

Critical and bulk material considerations for designing low-carbon transport-energy pathways in Kenya

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ABSTRACT

This paper evaluates critical and bulk material demand and associated emissions for Kenya's transport-energy futures using a bottom-up transport-energy-environment model (TEAM-Kenya) and a material demand projection tool (Mat-dp). Four pathways reflect varying levels of government involvement, shaping divergent pathways for transport electrification, vehicle ownership, and public transit to 2050. Scenarios prioritising public transport infrastructure and accessible finance drive higher material demand linked to electrification but yield lower overall emissions and reduced fuel import dependency, which consumes a significant proportion of Kenya's foreign exchange requirements. Scenarios with minimal government intervention sustain reliance on internal combustion engine vehicles, producing higher fuel imports despite lower vehicle material demand. Critical minerals and material demand grows under high electrification pathways reaching 0.13 Mt by 2050 in the highest-electrification scenarios and 0.07 Mt in the lowest. Battery materials and non-aluminium metals together rise from 19 to 22% of critical material demand in 2025 to 42–48% by 2050 in high electrification pathways but only reach 18% in the lowest electrification pathway. Embodied emissions from material production reach 1.8–2.3 Mt CO₂e for bulk materials and 1.0–1.3 Mt CO₂e for critical materials by 2050, an order of magnitude below direct transport emissions. The additional battery-import cost under high-electrification pathways offsets only 12–19% of the annual fuel-import saving they deliver, indicating that fossil-fuel import dependence is not substituted for an equivalent battery dependency. These findings underscore the importance of coordinated policy support for electrification and mass transit to balance material resource needs with emissions reductions.

1. Introduction

1.1. Background

Vehicle adoption in Low-and Middle-Income Countries (LMICs) is rapidly increasing alongside transport demand. LMICs face the challenge of increasing transport provision availability while reducing emissions based on local and international commitments. This is not the only challenge, transport technology uptake requires increasing demand

for materials and components. Such materials are used in new vehicle technologies across road, rail, water and air modes supplying passenger and freight transport demand [1]. Materials identified include critical minerals such as cobalt, nickel or lithium, as well as bulk materials like steel, aluminium and cast iron [2]. Despite low-carbon transport transitions being widely studied and the growing literature on materials for energy systems [3–5], the studies covering LMICs remain limited, both for projected transport modes and for material considerations for transport technologies, which is in part due to the lack of available data

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such as detailed stock information.

In this paper, we quantify the critical and bulk material requirements for transport-energy transitions in Kenya, a lower-middle income country in East Africa with a quickly urbanising population, a growing motorisation rate and a set of ambitious targets in economic development [6] and climate change mitigation [7]. We provide detailed materials requirements projections of vehicle stocks based on four future transport-energy pathways for Kenya, which were co-developed as part of a socio-technical modelling exercise in 2024 using the Transport Energy Air pollution Model (TEAM)-Kenya framework [8]. The four pathways propose radically different futures, from the dominance of ICE personal cars to the promotion of mass transport. The material implications of such different futures are therefore a clear gap to inform transport planning.

1.2. Kenyan aims for transport and related industries

Kenya's industrialisation ambitions target an annual industrial growth rate of 15% through sectoral transformation and value addition [9]. These goals align with Kenya's broader (and longer-term) Vision 2030 agenda, and are currently being implemented under the Fourth Medium Term Plan (MTP IV), 2023–2027 [10]. Central to this strategy is a set of large-scale transport infrastructure projects, including the Standard Gauge Railway (SGR), the Lamu Port-South Sudan-Ethiopia Transport (LAPSSET) Corridor and the Northern Corridor road network, which connects the Great Lakes region to the Port of Mombasa.

Complementing the broader manufacturing agenda, Kenya has increasingly focused on value addition within the transport sector, particularly through the transition to electric mobility. The National Automotive Policy seeks to promote local vehicle assembly and the manufacture of automotive components, aiming to strengthen domestic capabilities and reduce reliance on imports [11].

Kenya's aims in value addition are closely tied to the country's growing EV sector, particularly for 2-3 wheelers [12]. Kenya's Draft National E-Mobility Policy (2024) explicitly promotes local EV production, charging infrastructure development, battery assembly, and workforce capacity building [13]. Early outcomes include initiatives such as the Kenya Vehicle Manufacturers' assembly of electric buses [14]. To stimulate local EV adoption and manufacturing, the government has introduced fiscal incentives, including reduced excise duty on domestically assembled EVs and tax relief on imported EV components [15].

