals in the transport-energy system? Modelling co-developed scenarios in Kenya using a socio-technical approach☆

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ABSTRACT

Transport-energy transitions pose complex challenges that have been extensively studied in high-income countries in response to national mandates for climate action. Low- and middle-income countries, however, have low but rapidly growing motorisation rates and face very different challenges in adopting new technologies to foster economic development and ensure equitable access to clean transportation. Here, we present a set of narrative scenarios for the future of the Kenyan transport-energy system co-developed through engagement with 41 local experts and decision-makers. Through the co-development of a Kenyan transport-energy system model, we present a decision-support tool, populated with those scenarios, to assist policymakers at regional, national and international levels in building policy and investment pipelines to support low-carbon economic growth. We find that Kenya's transport-energy system can meet both development and climate goals, but this demands strong policy support for efficient public transport and targeted support for road vehicle electrification. Increased support for non-motorised transport is essential to provide equitable access to services and economic opportunities. Favourable pathways result in significant e-mobility uptake, which is anticipated to increase electricity demand by 5%–56% from 2023 to 2040, relative to the IEA Kenya Energy Outlook's *Stated Policies* scenario, representing a 2.7–3.9x increase in Kenya's total electricity demand over the same period. From a macro-fiscal perspective, results show that e-mobility has two important consequences for Kenya. Firstly, under high e-mobility scenarios, there is a negative fiscal impact that taxation revenues

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from the sale of transport fuels reduce by up to 41% relative to the low e-mobility scenario (though, notably, they still increase marginally from the 2023 level because of increasing transport demand). Secondly, high e-mobility scenarios have a positive impact on balance of payments by reducing the fuel import bill by up to 69% relative to the low e-mobility baseline. This corresponds to a reduction in foreign exchange requirement of up to $4.2bn annually by 2050.

1. Introduction

Kenya's past and present responsibility for climate change is negligible. In 2021, Kenyan greenhouse gas (GHG) emissions represented 0.05% of the global total and, in the same year, per-capita emissions were under 0.4 tCO_2e [1]. This is an order of magnitude lower than the per-capita emissions of the UK (5.2 tCO_2e), Germany (8.1 tCO_2e), and the USA (14.9 tCO_2e) [1]. As per the well-documented inequity of the climate crisis, Kenya is much more vulnerable to its impacts than any of those countries, ranking 152 out of 181 countries on the ND-GAIN index for climate vulnerability [2], due to a combination of factors including the fact that a majority of its population depend on highly climate-sensitive sectors including agriculture [3].

It is not therefore of great global importance to reduce emissions in Kenya or the majority of other sub-Saharan African states, which share a similarly minuscule contribution to climate change. It is, however, of significant importance to consider the future of transport-energy systems in Kenya and other low- and middle-income countries (LMICs) as part of just transitions to environmentally sustainable economies.

With rapid population growth (Kenya's population is forecast to grow 70% from 2020 to 2050 [4]), urban migration (Nairobi is one of the world's fastest growing cities, expected to double in population in the next 20 years [5]) and an expanding middle class (reported in 2016 to be growing at over 5% per year [6]), demand for both passenger and freight transport will inevitably increase significantly over the coming decades. As an indication, transport emissions across the African continent grew by 84% between 2010 and 2016 [7].

The future of its transportation system and the implications for the wider energy sector is a determining factor in Kenya's ability to meet its targets in economic development – to become an industrialised, middle-income country by 2030 [8] – in a manner that is compatible with global targets in climate mitigation and adaptation – by limiting economy-wide emissions to 32% below the business-as-usual (BaU) baseline by 2030, as per Kenya's commitment to the Paris Agreement [9]. Aside from GHG emissions, petroleum-powered transport is a source of harmful air pollution in major cities globally: the quantity of old vehicles and ill-enforced standards means that urban Kenya, particularly Nairobi, suffers from extreme levels of harmful air pollution [10].

Transport-energy transitions entail co-evolution and multi-dimen sional interactions between industry, technology, markets, policy, culture and civil society [11,12]. Such transitions have been extensively studied in high-income countries (HICs), given their national mandates for climate mitigation. LMICs, however, have low but rapidly growing motorisation rates and face different challenges in incorporating rapid transport technological change that could accelerate their economies' development while ensuring access to affordable and equitable transportation.

Based on a review of the literature, we identify a wide research gap in scenario development and decision-support tools in the Kenyan context, which is shared by many sub-Saharan African nations. Taking this as a starting point, our objective in this paper is to identify the narratives and perspectives of Kenyan experts and decision-makers, construct integrated scenarios that can be matched to policy options, and feed that information into a strategic decision support tool of the kind that is routinely deployed in HICs to guide policy.

Specifically, the objectives of this study are (1–3):

1. To co-develop a set of scenarios, based on interviews and workshops with Kenyan transport/energy system experts across government, academia, non-governmental organisations (NGOs) and the private sectors;
2. To co-develop, with Kenyan research institutions, a strategic modelling framework for the Kenyan transport-energy system, TEAM-Kenya, based on the Transport Energy Air pollution Model (TEAM), originally developed under the auspices of the UK Energy Research Centre (UKERC) at the University of Oxford (2012-present) for strategic policy analysis and scenario development in the UK, Scotland and South Korea;
3. To use TEAM-Kenya in quantifying credible impacts of the developed scenarios on key indicators, including vehicle stock evolution, vehicle-kilometres (VKM), energy consumption, greenhouse gas emissions, air pollutant emissions and taxation revenues, and in demonstrating the use of decision-support tools in transport-energy system planning at a national level.

The rest of this paper is organised as follows. Section 2 presents an outline of the Kenyan transport-energy context, including the current state and plausible futures; Section 3 presents a review of previous work on transport-energy modelling and scenario development in LMICs; Section 4 describes the scenario development part of this work in detail, including the methodology and results; Section 5 describes the modelling part of this work in detail, including the methodology and results; Section 6 presents conclusions and suggests pieces of future work based on this research.

2. The Kenyan context: the current state and plausible futures

An effective transport system is considered as a foundation for Kenya achieving its ambition of becoming an industrialised middle-income country by 2030 [8]. By far the largest percentage of total passenger and freight movement is currently by road, comprising 80% of motorised passenger-kilometre (PKM) and 76% of freight by tonne-kilometre (TKM) [13]. Due to its high carbon intensity per PKM and TKM, road transport accounts for 98% of total transport sector GHG emissions [14]. Kenya's high level of vulnerability to the impacts of climate change, with a majority of the population dependent on climate-sensitive sectors [3], necessitates adaptation policies to be a mainstay of future transport-energy scenarios in addition to mitigation policies [9].

Private motorised transport in Kenya is relatively scarce when compared to HICs. As part of the Advancing Transport Climate Strategies (TraCS) project [15], which in Kenya was co-led between the University of Nairobi and the German international development agency GIZ, it was estimated that there were 532,406 passenger cars on the road in 2015 (this represents, to the authors' knowledge, the most recent detailed study on the Kenyan vehicle fleet). Based on the 2015 population of 46.9 million, that equates to a car ownership rate of 11 per 1000 inhabitants. When compared to the UK in 2022 (493 cars per 1000 inhabitants [16]) or the USA in 2017 (over 800 cars per 1000 inhabitants [17]), it stands to reason that the car sector in Kenya is not the dominating energy consumer and emitter as it is in the UK or USA. However, unlike the latter two countries, Kenya has an important and growing motorcycle segment. As part of the TraCS project, it was estimated that there were 539,768 motorcycles on the road in 2015. This is arguably Kenya's most important vehicle segment; due in part to national policy of waiving the 25% importation tax

for locally assembled motorcycles in 2008 [18], they have become a relatively affordable means of accessing mobility for millions of Kenyan households and have grown significantly in number through the 2010s and beyond. Of the approx. 2.6 million cumulative motorcycle registrations since records began in 1968, over half (1.3 million) of them have been brought onto the roads since 2018; furthermore, registrations in the latest year that data is available (2022) were 57% higher than in 2018 [19]. Motorcycles are also an important part of the economy for providing livelihoods as well as mobility: it is estimated that 90% of Kenyan motorcycles are *boda bodas* (motorcycle taxis and couriers) [20].

Aside from *boda bodas*, which provide on-demand private transport across the country (mostly for shorter trips), public transport is dominated by *matatus* (privately owned vehicles that can carry 11–35 passengers) and tuk tuks (three-wheeler taxis). Travel survey data analysed by Salon et al. in 2019 [21] suggests that approx. 60% of commuting trips in Nairobi are made by *matatu*; mode splits over 40% by *matatu* are consistent across the other four major cities in Kenya (Mombasa, Eldoret, Kisumu and Nakuru). *matatus* are generally either 11–14 seater minibuses (e.g. Toyota Hi-Ace) imported second-hand from abroad (e.g. Japan or the UK), or are locally-built 35-seater buses constructed on (mostly) Japanese truck frames. Official Kenyan government policy has been to move towards larger capacity buses in urban centres, particularly Nairobi [22].

As with the majority of sub-Saharan African countries, non-motorised transport (NMT) (particularly walking) is an important part of passenger travel: it is estimated that urban walking modal splits (by number of trips) for commuting are between 35% (Nairobi) and 80% (Kericho) [21]. In the Nairobi example, it is estimated that 2.3 million trips per day are made by walking, and 55,000 by cycling [23]. Many people walk to work, largely due to low income levels and a lack of available alternatives: more than 75% of total daily trips made by Africa's low-income population are made by walking, compared with 45% by more affluent segments of the populace [24]. Whilst these mode shares are high, and could be considered the envy of many HIC economies that are actively trying to push their passenger transport demand towards non-motorised modes in seeking better emissions, air quality and public health outcomes [25], pedestrians and cyclists in SSA cities like Nairobi are faced with pervasive challenges from traffic accidents, lack of green spaces and pollution, to muggings, congestion, a lack of footpaths and cycle lanes, and encroachment upon their designated spaces. The majority of these challenges are safety- or infrastructure-related: NMT users account for two thirds of traffic fatalities in Nairobi [23].

Freight transport is mostly served by trucks, the majority of which are imported second-hand from HICs. As freight demand shares a strong positive correlation with GDP [26], it is expected that as the latter increases, so does the former. Therefore, strategies around future-proofing Kenya's freight sector to ensure an affordable and sustainable future are needed as part of national-level policy planning.

Given the importance of the transport sector in Kenya's economic development, it is crucial to implement measures that enhance sustainable development within the sector. Plausible future measures relate to a series of drivers and levers of change that were identified as part of discussions with Kenyan stakeholders for the scenario co-development, and include: (i) subsidisation of certain technologies, such as the removal of VAT for electric cars (E4Ws[1]) or motorcycles (E2Ws) (as announced for the latter by the Kenyan president in 2023 [27]); (ii) the provision of infrastructure for the supply of low-carbon energy vectors to the Kenyan transport-energy system [28]; (iii) extension of public transport projects, such as segregated bus lanes, bus rapid transit (BRT) systems [29], and other mass-transit passenger transport; and (iv) urban transport projects to encourage the utilisation of sustainable modes, including public transport and NMT [30]. Sustainable development pathways such as these have the potential for significant co-benefits, including the impact of improved air quality on public health outcomes, more inclusive urban realm design and higher levels of economic productivity.

3. Literature review: previous work on transport scenario development and modelling in LMICs

3.1. Scenario development for transport-energy systems in LMICs: previous work, barriers and opportunities

Time-bound scenarios are narrative tools that aid their users imagine and depict plausible futures. Once identified, scenarios are instrumental in elucidating underlying assumptions as well as challenges and opportunities in a course of events set in the future, allowing comparative analyses across two or more futures (see Dixon et al. [31]) and the design of policies, projects and financial pipelines in addressing a set of stated ambitions. As asserted by Lyons et al. [32], plausibility in a scenario consists of the futures that are preferable and the futures that are probable, as well as the overlap of the two.

Scenario development and modelling are major part of policy planning for technology, innovation, infrastructure and demographic dynamics, and as such they have become a critical tool for envisioning and meeting socioeconomic goals [33]. In the field of climate mitigation, scenarios are consistently used for understanding the global energy transition needed to decarbonise complex energy systems (for a review see [34,35]). Scenario-based planning has also become mainstream in the transport sector to improve connectivity, usability and the efficiency of investment, see [36], as well as to manage uncertainty of their intricate, fast-changing and interconnected socio-technical systems.

Despite scenario development and modelling becoming a normalised aspect of policy planning, their use and the resources for their development remain deeply unequal. According to Mutiso [37], African countries have been largely left out of the pools of data and expertise on scenario modelling produced worldwide, thus limiting opportunities for development and sustainability, and also impairing their ability to engage in meaningful global discussions on net-zero, climate and energy ambitions. As explored by Dioha et al. [38], scenario modelling in the region faces constraints that makes models in African countries overly reliant on the use of proxies that offer only vague approximations to local dynamics. Furthermore, such approaches are often based on 'accumulated models of models' with little reflection of local priorities because these are designed through other value lenses [37].

The challenges to equalise access to scenarios development and modelling are steep. Yet, scenario development techniques can contribute to bringing local priorities closer to modelling exercises by ensuring scenarios are built and envisioned by the experts in situ, and by later ensuring that the capacity and the expertise in scenario work is developed and continued, and not only carried as a floating and isolated activity [39]. Engaging with local policymakers early in the scenario work to align assumptions with local visions, as well as ensuring different views are represented, are practices that scenario development and analysis could foster to bridge inequality and speed development in understudied regions [37]. To help address these concerns, the present study adopts a participatory scenario-making approach, where local stakeholders identify, discuss and highlight their views on the present and future of energy and transport in Kenya, within the broader socio-economic context of plausible transport-energy futures.

[1] For clarification, in this study we use E4 W to refer to private passenger cars powered solely by a battery electric powertrain; other four-wheeled vehicles powered by electricity are referred to as e-buses, e-trucks, etc.

3.2. Transport-energy modelling in LMICs

The ASIF framework (1) sets the hierarchy of many high-level transport-energy models, which are generally used to explore changes in either transport activity A, mode shares S, energy intensity I or fuel intensity F to give a different GHG emissions value E over time [40].

$$E = A \sum_i \sum_j S_i I_i F_{ij} \tag{1}$$

According to Krey [41], Energy system models can be distinguished along three main axes: (i) the mathematical solution concepts (e.g. whether optimisation or simulation); (ii) the system boundaries (e.g. whether sectoral or temporal); and (iii) the level of detail (e.g. technology, spatial resolution).

In this paper, we will consider axes (ii) and (iii) fixed: in developing a transport-energy model for the Kenyan context, it is necessary that it covers the transport system as a boundary, and that its level of detail is at the level of a national economy.

Variations across axis (i), however, are visible across the literature. Optimisation models force the 'right' answer, in terms of minimal overall system cost (usually supplying a set of transport-energy demands – A and S in (1)). Prominent optimisation models used for the transport sector include OSeMOSYS (Open Source energy MOdelling SYStem) [42], MESSAGE-Transport (the transport module of the Model for Energy Supply Strategy Alternatives and their General Environmental impact) [43], and MoCho-TIMES (Mobility-Choice adaptation of the widely-used TIMES energy modelling framework) [44]. To produce multiple pathways, rather than one 'right' answer, constraints are placed on the optimisation to produce an answer within specific bounds (e.g. the lower or upper limit of the rate of market penetration of a certain technology by a particular year). On the other hand, simulation models do not seek an optimal solution planned by some central coordinator, but rather seek to simulate (or calculate) how certain actions or outcomes will affect the 'end result' (e.g. energy, emissions or cost) of the modelled system. Whilst this means they cannot direct the user to the least-cost means of achieving a desired target, they can be more readily utilised to explore imperfect or irrational actions from different actors, including individual consumers. Prominent simulation models used for the transport sector include LEAP (Low Emissions Analysis Platform) [45], Roadmap [46], MoMo (Mobility Model) [47], and TEAM (Transport Energy Air pollution Model) [48].

Efforts at building mathematical model representations of transport-energy systems in LMICs are relatively scarce compared with efforts in HICs. A selection of the most prominent examples from the literature are presented in this section.

Godinez et al. [49] present alternative pathways for the future of Costa Rica's transport-energy system. They use OSeMOSYS to create an optimisation model representing the Costa Rican energy system, with transport represented as a set of demands, in terms of a total transport demand in terms of VKM (A in (1)), modal split (S in (1)) and a set of technologies that can be dispatched with varying energy and fuel intensities (I and F in (1)). The model is used to explore two separate pathways to a low-carbon future for Costa Rica, in comparison to a BaU baseline. The low-carbon pathways are based on technology uptake constraints; conversely, in the BaU pathway the central coordinator is left 'free' to choose the minimum-cost pathway based on BaU technology costs and a BaU evolution of demand based on regression of historic energy demand trends.

Azam et al. [50] present a LEAP model of the Malaysian transport sector to explore the energy, GHG and air pollution implications of future transport scenarios. Energy demand is constant across all scenarios in [50]: a set of energy demands in various subsectors of the Malaysian transport sector in the base year is forecast to increase according to a fixed compound annual growth rate. The scenarios are differentiated in [50] purely on the proportion of supply-side technologies, including battery electrification, biofuels and compressed natural gas-powered vehicles.

Emodi et al. [51] present a study on future scenarios for the Nigerian energy and transport system using the LEAP modelling framework. The study uses published Nigerian national policy to populate a reference scenario for the future evolution of the energy system, and develops three alternative scenarios to the reference based on energy efficiency (demand-side) and supply-side changes, including changing the proportion of renewable energy sources in the country's electricity mix. The model in [51] relies on the insertion of energy service demand in petajoules, and does not allow for the exploration of how changing explanatory variables might affect demand. Furthermore, while the scenario development is relatively comprehensive amongst options for low-carbon development, they are created with only a select few levers by the authors themselves.

Maduekwe et al. [52] apply the LEAP framework to the city of Lagos, Nigeria, to explore the energy and GHG implications of different scenarios relating to policies formulated according to the Avoid-Shift-Improve (A-S-I) framework [53]. In this way, Maduekwe et al. develop scenarios classified according to reductions in transport service demand (Avoid), mode shift to higher-occupancy modes (Shift) and increased uptake of alternative-fuelled vehicles (Improve). The authors are able to compare the outcomes of their study against Lagos' emissions target in making policy recommendations to the city. Whilst the scenario development in [52] more closely resembles the use of policy application in the current study, rather than modelling vehicle technology uptake through a discrete choice modelling approach as in the current study, which is used to investigate the potential impacts of policy surrounding technology subsidy and charge point coverage, Maduekwe et al. use policy targets from Lagos' local transport authorities to set assumed levels of uptake of certain technologies by particular years, thus linking the impact of the successful realisation of these targets with transport sector energy and emissions outcomes.

Wambui et al. [54] present an application of LEAP and the Next Energy MOdelling system (NEMO) for the development of future pathways for the electricity sector in Kenya. Similarly to Emodi et al. [51], the reference scenario is based on a build model using the LEAP framework to forecast credible energy and GHG implications of existing national policy. In [54], the authors generate a set of scenarios relating to the (i) the endogenous modelling of demand, relating to changing socioeconomic and demographic factors; and (ii) the exogenous addition of a set of energy demands from new infrastructure developments, including the electrification of Kenya's main railway line. The work by Wambui et al. [54] more closely resembles the objectives in the current study, in that it examines the impact of potential policy options (in this case, of approving infrastructure projects) on energy system pathways. However, only the electricity sector is considered in [54]; indeed, we suggest that the current study is complementary to what was found in [54] in advancing the level of data-driven policy support for energy and transport in Kenya.

3.3. Research gap and contribution

Through reviewing the existing literature, we summarise that to our knowledge, there has been no attempt at the development of a detailed transport-energy system model for Kenya, or any sub-Saharan African nation, that allows users to explore policy futures and their credible outputs in building pathways towards desirable futures of equitable access to clean transportation. Of the works reviewed (for example, [50–52,54]), models rely on simplistic inputs of total energy requirements from the transport sector and do not allow users to build scenarios based on contextual and policy variables. To fill this gap, we present through this study:

1. Scenario development for the Kenyan transport-energy system using a participatory approach based on an application of the *Oxford Scenario Planning Approach* [55].