Supporting this transition, Kenya has begun establishing regulatory frameworks, including the Energy and Petroleum Regulatory Authority (EPRA) guidelines (2023) for EV charging station licensing and safety [16], Kenya Bureau of Standards (KEBS) standards for imported used EVs [17]. Environmental considerations are also being addressed through National Environment Management Authority (NEMA) guidelines on battery recycling and disposal [18].

The materials needed for transport as identified by Mat-dp included have trade and local manufacturing implications in Kenya.

1.3. Kenyan trade related to vehicles

Fig. 1 shows trade data for Kenya [19,20], specifically import and export flows, sliced for categories relevant to the materials included in Mat-dp for transport. The figure therefore does not show all trade categories but focuses on: transport-related products (cars, tractors, trucks, buses and their parts), mineral products (mineral ores and mineral fuels), and (metal products (including copper, iron and steel, aluminium, and nickel). These groups were selected because they represent the main material inputs in Mat-dp vehicle categories.

Kenya's 2023 imports (~US\$ 21.2 billion) are almost 2.5 times higher than its exports (~US\$ 8.6 billion). The transportation sector is prevalent for imports which has a share of 6.3% of total imports in 2023, and within this sector, cars, tractors, trucks and their parts constitute

84% of its value (HS2 1787). In the past, this same subsector required the largest share, showing fluctuations in its share such as 80% in 2013 and 69% in 2018. Mineral products (in ochre) have the highest or second highest share of imports with a marked increase from US\$ 5 million in 2013 to US\$ 78 million in 2023. Metal imports (in dark blue) show smaller changes over the decade; copper imports remain stable, while aluminium or nickel decrease in value (e.g., decreases almost three times between those two years). The changes can be influenced by metal prices but it also reflects the type of manufacturing available in Kenya.

For exports, mineral products have the highest shares over the period studied with between 8.7 and 15% of total exports depending on the year. This is only surpassed in 2023 by the chemical products (in orange) sector dominated by an increase of pharmaceutical product exports. Transportation exports are also highest for cars, tractors, trucks and their parts with 89% of transportation's value in 2023. This particular subsector has increased its trade value going from between 80 and 88 million USD in the previous years to 104 million USD in 2023 reflecting the rise in Kenyan car manufacturing. Metal exports are led by iron and steel products, and interestingly, copper article trade is balanced with similar import and export values (61 vs 57 million USD in 2023).

1.4. Kenyan vehicle and battery manufacturing sectors

Kenya's automotive industry has undergone significant evolution since the initiation of vehicle assembly operations in the 1960s, which included an early state-led effort to produce a domestically manufactured car, the Nyayo [21]. By 2013, to promote local assembly of the automotive sector, the Kenyan government implemented a series of tax measures including exempting imports of parts used in local vehicle assembly from the 25% import duty that was typically levied on fully assembled imported vehicles. This exemption aimed to bolster the competitiveness of locally assembled vehicles against fully built imports. According to the KAM Automotive Sector Report of 2020 [21], the total number of vehicles registered in Kenya in 2019 were 109,750. Out of the total vehicles registered in 2019, 12% (12,981) were new vehicles and 88% (96,770) were used vehicles. If all the vehicles assembled locally were all sold in the same year, the percentage of locally produced vehicles to the total vehicles registered is 7.4%.¹ From domestic manufacturers, utilised capacity is low with between zero and 40% depending on the manufacturer reaching an average of 20%. These numbers reflect a wide gap for domestic manufacturing.

Table 1 provides examples of firms operating across various stages of the vehicle supply chain within Kenya. These range from raw material processing and component manufacturing to vehicle assembly and end-of-life services, including battery refurbishment and recycling. An example of a recent initiative is also shown, underscoring increased attention in the sector.

1.5. Past studies on material requirements for transport-energy transitions

There has been increasing interest in quantifying materials demand for low-carbon energy and transport transitions in recent years, driven by the changing nature of the materials demanded [31]. Generally, studies adopt the lens of whole energy system transitions, whereby changes in passenger and freight mobility service demand (via "Avoid" or "Shift" measures) and changes in energy efficiency (i.e. "Improve" measures) are framed as transitions within transport as an end-use of energy [32].