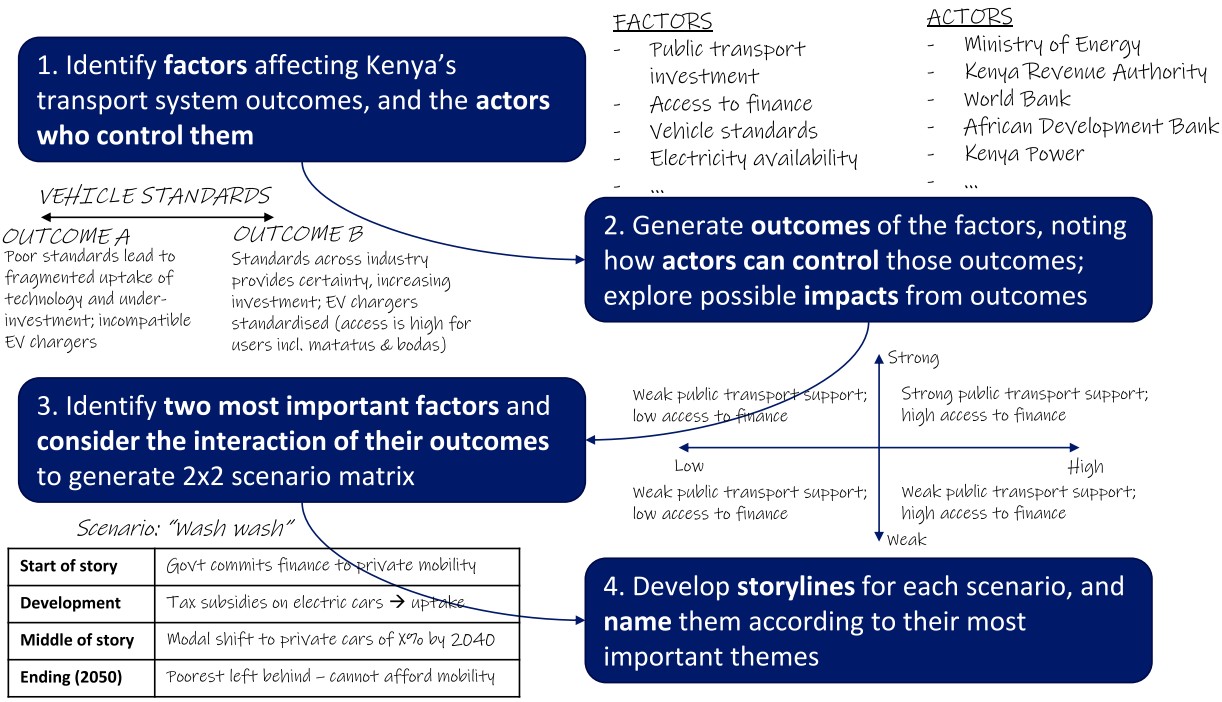

Fig. 1. Schematic summarising scenario development process used in workshop.
Source: Adapted from Ramirez and Wilkinson [55].

2. The development of a transport-energy system model for the Kenyan context, TEAM-Kenya, with an interactive results dashboard to effectively communicate model results to stakeholders.

The methodologies and results of these two contributions are described in Sections 4 and 5 respectively.

4. Kenya transport-energy futures: integrated narrative scenarios for the future transport-energy system in Kenya

4.1. Scenario development: stakeholder engagement, interviews and workshop

The study engaged in an in-depth process of consultation with 41 local experts and decision-makers to provide insights from the current state of transport in the country and the key areas of transformation in the sector but also into wider social and economic dynamics. The project included participants from national and local government (25), NGOs and international organisations (7), private sector (7) and academia (2). This process of consultation consisted of:

1. **One-on-one semi-structured interviews** led by Kenyan researchers during February–March 2023, in which respondents answered open-ended questions to convey their world-view of the transport sector;
2. An **in-person workshop**, held in Nairobi on the 28th of March 2023, with a total of 30 in-person participants, plus facilitators from the project and from the host universities in the country.

The workshop was designed and conducted based on a loose adaptation of the *Oxford Scenario Planning Approach* as detailed by Ramirez and Wilkinson [55]. This method emphasises gathering narratives from the central actors as the core-basis of scenario building. Rather than extracting knowledge or prescribing outcomes, the workshop aimed to engage participants in structured exercises to tap into their expertise and imagination. This participatory process generated contrasting scenarios based on the sector's collective experience, steering clear of detached research practices. The steps of the workshop are summarised in Fig. 1.

The workshop discussion considered the transport system itself and any part of the wider economy that was thought to influence demand for transport and the supply of technologies for it. This required participants to consider wider interrelated sectors, subjects and issues at the local, national, and international levels.

As shown in Fig. 1, the workshop activities were divided into four steps. All four steps were conducted with the participants in 3 groups of 10 individuals.

1. Firstly, participants identified the most important **actors** (as organisations, institutions, collectives) and **factors** (as the elements in the context whose outcomes directly influence actors) in the context of the sector, including socio-economic, political, environmental, technological, and geopolitical. The most important factors identified in driving the transport energy scenarios in Kenya covered diverse subjects from regulation and government, to global and socioeconomic dynamics. Fig. 2 describes eight categories of factors that comprised most of the discussion.
2. Secondly, the groups worked on describing plausible **outcomes** for each of the factors. The result is a dyadic description of future state of each factor. This step requires significant debate and these dyadic description of the factors are the building block of the scenarios.
3. Thirdly, having completed this discussion, the groups select the two factors that they view are the most significant, which are not directly related to each other, to create a quadrant system – or **two-by-two matrix** – in which specific scenarios are anchored. This means that each scenario is built based on its relative position in the quadrant or matrix, but other factors can then be integrated into the narrative of the scenario.
4. Finally, the participants were asked to provide the **storyline** of how each scenario would unfold. The starting point was chosen depending on the first crucial steps taken towards that scenario, or the event setting the scenario in motion, creating a narrative of both the future and the processes that leads to that future from today's present.

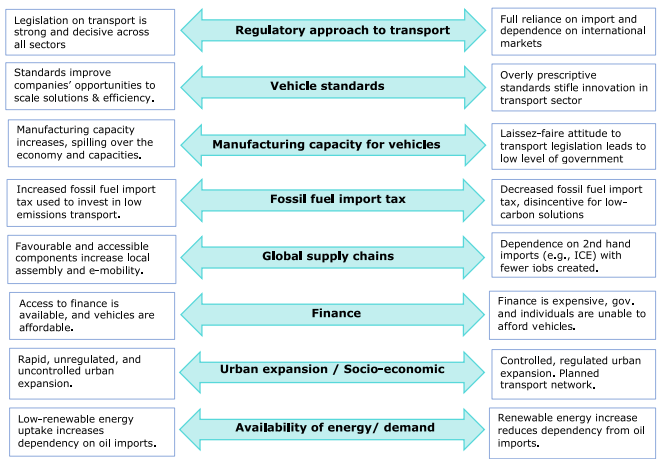

Fig. 2. Axis of key factors of change and uncertainty for scenario development.

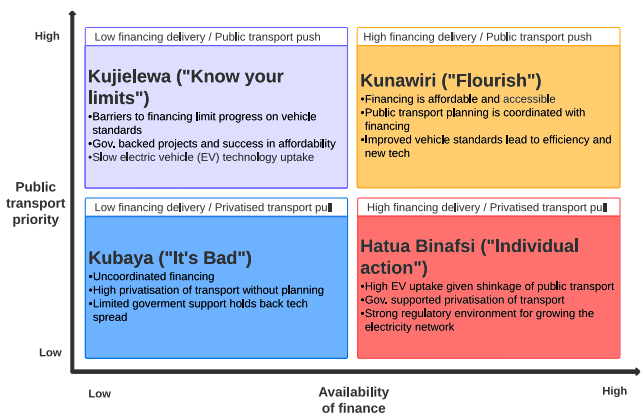

Fig. 3. Scenario matrix for Kenya transport-energy futures.

After the workshop, the research team (represented by the authors of this paper) synthesised the scenarios produced by the different groups to capture the logic of the debates. The resultant scenarios are summarised in Section 4.2.

4.2. Summary of scenarios

30 factors were identified and discussed in the workshop. Those that were deemed the most significant by participants are shown, together with their plausible outcomes, are shown in Fig. 2. In the workshop, all 3 groups chose the most important factors to be (a) the importance of public transport in policy, and (b) the availability of affordable finance.

Based on the outcome of the workshop, we present four generalised scenarios based on those presented by all 3 groups. A visual summary of the scenarios is shown in Fig. 3; more descriptive summaries of the scenario narratives are given in Table 1. These scenarios were then used to develop demand and policy levers for modelling as shown in Table 2.

5. Modelling credible impacts of future scenarios on transport-energy system outcomes

5.1. Re-introducing TEAM: Transport Energy Air pollution Model

In developing decision support tools, a strategic transport-energy systems model, the Transport Energy Air pollution Model (TEAM) [48], has been adapted to the Kenyan case from the UK case in which it was originally developed.

TEAM is a strategic transport, energy, emissions and environmental impacts systems model, covering a range of transport-energy-environment issues from socio-economic and policy influences on energy demand reduction through to lifecycle carbon and local air pollutant emissions and external costs. It is built around exogenous and quantified scenarios, covering passenger and freight transport across all modes of transport (road, rail, shipping, air). It provides annual projections up to the year 2100, is technology rich with endogenous modelling of 1246 vehicle technologies, and covers a wide range of output indicators, including travel demand, vehicle ownership and use, energy demand, life cycle emissions of 26 pollutants, environmental impacts, government tax revenues, and external costs. For more information on how TEAM works, the reader is directed to the methodology guide [56]. For a set of published research papers where TEAM has been used directly in answering a diverse set of research questions spanning many areas of the transport-energy context, see [57–63]. TEAM-Kenya, and the original TEAM-UK, are written in VBA and SQL and run using the user interface in Microsoft Access. The model is available open-access via [64].

TEAM quantifies the likely impact of policy pathways – given a background context – on transport system energy demand, GHG emissions and air pollutants. TEAM requires various inputs that come from the development of narrative scenarios that cover:

- **Context** variables, broadly defined as those that are beyond direct government control, such as fuel prices before tax, demographics and GDP per capita;
- **Policy** variables, broadly defined as those that are within direct government control, such as taxation (e.g. on fuel and vehicle purchase), vehicle purchasing (dis)incentives or scrappage rebates (e.g. tax exemption for EV purchase), and regulations (e.g. air pollution);
- **Demand** variables, broadly defined as changes to travel demand that may result from a combination of policy and context changes, such as reductions in commuter trip PKM amongst the working-age population due to growth in teleworking.