¹ This number is based on a desktop review of the taxation regime of the automotive sector and the number of locally assembled vehicles in Kenya, from the Finance Acts of 2013 [22] to 2023 [23] and the KAM Automotive Sector Report. A detailed analysis of the impact of the tax incentives issued to the automotive sector to encourage localisation of vehicle assembly and manufacturing will give a near accurate scenario.

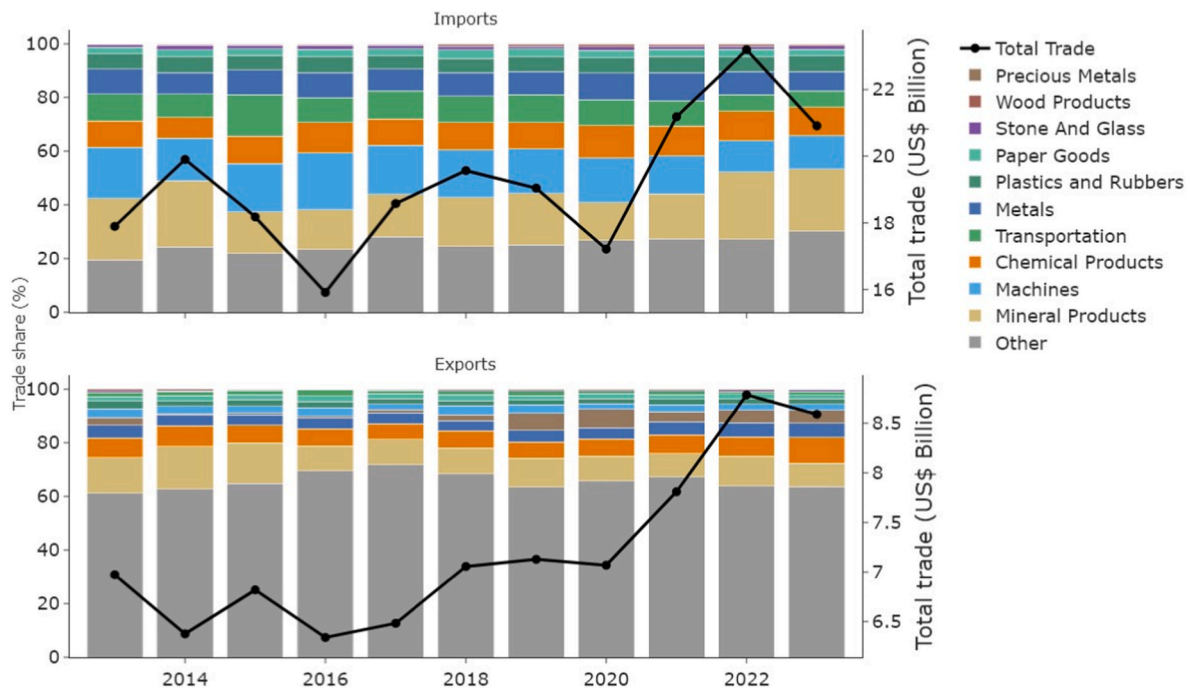


Fig. 1. Import (top) and export (bottom) shares of relevant sectors and total trade value (secondary y axis) between 2013 and 2023 in Kenya. These include: transport-related products (cars, tractors, trucks, buses and their parts), mineral products (mineral ores and mineral fuels), and (metal products (including copper, iron and steel, aluminium, and nickel). Values shown in the figure represent the aggregated import and export flows for these groups.

Table 1

Examples of company characteristics operating across different stages of the transport supply chain in Kenya.

Stage	Manufacturer name	Operating Since	Annual Capacity ^a	Vehicle Types	Source
Component manufacturing (metals)	Numerical Machining Complex Ltd	Started in 1994 (formerly Nyayo starting in 1986)	Not specified	Manufactures metal parts for various local industries	[21, 24]
Vehicle assembly	Kenya Vehicle Manufacturers (KVM)	First vehicle assembly plant in Kenya. Incorporated in July 1974.	~6600 vehicles (single shift)	Passenger vehicles, freight vehicles for several brands	[25]
Vehicle assembly and conversions	Associated Vehicle Assemblers Ltd (AVA)	1975	30,000 units	Trucks, buses, passenger vehicles for several brands	[26]
Vehicle assembly, retail	Isuzu East Africa	Since at least 2017 (as Isuzu East Africa. Formerly General Motors Kenya starting in 1975)	11,000 units	SUVs, pickups, buses, freight vehicles	[21, 27]
Battery refurbishment, battery recycling	Qtron Industries	Established 2016	>100 EV batteries to date (note this is not annual)	Custom batteries for scooters, e-bikes, solar, energy storage systems	[28, 29]
EV battery and motor chassis manufacturing	Oasis	2025 (won UNIDO grant)	Not yet started	Motorcycles and tuk-tuks	[30]

^a Except for Qtron industries which only provided cumulative production instead of annualised.

Techniques prominently used include system dynamics, material flow analysis, bottom-up simulation tools and optimisation models [33]. present a global material flow analysis of lithium to establish the level of its criticality in the energy system, focussing on policy gaps in the transport sector [34]. employ a material flow analysis to derive spatially-linked commodity production and international trade for lithium in China, given different options for lithium resource efficiency (including recycling) [35]. present a system dynamics model for the supply of tellurium for the growing solar photovoltaics sector which, while not directly relevant to transport, provides an example of a modelling technique that could be readily employed for the transport sector [36]. develop a bottom-up energy transition simulation tool for France to characterise credible ranges of raw material requirements for a climate-neutral French energy system [37]. employ the TIMES cost optimisation modelling framework to produce bottom-up transport scenarios based on technology uptake of EVs, focussing on varying penetrations of pure battery, plug-in/mild hybrid, and hydrogen fuel cell EVs, using the technology-rich nature of TIMES to derive critical

materials pathways for these scenarios [38]. assess five pre-existing global energy transition scenarios via a bottom-up quantification of required material stocks, including bulk and critical materials, focussing on the climate implications of these material pathways.

Across the reviewed literature, there is a lack of open-source tools and open data in the development of material pathways for energy and transport decarbonisation. In the current study, we employ an open-source model, Mat-dp [2], to estimate material demand projections from energy and transport technologies and their environmental implications. By using open-source models and open data, we seek to promote transparency and accountability in future energy and transport system planning, with the ultimate goal of de-risking investment in the sector [39].

The majority of studies are at a global level – for instance, see Ref. [40–43]. However, as argued by Ref. [44], national-level studies are underrepresented and, of these, the majority are focused on developed countries (e.g. USA, see for instance Ref. [45], and Germany, see for instance Ref. [46]) and emerging economies (mostly China, see for

instance Ref. [47]). National material studies can provide evidence to facilitate political discourses towards decisions relating to national material needs given national endowments, geopolitical circumstances and trade. In this study, we present an application of a recently published open-source materials demand pathway tool Mat-dp, to the case of Kenya, a lower-middle income country with a high potential for transport electrification [48].

2. Methods and data

This paper builds on four future transport-energy scenarios in Kenya and their associated vehicle stocks developed by (Dixon et al. [8]), extending the work by quantifying the bulk and critical materials, embodied emissions and battery-import costs of each scenario.

2.1. Re-introducing TEAM-Kenya and kenyan transport-energy scenarios

This study uses the scenarios created for Kenyan transport futures [8] using the Transport and Energy Demand Model (TEAM) [49]. TEAM is a strategic transport, energy, emissions and environmental impacts systems model, covering a range of sectoral issues resulting from socio-economic, policy and technology-based scenarios in transport and adjacent sectors. TEAM-Kenya is the first application of the TEAM framework outside of the UK (including a Scotland-specific TEAM, STEAM [50]); specific changes to TEAM for its Kenyan application include the modelling of second-hand imported vehicles, which make up the majority of the Kenyan road vehicle market, country-specific vehicle choice and travel survey data, and Kenyan vehicle scrappage data Ref. [51]. For full details on TEAM, the reader is referred to Ref. [52]. For full details on TEAM-Kenya, the reader is referred to Ref. [8].

As described by Dixon et al. [8], TEAM-Kenya was used to facilitate decision-makers' exploration of the transport-energy-emissions-environment implications of four co-developed scenarios. These scenarios were developed based on an in-depth consultation with 41 local experts and decision-makers from national and local government, NGOS, international organisations, the private sector and academia. The scenario development process gathers

central-actor narratives and uses them as the core of modelled scenarios (see *Oxford Scenario Planning Approach* [53]). Rather than eliciting knowledge or prescribing pre-determined outcomes, this approach aims to engage participants in structured exercises to tap into their collective imagination, backed by their expertise in the sector.