The TEAM framework can be adapted to a range of geographical and administrative scales, from city to region, country and global scales. To date, three versions have been developed and used in policy analysis: a UK version, TEAM-UK, a Scottish version, STEAM, and a South Korean version. All were designed to explore alternative transport futures to meet carbon mitigation, air quality and energy policy goals. As part of the Climate Compatible Growth (CCG) research programme [65], TEAM was adapted to the Kenyan context through co-development between academics at British and Kenyan institutions. TEAM-Kenya represents the first time that the TEAM framework is being used in a country with (i) limited data on travel demand and vehicle stocks and (ii) a sizeable second-hand imports market. These factors require some steps to re-design the fundamentals of the TEAM framework, which have been addressed as part of this project as covered in Section 5.2.

5.2. Updates to the TEAM framework for the Kenyan context

5.2.1. Data collection

Due to a persistent lack of data in Kenya regarding household characteristics, passenger travel demand and vehicle choices, this study filled the gaps in available online data by conducting a survey of households in Kenya (n = 1016) labelled the Kenya EV-APS survey. The survey was conducted by researchers at the University of Nairobi. Data collected that is directly relevant to TEAM-Kenya includes:

- The number of household members; and of those members, the number of them of driving age (over 18 in Kenya) and the number of them of public-sector retirement age (over 60 in Kenya);
- The monthly household income;

Table 1
Summaries of scenario narratives on Kenya's transport-energy futures.

Scenario	Description
Kunawiri (*'Flourish'*)	Strong legislation for transport planning focused on the efficiency of public transport planning is aided by accessible finance to accelerate the uptake of new technologies. Efficiency is actively pursued by the government by improving standards for new and imported second-hand vehicles, regulating emissions, and limiting the age of second-hand imports. Good access to affordable financing to the government, businesses and individuals, and public subsidy focused on support for *matatu* sectors means that paratransit reaches reasonably high levels of electrification and efficiency, with newer buses serving main routes in cities, and progressive digitalisation acting to formalise paratransit services across Kenya. New mass transit systems are constructed, including electric Bus Rapid Transit (BRT) systems in major cities and the development of a metro rail system in Nairobi. NMT infrastructure is provided to all new road projects in Kenya, improving safety of pedestrians, and improving the attractiveness of walking in urban centres.
Hatua Binafsi (*'Individual action'*)	E-mobility is seen as the main opportunity in the transport sector. The government takes a role in coordinating the uptake of the new e-technologies, with a focus primarily on making subsidies available for the purchase of E2Ws and E4Ws, with a lower level of subsidy on electric public transport. New regulation backs the policy focus on electrification, such as fossil fuel import taxes, yet the government lacks a role in planning transportation. Due to the focus on private vehicles and the high level of access to finance, vehicle ownership increases at the greatest rate in this scenario. Due to the increase in vehicle ownership and the comparative stagnation of public transport, traffic congestion in major cities is an increasing problem, and mobility poverty persists in lower income groups for whom vehicle ownership remains unachievable.
Kujielewa (*'Know your limits'*)	Government is active in the provision of new regulation and standards, i.e., safety, capacity, speed, road building and configuration of routes. However, high-quality BRT and other government backed projects have limited uptake due to insufficient financing. Improving transport access is a priority; cycle lanes, footpaths and public transport corridors ensure transport provision and affordability. Given budget constraints, old, imported buses and trains are still meeting the demand for passenger transport. Private cars are expensive to import. A boost in two-wheeler vehicles follows the removal of taxes to motorcycle imports. Limited finance affects e-mobility uptake across all private modes. Based on the relatively low cost of doing so, NMT infrastructure is applied to urban road developments in this scenario, which improves the safety of pedestrians.
Kubaya (*'It's bad'*)	Assumes minimal government involvement in transport planning and in providing financing access. Due to poor transport service provision, economic growth in the country is stunted. Private and largely informal transport provision continues to grow with demand, but more slowly than in other scenarios. Electrification is low due to poorly coordinated and piecemeal planning in supporting infrastructure. Old vehicles prevail given inadequate financing opportunities. In this scenario, new technologies – such as electric buses and electric two-wheelers – see a modest level of adoption but at the hand of private operators with their own charging infrastructure.

- Travel patterns of a representative individual from each household, including (i) the frequency of trips made in a month by purpose (4 purposes) and mode (10 modes), and (ii) their expected average kilometrage on weekdays and weekends.

5.2.2. Context data

Unlike other prominent transport-energy models used in LMICs (e.g. OSeMOSYS [42] and LEAP [45]), demand data is not directly input into TEAM (other than the base year). Instead, the evolution of demand is simulated as a function of a set of context data: GDP per capita, population, the number and structure of households, household-level income, technology costs and technology availability. Data for household characteristics were input from the Kenya EV-APS survey data (Section 5.2.1); data for technology costs and availability are further detailed in Section 5.2.3.

Aside from a lack of data on the current state in Kenya, there also exists a lack of forecasts for future trends. This study uses several broad assumptions and proxies to produce forecasts for context data in the future. Key assumptions regarding key variables are listed below:

- **Number and structure of households**: In this study, number of households are assumed to grow at same rate as overall population.
- **Household income/income growth rate**: In this study, household income is assumed to change at the same rate as GDP per capita.

Other context data for TEAM-Kenya are the total number of households and urban/rural split [66]; the total population and predicted growth [67]; and the recent historic and predicted GDP growth rate — the baseline case for the latter taken from the IEA's Stated Policies scenario from their Africa Energy Outlook [68].

Technology costs were kept the same for Kenya as they were for the UK, based on the assumption that the relative baseline costs of those technologies are the same between those two countries. (Note that costs are changed for second-hand imported technologies, as further explained in Section 5.2.3.)

5.2.3. Vehicle stock model

Vehicle stock data: The vehicle stock in TEAM-UK was represented by 1246 vehicle technologies across seven modes (motorcycle, car, bus and coach, van, truck, ship and aeroplane). Due to the prevalence of second-hand imported vehicles in Kenya, and their relative importance to the vehicles registered each year, more technologies were introduced to the model to represent those second-hand technologies. Second-hand import technologies were created based on all car, minibus, truck, train and ship technologies. The two changes made to the underlying new technology data were that: (i) the year of availability and the year of phase-out was lagged relative to the corresponding new technology by eight years, to represent the maximum age at which a second-hand road vehicle can be imported into Kenya; (ii) the purchase price of each technology was set to a fraction of the purchase price of its corresponding new technology. Based on a survey of car showroom websites in Kenya, and advice from representatives of the Ministry of Transport who were present at the scenario development workshop, this fraction was set to 0.4 for all scenarios. When including the second-hand import technologies, the total number of technologies in TEAM-Kenya is 2246.

Technology choice model: Technology choice is modelled in TEAM differently according to different segments of the vehicle market. For full details, see the TEAM reference guide [56]. For cars and vans, the model is most complex. A multinomial logit model is used to predict the relative market shares of each technology in a given year, which is influenced by a set of cost (e.g. upfront costs, fuel costs) and non-cost (e.g. range anxiety, technology supply penalty based on market availability of battery electric makes and models) attributes in a given year and how those attributes might be influenced by any chosen policies. The choice parameters that drive the multinomial logit model in TEAM-UK were based on stated choice experiment data conducted by Anable et al. [69]. At present, because of a lack of data to suggest otherwise, it is assumed that the choice parameters that drive car and van technology uptake in Kenya are the same as those for the UK.

Another major change made to the choice model relates to the representation of the second-hand imported vehicle market. It is estimated that, in 2019, 85% of cars registered on the road that year were second-hand imports [70]. Second-hand imports also make up a sizeable proportion of the market for registrations of minibuses (used as smaller 11–14 seater *matatus*), intercity coaches, trains and trucks. Due to a lack of available data, it was assumed that the 85:15 split in cars is also true across those other sectors. It was assumed that the 85:15 split is fixed for the base year and all future years, though it is a scenario variable to be explored in future scenario-building exercises.

Scrappage parameters: Scrappage and vintaging is calculated in TEAM by approximating the number of scrapped vehicles of a given type (car, bus, motorcycle, etc.) in a given year from a Weibull approximation of the probability of a vehicle of that type and age being scrapped in a given year [56]. This is based on age profiles of each technology type. For Kenya, these are taken from the GIZ Transport Inventory and Greenhouse Gas Emissions Reporting (TrIGGER) project [71], which were in turn based on a modelling exercise carried out by University of Nairobi.

5.2.4. Transport demand

The base year transport demand per mode are taken from data in the TrIGGER project [71]. These data are provided in terms of VKM by mode, which are based on estimated average vehicle distances per year multiplied by the predicted number of vehicles in each segment on the road. A listed set of average occupancy rates of each vehicle was also produced for that same project as outlined in the methodology report [72], which were used in this study to calculate PKM for each mode. These travel demands are then further disaggregated into average distances travelled per person, by mode, trip length and trip purpose, based on the travel survey data collected as described in Section 5.2.1.

Passenger and freight transport demands after the base year are calculated according to the evolution of the key drivers of demand, outlined above. Modal shift relative to the base year mode shares are an exogenous input from the scenario development (Section 5.3).

5.3. Modelling drivers and levers of change

To translate the scenario narratives into quantifiable scenarios, levers were generated based on the data from the workshop and further clarification with key stakeholders. Table 2[2] shows detail on the model levers used in TEAM-Kenya with candidate policies, derived from the workshop, in actioning these levers.

Levers for public transport and NMT investment were modelled exogenously by altering the modal shift of each scenario based on input from the deliberative workshop and expert interviews (Fig. 4).

5.4. Model results

5.4.1. Vehicle stock

Fig. 5 shows the evolution of active vehicle stock by type and powertrain for each scenario, allowing comparison for the years of 2030, 2040 and 2050.

The total vehicle fleet increases between 3.4 (*Kubaya*) and 6.6 (*Hatua Binafsi*) times from the base year of 2015 (calibrated to vehicle stock data of the same year in the TrIGGER dataset [71]). The total number of vehicles increases in every vehicle type across all scenarios, but the highest variation is expected in the number of motorcycles.