Dixon et al. [8] specify that the four scenarios are based primarily on what were deemed to be the two most important driving factors in the Kenyan transport-energy sector from the present-day to 2050: the level of priority that national and local governments place in the development of public transport systems; and the availability of finance, to the government, private individuals and companies in advancing infrastructures and technologies in the future. The four scenarios are shown in Fig. 2 and described in Table 2.

Fig. 3 shows the output of the vehicle stock model in TEAM-Kenya: the share of new vehicles grouped by type of vehicle and general powertrain in the scenarios considered. Internal combustion engine (ICE) two-wheelers have the largest shares in all scenarios with the *Hatua Binafsi* scenario showing the largest share of electric two-wheelers. Passenger cars have the second-largest shares with differences between the shifts from ICE to electric. In particular, the *Kubaya* scenario shows no transition to electric mobility and a higher dependence on passenger cars compared to the other scenarios. However, transitions to electric mobility for passenger cars are reflected in the higher shares of electric cars over time, with the *Kunawiri* scenario having the highest shares of electric vehicles. The shares of other modes are smaller. Notably, the *Kunawiri* and to a lesser extent the *Kujielewa* scenario show a move towards mass transport modes with the introduction of buses and even electric buses in the *Kunawiri* scenario.

2.2. Material demand projections using Mat-dp

The vehicle stock output from TEAM-Kenya (Fig. 2) are used in this study alongside Mat-dp [2], an open-source model created to estimate material demand projections from energy and transport technologies and their environmental implications. Mat-dp relies on its database with material intensities which includes 101 materials and 184 different

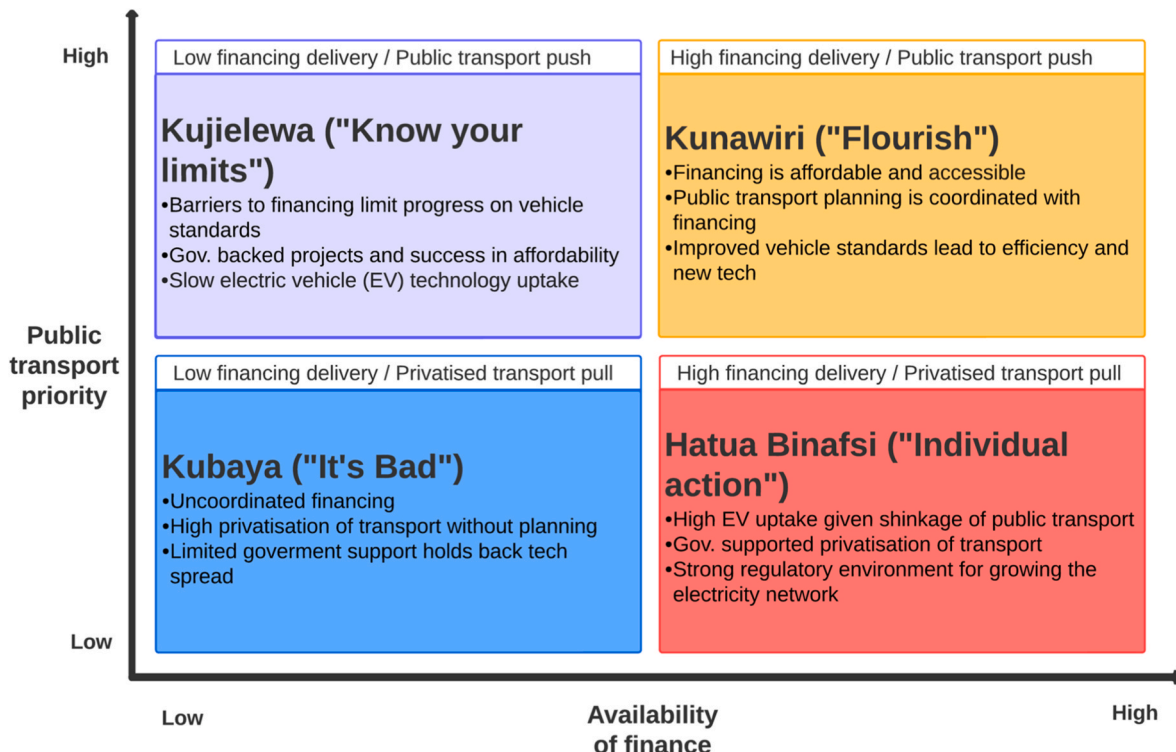


Fig. 2. Scenario matrix for Kenyan transport-energy futures taken from [8].