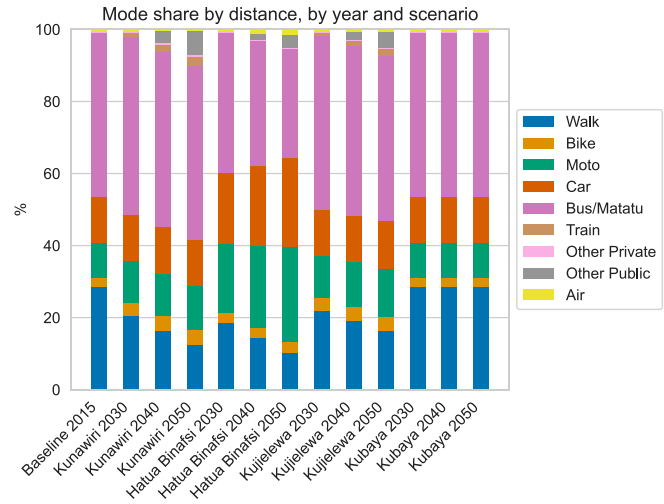

Fig. 4. Modal shift by scenario for 2030, 2040 and 2050.

This is driven primarily by the calibration of the model between the years 2015 and 2017 – and hence the rapid growth of the motorcycle stock – and by modelling the Kenyan government's existing policies in the motorcycle segment that have been driving the sector, namely the elimination of import tax for locally assembled motorcycles. In the higher uptake scenarios, particularly *Hatua Binafsi*, subsidies directed at alternative fuel vehicles (without levies raised on other technologies) act to reduce the average price of vehicles in each vehicle type, which further drives growth in vehicle numbers.

Fig. 5 shows the dominance of fossil fuelled vehicles in the base year (2015), with the vast majority of light road vehicles (motorcycles and cars) being powered by petrol, the vast majority of heavy road vehicles (buses, *matatus*, trucks) being powered by diesel, and other vehicles (ships, trains and planes) powered by other petroleum-based fuels. Over time, the rate of uptake of alternative fuel vehicles varies significantly by scenario. This is driven by the subsidies on different powertrains within each vehicle type, changes in awareness of EVs and access to charging (Table 2). Motorcycles see the most consistent electrification across all scenarios, with the exception of the *Kubaya* scenario in which only 9% of motorcycles are battery electric by 2040. Strong uptake in other scenarios is due to (i) the comparatively short mean age of a motorcycle in Kenya, estimated to be 3 years in [71], and thus the high turnover rate of stock, and (ii) the reduction in running costs of electric motorcycles, which quickly pose relative advantages to petrol-powered counterparts under the supposed continuation of the Kenyan government's current policies (the removal of VAT for E2Ws, as announced in 2023 [27]). This is in general agreement with scenario analysis in [73], in which it is predicated that E2Ws will compose 60%–75% of the Kenyan motorcycle stock by 2040.

5.4.2. VKM

Fig. 6 shows the change in VKM by vehicle type and powertrain for each scenario, allowing comparison for the years of 2030, 2040 and 2050.

VKM are shown to increase dramatically in all scenarios, in accordance with baseline projections regarding increasing population and wealth. Even in the *Kubaya* scenario that depicts low financing delivery and privatised transport pull, total VKM are projected to increase by a factor 2.4 between 2015 and 2040. In higher growth scenarios, the projected increase is higher — up to 4.1 in the case of the *Hatua Binafsi* scenario to 2040. This increase, higher than the other high-growth scenario, *Kunawiri*, is primarily due to the growth in private vehicle

[2] A note regarding vehicle subsidies: from consultation with local experts through the workshop, motorcycles in Kenya are assumed to be locally assembled from knock-down kits, thus making all motorcycles ineligible for import taxation placed on road vehicles.

Table 2
Detail on model levers used to translate storylines into modellable scenarios in TEAM-Kenya.

Lever	Affects	Kunawiri	Hatua Binafsi	Kujielewa	Kubaya	Potential policies
GDP per capita and household disposable income	Transport activity	Avg. 5.6% compound increase 2023–2050.	Avg. 5.2% compound increase 2023–2050.	Avg. 4.7% compound increase 2023–2050.	Avg. 3.7% compound increase 2023–2050.	*Context variable.*
Public transport (PT) investment	Mode shift (see Fig. 4)	High PT investment supports mode shift away from walking to bus/matatu, rail and light rail/metro. In 2050, 48%, 3% and 6% are the distance-based shares of those modes respectively.	Low priority of PT fails to lock-in attractiveness; passengers shift towards private 2W/4 W use. In 2050, 26% and 25% are the distance-based shares of those modes respectively.	High priority of PT supports sector, but lack of finance constrains ambition: walking shares move to PT, but slower than for *Kunawiri*.	Lack of focused policy and low access to finance leads to stagnation of current modal shares (no change 2015–2050).	Development of large-scale public transport projects (BRT; underground rail) and formalisation of paratransit, including creation of bus lanes in urban centres and improvement of reliability, can make public transport more appealing and efficient, thus improving economic efficiency and discouraging car use in urban environments.
Non-motorised transport (NMT) investment	Mode shift (see Fig. 4)	Infrastructure investment means that NMT becomes an active choice. 12/4% distance walked/cycled in 2050.	Low priority sees shift away from NMT to private motorised modes: 9/2% distance walked/cycled in 2050.	Some priority in NMT, but due to poor finance many still walk not out of choice. 16/3% distance walked/cycled in 2050.	Lack of focused policy and low access to finance leads to stagnation of current modal shares (no change 2015–2050).	Investment in NMT infrastructure discourages car use in urban environments, and can vastly improve the wellbeing of non-motorised transport users who currently walk and cycle not out of choice but poverty.
Road vehicle subsidies (purchase tax waivers)	Technology uptake	No taxes on e-buses from 2025 and E2Ws from 2028; import duty reduction for E4Ws from 2040; VAT reduction for electric and hydrogen trucks from 2035.	No taxes on E2Ws and E4Ws from 2025; reduction in import & excise duties and VAT on e-buses from 2040; removal of taxes for electric trucks from 2035	Removal of VAT on E2Ws by 2025 (as per statement made by Kenyan Government, 2023 [27]).	No subsidies relative to current taxation regime (25% import tax, 10% registration tax and 16% VAT on road vehicles).	Subsidies for alternative powertrains within certain vehicle types influences technology uptake within that mode and can be used to direct government spending in subsidy (e.g. prioritising electric buses over cars).
Charging infrastructure	EV uptake	100% of EV users have access to overnight charging by 2035.	100% of EV users have access to overnight charging by 2030.	75% of EV users have access to overnight charging by 2040 (no further increase).	50% of EV users have access to overnight charging by 2040 (no further increase).	Development of taskforce for EV charging provision, linking electricity grid operators with local governments, EV manufacturers and local points of interest where charging could be located.
Awareness and market availability of e-mobility	EV uptake	100% consumers aware of EVs & any subsidies by 2032.	100% consumers aware of EVs & any subsidies by 2028.	75% consumers aware of EVs & any subsidies by 2035 (no further increase).	50% consumers aware of EVs & any subsidies by 2035 (no further increase).	Awareness campaigns and public advertising (or enabling private sector companies to build public awareness) can grow awareness of EVs and subsidies.

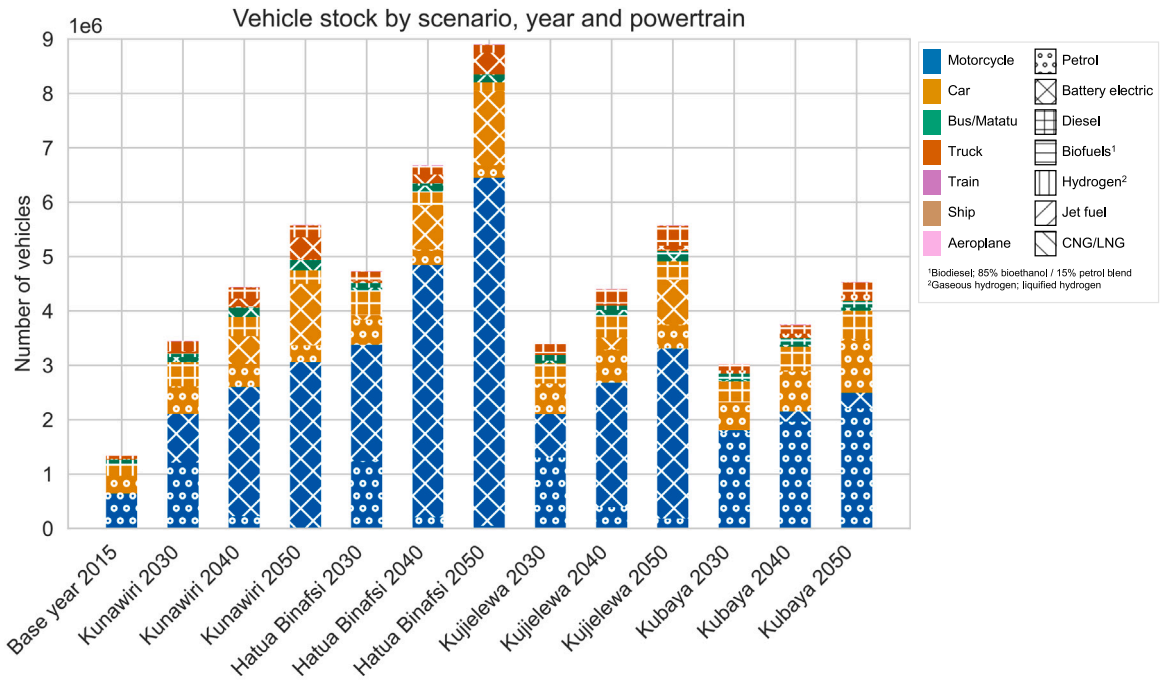

Fig. 5. Total active vehicle stock by year, scenario and technology.