Table 2

Summaries of Kenya's scenario descriptions based on [8].

Scenario	Description
Kunawiri ('Flourish')	Strong transport legislation and accessible financing drive efficient public transport in Kenya. The government enforces stricter vehicle standards, emission controls, and import age limits, while subsidies support the matatu sector's shift to electrification and digitalisation. Newer buses serve main city routes, and electric Bus Rapid Transit (BRT) systems and Nairobi's metro rail expand mass transit. All new roads include pedestrian infrastructure, boosting safety and walkability in urban areas.
Hatua Binafsi ('Individual action')	E-mobility is the main transport opportunity, with government subsidies prioritising E2Ws and E4Ws and smaller incentives for electric public transport. Regulations, such as fossil fuel import taxes, support electrification, but the government does not plan transport systems. High access to finance fuels rapid private vehicle growth, leading to worsening congestion in major cities, stagnant public transport, and persistent mobility poverty for low-income groups.
Kujielewa ('Know your limits')	The government sets new transport regulations and standards but limited financing hinders high-quality BRT and other projects. Efforts to improve access focus on cycle lanes, footpaths, and public transport corridors. Old imported buses and trains meet demand, while high car import costs and tax-free motorcycle imports boost two-wheeler use. Limited finance slows e-mobility adoption, but low-cost NMT infrastructure is added to urban roads, improving pedestrian safety.
Kubaya ('It's bad')	With minimal government role in planning or financing, poor transport services slow economic growth. Private, informal transport expands slowly, electrification remains low, and old vehicles dominate. New technologies like electric buses and two-wheelers see only modest uptake, driven by private operators with their own charging networks.

technologies.

For this study, the vehicle categories used in TEAM and Mat-dp were standardised. TEAM contains specific vehicle categories depending on power train, size (mostly for passenger cars), and age due to its use of European vehicle classifications. In turn, Mat-dp database contains several categories (with sizes) for two- and three-wheelers, cars and vans, lorries, trains, buses and airplanes. While most vehicles were able to have a match between the two models, some sizes and power trains are not included in both models which led to deciding which categories to assign. The most significant mismatch is Medium rigid lorry which represents a vehicle type present in the TEAM-Kenya scenarios but absent from Mat-dp database, which contains only Small rigid lorry (16t) and Large rigid lorry (28t) entries. A sensitivity analysis is included to understand the impact of such selection. For more information on classification details, please see Supplementary Materials (Table 4).

For electric vehicles, TEAM-Kenya does not include assumptions on battery chemistries. Thus, we make assumptions on battery chemistries applicable to Kenya as shown in Fig. 4 where the penetration of low-cost lithium-iron phosphate (LFP) batteries increases over time, replacing nickel-manganese-cobalt (NMC) chemistries.

It should be noted that the study covers materials required for vehicles but does not quantify materials required for supporting infrastructure such as roads, bridges, railways, charging stations, or bus stations. While we cannot compare the effects of such infrastructure as it is outside the scope of the paper, it should be noted that scenarios with high penetration of public transport would have different requirements (for example BRT stations) to scenarios with high penetration of private vehicles (which may require roads including multi-lane motorways or elevated roads depending on planning). The configurations of such infrastructure selection would mostly lead to increased bulk material demand needed such as gravel for roads, cement for stations or roads or steel for BRT and elevated structures.

2.3. Estimation of emissions

Mat-dp database includes the object references for each material from Ref. [54] which can be used to obtain the Global Warming Potential (GWP) 20 and 100. These can then be used to estimate the emissions associated to the projected material demand. The values used are not representative of Kenyan production given available data. This is

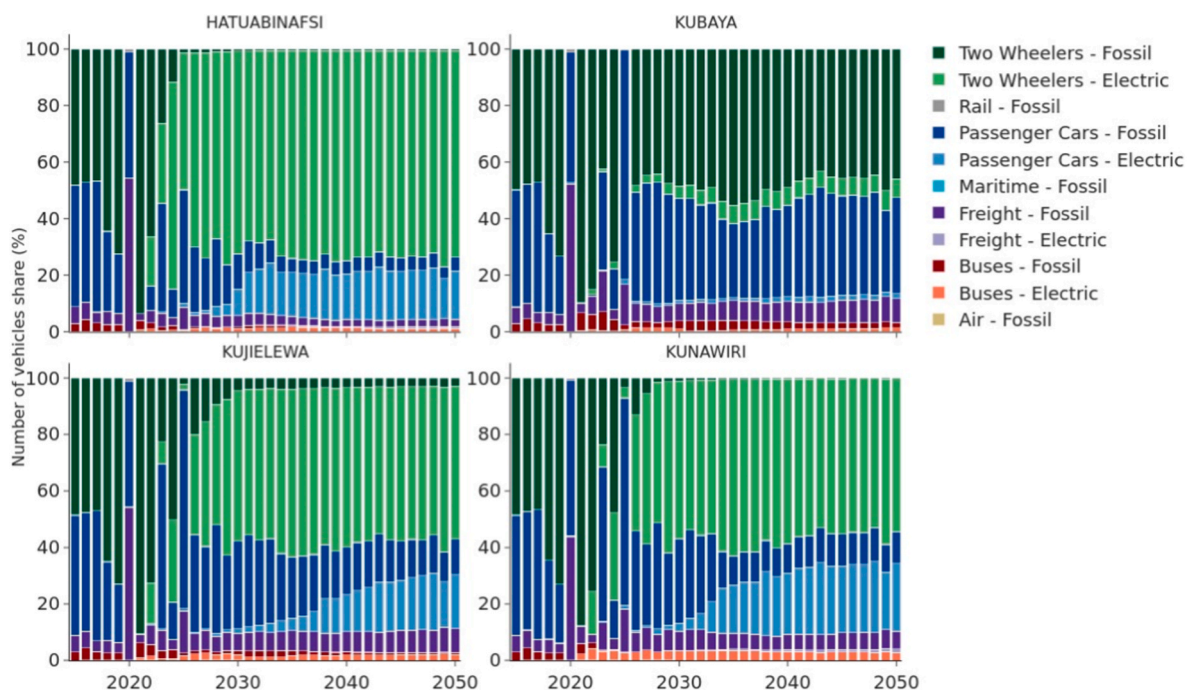


Fig. 3. Number of vehicles (% share) by general vehicle category per scenario. Note that the original model included walking as a mode of transport, but this was not included in this study as no materials are needed for it.

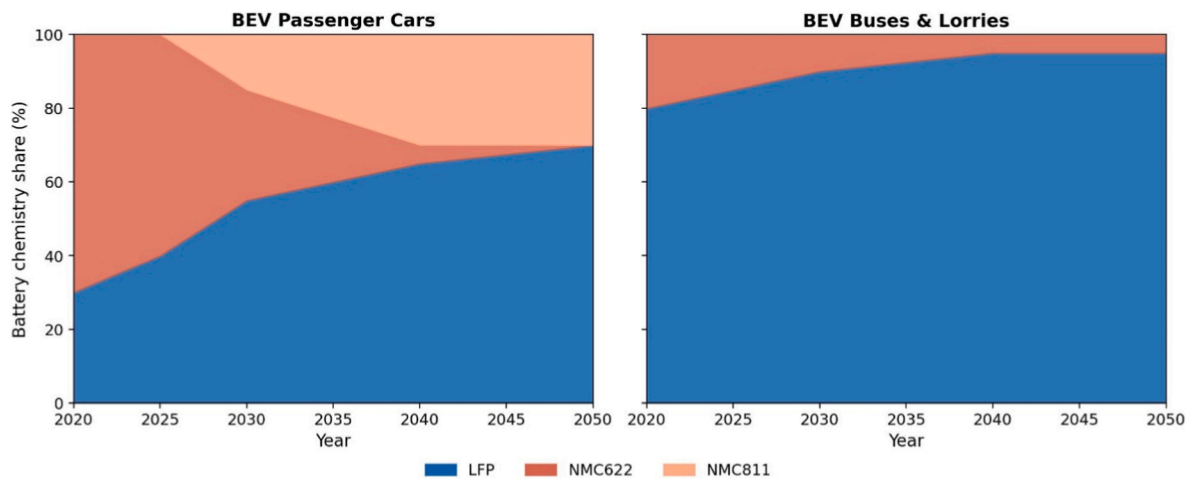


Fig. 4. Assumed battery chemistry mix for electric vehicles in scenarios that assume they are used. The battery chemistries used are lithium-iron phosphate (LFP) batteries and two types of nickel-manganese-cobalt (NMC).

acceptable at this stage since the results would still allow to showcase an estimation of embedded emissions in vehicle fleets in the country mainly as imports since most vehicles are not manufactured locally.