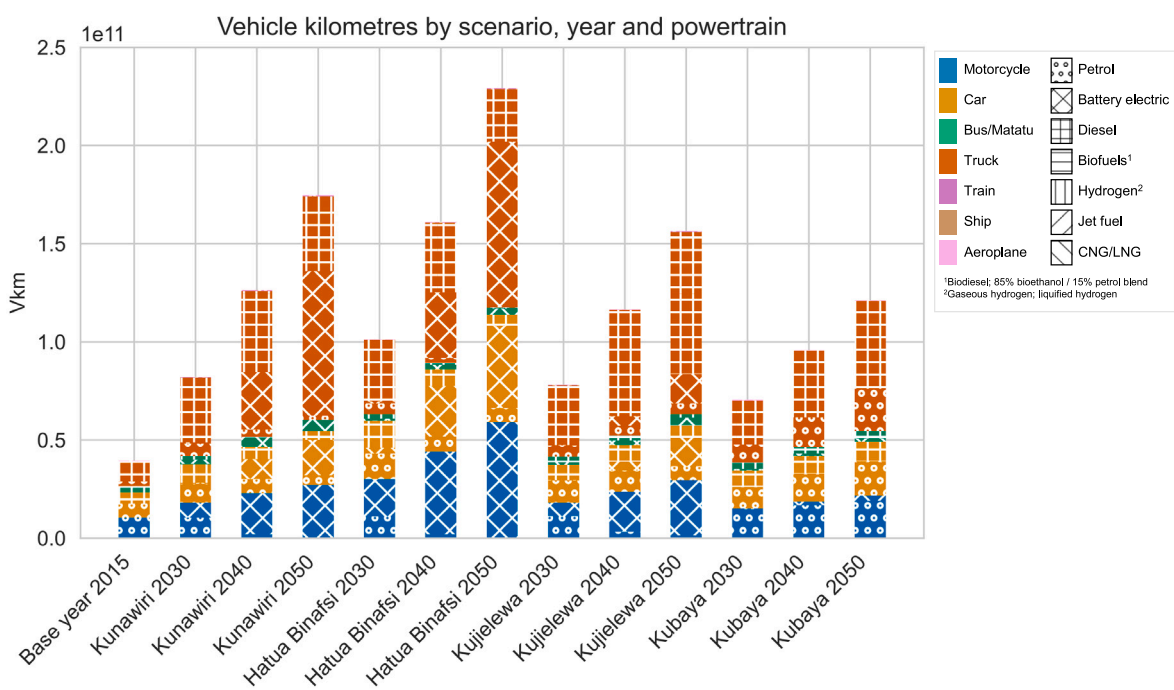

Fig. 6. Total VKM by year, scenario and technology.

usage. In *Kunawiri*, there are still significant increases in motorcycle and car VKM (increasing by factors 2.2 and 1.8 respectively between 2015 and 2040), but the increase is driven by increases in bus/matatu VKM (increasing by a factor 1.8) and particularly truck VKM (increasing by a factor 5.8). The increase in truck VKM is consistent with the strong forecasts in freight and international trade within the African continent — in the African Union Development Agency's Africa Transport Outlook 2040 [74] (published in 2010), the authors predict that African freight demand increases by up to a factor 6 between 2010 and 2040, a broadly similar timescale to what is stated in the current study.

5.4.3. Energy consumption

Fig. 7 shows the change in total primary energy consumption by vector (fuel or electricity) for each scenario, allowing comparison for the years of 2030, 2040 and 2050.

Whilst Fig. 6 shows that transport passenger and freight activity, as measured by total VKM, is projected to increase significantly – between 2.5 and 4.8 times – between 2015 and 2050, Fig. 7 paints a picture of less stark changes in magnitude. The high-growth scenarios, *Kunawiri* and *Hatua Binafsi*, show the greatest increase in transport activity and also the greatest transition from petrol and diesel to other energy vectors, particularly electricity. In Fig. 7, most of the increase in energy

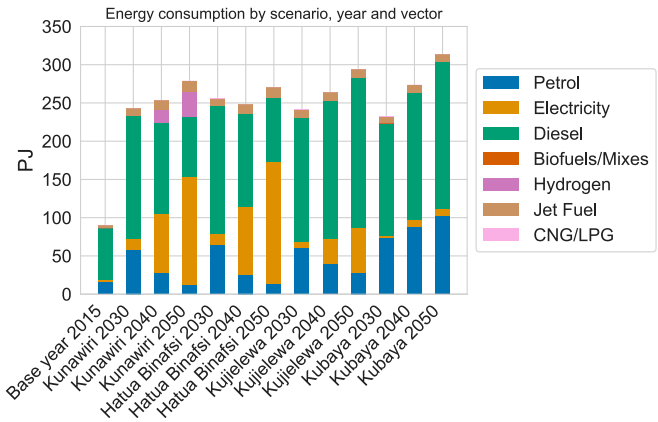

Fig. 7. Total primary energy consumption by year, scenario and vector.

demand between 2015 and 2050 happens in the first 15 years (i.e. 2015 to 2030). This is commensurate with (i) this being a longer interval than between the other comparison years, and (ii) the fact that much of the alternative vehicle uptake – particularly battery electric – is shown in Figs. 5 and 6 to happen after 2030. As battery electric vehicles are typically 3–4 times more energy efficient than their fossil-fuelled counterparts [75], it stands to reason that the increase in overall energy consumption should not be as stark as the increase in transport activity, if a shift to electric powertrains accompanies a growth in service demand. Because of the low efficiency of burning fossil fuels to produce kinetic energy, the *Kubaya* scenario, whilst having the lowest VKM by 2050, has the highest transport sector primary energy consumption by 2050 of 320 PJ.

Across all scenarios, demand for electricity for transport increases significantly. By 2040, the total annual demand for electricity in the transport sector reaches 8 PJ in the *Kubaya* scenario, 33 PJ in *Kujielewa*, 78 PJ in *Kunawiri* and 89 PJ in *Hatua Binafsi*. Kenya's total electricity consumption for all sectors in 2022 was 44 PJ [76]: at first glance, it seems that electricity demand for transport in the high e-mobility scenarios (*Kunawiri* and *Hatua Binafsi*) is significantly higher than what could reasonably be achieved. However, this stark increase is not without precedence. In their Kenya Energy Outlook, the IEA predict that Kenyan electricity consumption will rise to 158 PJ by 2040 under the 'Stated Policies' scenario [77], which contains virtually no policies relating to e-mobility (in this scenario, only 0.5% of African transport energy demand will be from electricity by 2040) [68]. Therefore, if electricity does become a significant energy vector for transport in line with the scenarios in this study, e-mobility will increase electricity demand in Kenya by 5%–56% in 2040, relative to the IEA's scenario as the baseline demand for the wider economy. Taking that baseline into account, the total electricity demand in Kenya is likely to increase 2.7–3.9x relative to 2023, in only 17 years. This means that unprecedented levels of investment, in generation and network infrastructure, are required to support this transition. Kenyan policymakers can leverage international development finance in actioning these investment priorities to support its low-carbon growth. Additionally, support for technologies that can assist with the integration of e-mobility and electricity systems can reduce the burden of e-mobility growth on the grid, including smart charging [78] and vehicle-to-grid [79].

Kunawiri is the only scenario that sees growth in hydrogen demand in the transport sector, a direct result of subsidies applied to hydrogen fuel cell-powered trucks (Table 2). In *Kunawiri*, hydrogen demand in the transport sector reaches 17 PJ by 2040 and 33 PJ by 2050. However, even under these favourable environments for hydrogen in transport, hydrogen fuel cell trucks only make up 4% of total truck stock by 2050 in the *Kunawiri* scenario (compared to 64% battery electric and 31% diesel).

5.4.4. Greenhouse gas emissions

Fig. 8 shows the change in transport sector direct GHG emissions for each scenario, allowing comparison for the years of 2030, 2040 and 2050.

Kenya's updated NDC (as of COP26, Glasgow 2021) states that the country aims to reduce whole-economy emissions by 32% by 2030 versus the BaU projection of 143 $MtCO_2e$ by that year (therefore, the country aims for an economy-wide emissions of 97 $MtCO_2e$ by 2030). The NDC offers no transport-specific breakdown of emissions, but Fig. 8 offers insights to the transport-sector emissions implications of the scenarios modelled. By 2030, transport sector emissions are shown to increase between 145% (*Kujielewa*) and 159% (*Hatua Binafsi*) relative to the 2015 baseline. Commensurate with the results presented in Fig. 7. At this point, transport demand has grown (see Fig. 6), but the introduction of low-carbon technologies has not yet begin to offset this growth. In the high e-mobility uptake scenarios, *Kujielewa* and *Hatua Binafsi*, emissions are seen to reduce between 2030 and 2050. In *Kujielewa* and particularly *Kubaya*, emissions continue to increase to 2050, at which point in *Kubaya* they total 25.5 $MtCO_2e$, 226% higher than in 2015. Whilst any of these final emissions values could fit within the overall 97 $MtCO_2e$ emissions by 2050 required for meeting the NDC target, clearly lower emissions from transport puts less pressure on other emissions-intensive sectors that will see their demand grow as Kenya develops, including agriculture and construction. From this perspective, the *Kunawiri* and Hatua Binafsi pathways clearly represent policy packages that are favourable in Kenya meeting its ambitions.

Of course, any change in emissions must be considered with the change in transport services, which is critical in supporting Kenya's economic development. Whilst *Hatua Binafsi* was shown in Fig. 6 to provide the largest increase in vehicle activity, *Kunawiri* involves the highest level of modal shares in public transit (Fig. 4), which benefits lower-income groups and thus represents a pathway to more inclusive growth in Kenya's development.

Fig. 9 shows the transport sector emissions intensity of each scenario for every year 2015–2050 (total emissions divided by the GDP per capita of the wider economy, in US dollars).

The emissions intensity reduces over time in all scenarios, and begins to stabilise towards the late 2040s. This trend is commensurate with general trends observable as economies develop: for example, the UK, with a largely service-based economy, has an emissions intensity of approximately 2 tCO_2e/US$ GDP per capita, which aligns with the 2050 Kenyan value for the *Kunawiri* scenario. The GDP forecast drives many elements within the transport sector, including freight demand, vehicle purchase and passenger transport activity; therefore, the results in Fig. 9 show that the low-carbon, high-growth scenarios (*Kunawiri* and *Hatua Binafsi*) see Kenya achieve an emissions intensity akin to the present value of an industrialised nation within the next 2–3 decades.

5.4.5. Fuel tax revenues

Fuel taxes, typically imposed on gasoline and diesel fuel, have historically been a significant source of revenue for governments, including the Kenyan government. As low-carbon growth in these scenarios depends on significant shifts to e-mobility (Fig. 7), there is a growing realisation that traditional fuel tax revenue streams may be at risk. In this paper, we take the Kenyan government's current fuel tax rates (applied by the Kenya Revenue Authority (KRA) through the Kenya Power and Lighting Company (KPLC) for electricity and the Energy & Petroleum Regulation Authority (EPRA) for liquid fuels), and apply them to rate at which fuels are consumed. Note that for several alternative fuels (e.g. hydrogen), there is no established taxation policy. Relevant assumptions are stated in the 'notes' column in Table 3. Fig. 10 shows the total fuel tax (including electricity sales tax for transport) for all scenarios by year; Fig. 11 provides a breakdown for the three most significant fuels across all scenarios: petrol, diesel and electricity.

Figs. 10 and 11 show that the *Kubaya* scenario sees the highest contribution to tax revenue from the sale of fuels for transport: this

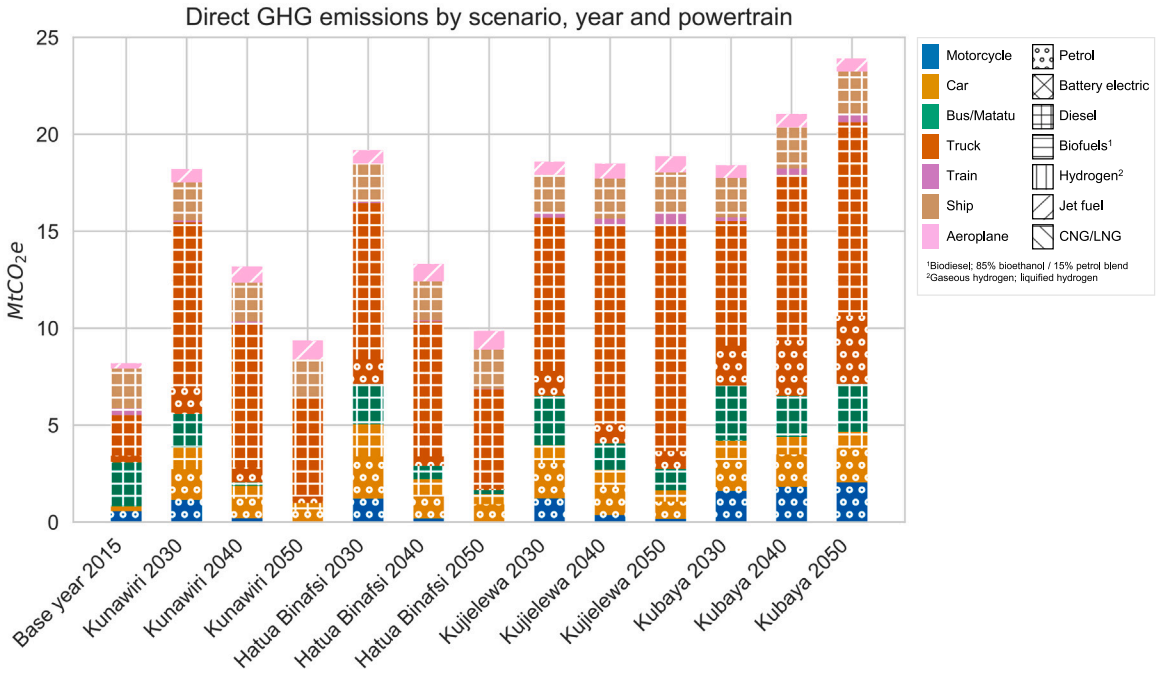

Fig. 8. Direct greenhouse gas emissions by year, scenario and technology.

Table 3
Taxation rates applied to transport fuels in Kenya.

Fuel	Taxation rate	Notes
Petrol	50 KSh/l + 16% VAT	EPRA and KRA apply total levies (excise duty; road maintenance levy; petroleum development levy) on petrol equalling 62 KSh/l, but spend 12 KSh/l on subsidy for 'price stablisation'. Petrol is subject to 16% VAT on the price of fuel (this was raised from 8% in 2023), including the levies.
Diesel	22 KSh/l + 16% VAT	EPRA and KRA apply total levies on petrol equalling 50 KSh/l, but spends 28 KSh/l on subsidy for 'price stablisation'. Diesel is subject to 16% VAT on the price of fuel (this was raised from 8% in 2023), including the levies.
Electricity	5% rural electrification levy + 16% VAT	EPRA and KRA apply a 5% levy on electricity to fund electrification of rural areas in Kenya; furthermore, electricity is subject to the standard 16% VAT rate.
Kerosene (jet fuel)	8% VAT	KRA apply a reduced rate of 8% VAT on kerosene to encourage its uptake for cooking.
LPG	8% VAT	KRA apply a reduced rate of 8% VAT on kerosene to encourage its uptake for cooking.
CNG	8% VAT	There is no established taxation policy for CNG in Kenya. It is assumed that it would be taxed at the same rate as LPG.
Hydrogen	16% VAT	There is no established taxation policy for hydrogen in Kenya. It is assumed that it would be taxed at the standard VAT rate.
Biofuels (bioethanol, biodiesel)	16% VAT	KRA apply a 16% VAT rate on ethanol.
Heavy fuel oil (shipping)	16% VAT	KRA apply a 16% VAT rate on shipping fuels.

is commensurate with high taxes on petroleum fuels and increasing vehicle activity. On this basis, the *Kubaya* scenario sees a 84% increase in total fuel tax receipts from 2015 to 2050 if fiscal policy (Table 3) is fixed. Against this baseline of a fossil fuel-based transport system, the other scenarios see a less pronounced rise over that same period (notably, no scenarios see a drop in tax revenues relative to the base year). Because of large-scale fuel-switching, the *Hatua Binafsi* sees the steepest drop versus *Kubaya*, whereby the total taxation in 2050 is 41% less in comparison. Whilst the gap between these scenarios is naturally concerning, the finding that these reductions are relatively small is in stark contrast to other countries. For instance, the UK expects significant decreases in fuel duty income, with a range of options on the table to mitigate revenue losses, including dynamic road pricing and introducing a separate fuel duty on road electricity at the point of charging [62]. For Kenya, due to the relatively high level of taxation on electricity and the forecast increase in transportation activity as the country undergoes sustained economic growth, it is likely that the government can continue to rely on income from the sale of energy vectors for transport for many decades to come.

5.4.6. Fuel import bill and foreign exchange

Whilst the reduction in petroleum consumption directly results in decreased fuel sales taxation revenue under the Kenyan government's current tax rules (Table 3), it also has a distinctly positive macro-fiscal effect. Kenya has no oil refinery and imports 100% of its transport fuel as refined petroleum products. As these goods are bought on the global market, Kenya must raise US dollars in order to import these products. Fuel imports in 2022 made up a quarter of the country's import bill [80] and is the single largest demand on foreign exchange. Conversely, a transport-energy future based on e-mobility can stimulate the Kenyan economy by creating demand for products that can more readily be owned and traded by Kenyan businesses (for example, electricity generation from renewable energy resources).

Fig. 12 shows the total Kenyan fuel import bill for all four scenarios from the base year to 2050. In this analysis, it is assumed that the price

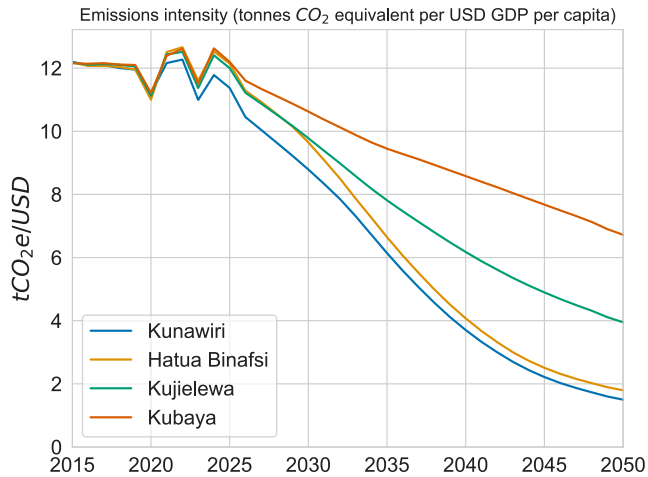

Fig. 9. Emissions intensity (tonnes CO_2 equivalent per US$ GDP per capita) by year and scenario.

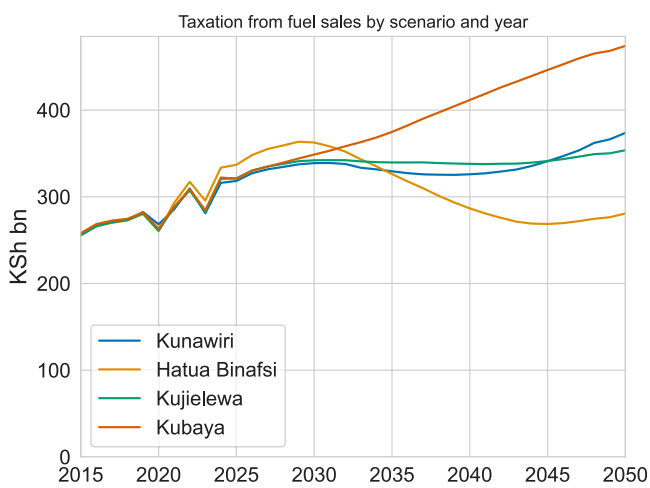

Fig. 10. Total revenues from fuel and electricity sales tax by year and scenario.

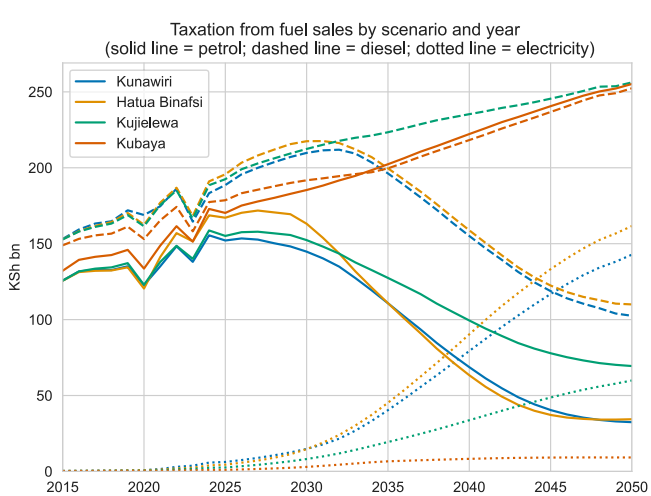

Fig. 11. Total revenues from petrol, diesel and electricity sales tax by year and scenario.

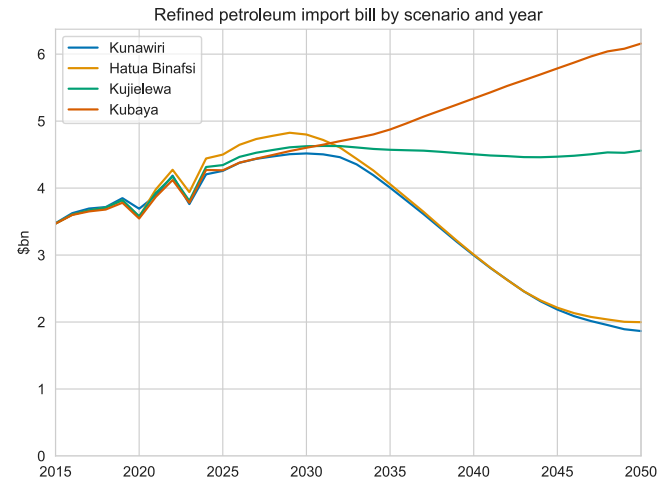

Fig. 12. Total Kenyan petroleum fuel (petrol and diesel) import bill in US dollars for all scenarios and years.

of imported petroleum fuel in Kenya remains the same as it was in 2022 ($0.72 per litre), based on the total fuel import bill [80] and volume of fuel imported [81].

Fig. 12 shows that the most fossil fuel-dependent scenario, *Kubaya*, produces the highest dependency on fuel imports and therefore the highest demand for foreign exchange: by 2050, $6.2 bn is needed annually for transport fuel imports. Conversely, in high e-mobility scenarios, the fuel import bill reduces from its present value (just over $4 bn in 2022 [80]) to approx. $2 bn annually by 2050. This represents a saving of 69%, or $4.2 bn, versus the *Kubaya* scenario.

5.4.7. *Online dashboard*

There is a TEAM-Kenya online dashboard for quick and easy communication of these results (Fig. 13). Users can explore scenario descriptions via climatecompatiblegrowth.github.io/team-kenya/.

6. Conclusion and further work

This paper has presented the development of a set of transport-energy futures for Kenya, co-created with a wide selection of stakeholders, in exploring how the country can meet its goals in economic development in a manner that is compatible with global climate targets. It places these results and lessons learnt from the project amongst the discourse on building decision-support tools in the generally data-poor context of an LMIC, thus generating valuable knowledge for rolling out similar tools across other emerging economies, many of which face similar challenges to Kenya.

Based on in-depth engagement with 41 local experts and decision-makers, it was identified that the two most important factors for the future of the Kenyan transport system are (i) the access of both government and consumers to finance, and (ii) the level of government priority in public transport. Based on varying these two axes, four scenarios were developed. These scenarios were modelled using TEAM-Kenya for their impact on the vehicle stock, transport activity, energy consumption and greenhouse gas emissions of the Kenyan transport system; further fiscal implications, specifically emissions intensity and fuel tax revenues, were then discussed.

From this work, we make the following conclusions:

1. The Kenyan transport system can evolve in a climate-compatible manner, vastly expanding passenger and freight services whilst maintaining a level of overall emissions within an acceptable level for the realisation of Kenya's climate mitigation goals as per its NDC. This requires strong policy decisions in public transport

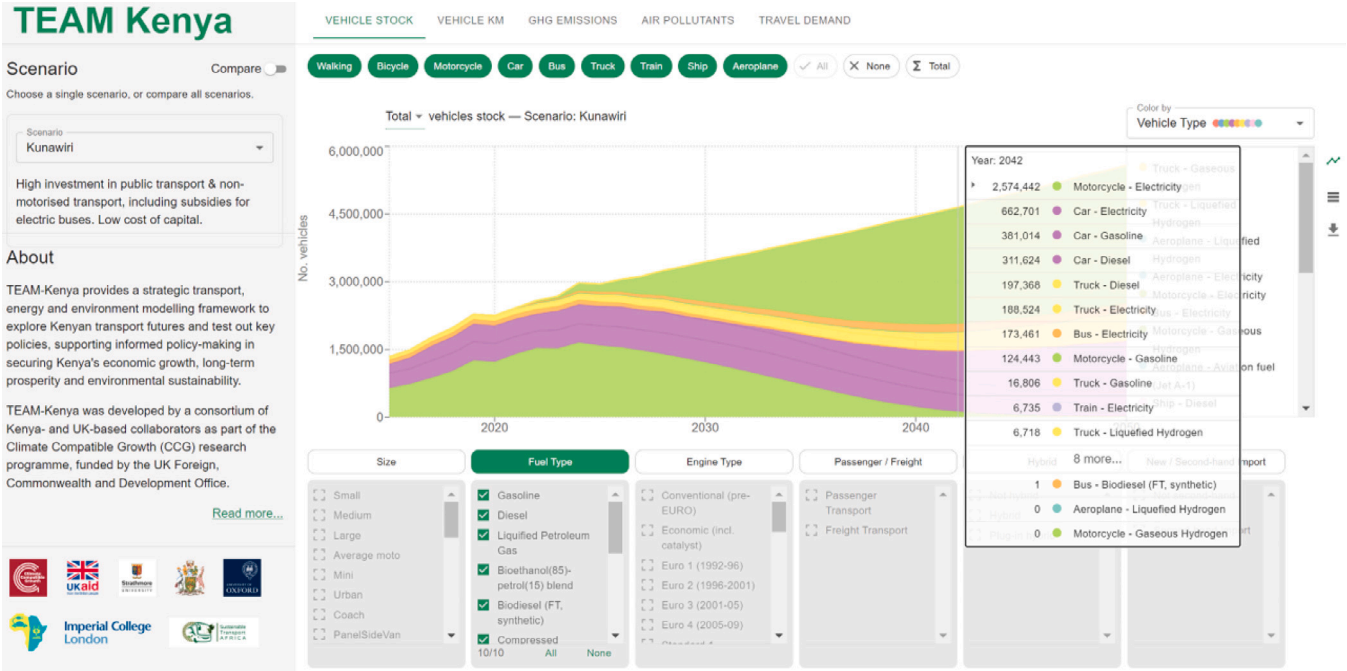

Fig. 13. Screenshot of TEAM-Kenya dashboard to be used for communication of results with decision-makers.

and targeted support for the electrification of road vehicles, whilst increasing support for non-motorised travel to ensure an inclusive transition.

2. Kenya's transport sector emissions intensity (tCO2/GDP per capita) can be brought in-line with that of an industrialised nation in the next 2–3 decades if the policies as outlined above are pursued.
3. E-mobility uptake in the presented scenarios will cause electricity demand in Kenya to increase 5%–56% by 2040 relative to the IEA's Stated Policies scenario for Kenya, which in total represents a 2.7–3.9x increase relative to consumption in 2022. Therefore, unprecedented investment in generation and network infrastructure is needed to support this transition (see point on international development finance below).
4. Whilst no scenario resulted in a reduction in taxation revenue from the sale of transport fuels, high e-mobility scenarios (particularly *Hatua Binafsi*) see a sharp reduction (up to 41%) in taxation revenue relative to the fossil fuel-dependent *Kubaya* scenario.
5. The loss in taxation revenue is offset by the reduction in fuel import bill associated with scenarios involving high e-mobility uptake. In the high e-mobility *Kunawiri* and *Hatua Binafsi* scenarios, the fuel import bill can be reduced by 69% – saving $4.2bn annually – by 2050 versus the fossil fuel-dependent *Kubaya* scenario.
6. The scenario with the highest emphasis on public transport (*Kunawiri*) had a higher impact in reducing walking compared to other scenarios, indicating a higher level of transport access and affordability.
7. The most favourable scenarios rely on good access to finance, which was identified as a crucial axis in the future of the Kenyan transport-energy system. Kenyan policymakers can leverage international development finance to lock in international support for the infrastructure required to support this transition by the use of decision support tools such as the one presented in this paper. Evidence from these tools can be used as part of national policies, NDC revisions and (for example) the World Bank's Country Climate and Development Reports (CCDRs). However, the onus must also be on the international community to make those funds available for Kenya.

In the future, it is recommended that the scenarios co-developed in this project are used as a basis to draft specific policies for the Kenyan transport sector, including for the upcoming E-mobility Strategy. In the long term, TEAM-Kenya will be maintained and used by Strathmore University (Nairobi) and the Africa E-mobility Alliance (AFEMA), and its use will be promoted for adaptation to other SSA states. As a demonstration of developing scenarios and applying decision-support tools to the transport-energy system in an LMIC, the lessons learnt from this study are applicable to a great many nations around the world that suffer a scarcity in such detailed decision support.

To reflect on the lessons learnt from this project, there remains a gap in a modular transport-energy systems support tool that can enable detailed socio-technical scenario development by stakeholders, but one that is flexible enough to apply readily in different country contexts with widely differing levels of data availability. TEAM-Kenya required bespoke alterations of a pre-existing model which was developed for a very different context (the UK); for the future, it is recommended that a modular socio-technical transport-energy modelling framework be developed to allow rapid deployment in different countries.

CRediT authorship contribution statement

James Dixon: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Funding acquisition, Supervision. **Elena C. Pierard:** Investigation, Data curation, Formal analysis, Writing – original draft. **Patrick Mwanzia:** Conceptualization, Methodology, Investigation, Writing – original draft. **Paschal Giki:** Methodology, Data curation. **Joshua Oduor:** Data curation, Writing – original draft. **Ignatius Maranga:** Conceptualization, Data curation. **Dominic Kemei:** Conceptualization, Data curation. **Joseph Onjala:** Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft. **Francis Mwangi:** Writing – original draft. **Warren Ondanje:** Conceptualization, Data curation, Writing – original draft. **Christian Brand:** Conceptualization, Methodology, Supervision, Funding acquisition, Writing

– original draft. **Thomas Courtright:** Conceptualization, Data curation. **Paul Muhia:** Conceptualization, Data curation. **Thomas Bundi:** Conceptualization, Data curation. **Samuel Balongo:** Conceptualization, Data curation, Formal analysis. **Tang Li:** Conceptualization, Methodology, Data curation, Formal analysis. **Abel Oyuke:** Conceptualization, Data curation, Formal analysis. **Winnie Mitullah:** Conceptualization, Methodology, Data curation, Funding acquisition, Supervision. **Aruna Sivakumar:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. **Holger Dalkmann:** Conceptualization, Funding acquisition. **Vivien Foster:** Writing – review & editing. **Stephanie A. Hirmer:** Conceptualization, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: James Dixon reports financial support was provided by Foreign Commonwealth & Development Office. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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