The emissions from materials resulting from using Mat-dp can be compared to the emissions from using the vehicles which are estimated by Ref. [8].

2.4. Estimation of battery import prices

Mat-dp database does not include commodity prices, yet understanding the battery import dependency in each scenario presents an opportunity to identify monetary constraints in high-electrification scenarios. Thus, battery price data is collected and future prices are estimated based on assumptions.

Annual battery pack expenditure is estimated by multiplying new EV registrations from the TEAM-Kenya scenarios by the battery capacity (kWh) and pack price (USD/kWh) for each vehicle type and year. Battery capacities are assumed as follows: city cars 40 kWh, medium cars 65 kWh, large cars 75 kWh, large SUVs/pickups 90 kWh, vans 70 kWh, minibuses 120 kWh, full-size buses 250 kWh, rigid lorries 200 kWh, and electric mopeds 2.5 kWh. Pack prices were derived from Bloomberg New Energy Finance (BNEF) annual battery price surveys for the historical period (2015–2025) [55], with 2025 anchor prices of \$81/kWh for LFP and \$128/kWh for NMC chemistries [56]. All prices are expressed in constant 2025 USD.

Three projection scenarios are constructed for 2026–2050 with annual declining rates from 2025, with rate steps at 2030 and 2035: Conservative (3% annual cost reduction to 2050), Moderate (6% to 2030, then 4% in 2035, and 2.5% in 2050), and Optimistic (9% to 2030, then 5% in 2035, and 2.5% in 2050). The rates are consistent with BNEF [55], ICCT [57], and McKinsey [58] forecasts. The blended pack price for each vehicle type and year was calculated as a weighted average of LFP and NMC prices according to a chemistry mix that evolves linearly between 2020 and 2050, reflecting the ongoing shift towards LFP dominance in commercial and two-wheel applications and a mixed LFP/NMC811 trajectory for passenger cars. To reflect differences in vehicle category batteries (such as their thermal management, form, and procurement scale), a pack price premium was estimated and applied relative to passenger cars (vans 1.05, minibuses 1.10, buses 1.15, lorries 1.20, mopeds 1.25).

3. Results and discussion

This section presents the results by scenario and year. The categories used for the different transport modes and materials were aggregated

into relevant groupings. Transport modes were mainly grouped based on their type of fuel (fossil or electric), while materials were grouped based on their type (as critical or bulk) and subtype (based on their general use or common classification). The classifications are shown in the Supplementary Material (Table 4).

3.1. Total material demand by scenario and transport technology

Fig. 5 shows the total material demand results as totals (top) and per technology category shares (bottom). The material demand only includes components of each vehicle types but no fuel needed to power them. All four scenarios follow a broadly similar trajectory, with a pronounced dip in new vehicle demand around 2020 followed by steady growth reaching approximately 0.45–0.65 Mt by 2050. *Kubaya* shows the lowest material demand in the middle years of the projection period (note fuel is not included in the model), consistent with its lower overall vehicle uptake, while all scenarios converge toward similar demand levels by 2050.

Given the small amounts of materials required per vehicle, two- and three-wheelers do not form a large share of total material demand even in *Hatua Binafsi* (the scenario with the highest uptake of electric mopeds). Electric two-wheelers first appear in 2022 at around 2% of total material demand in *Hatua Binafsi*, spike to approximately 10% in 2024, before dipping to around 4% in 2025 and subsequently ranging between 4 and 9% of annual material demand through to 2050. *Hatua Binafsi* projects 10% of material demand due to electric two-wheelers as they begin to be introduced in 2022 and subsequently ranging around 4–7% of yearly material demand. Passenger cars require the largest amounts of materials in all scenarios. In *Hatua Binafsi*, electric cars grow from around 21% of total material demand in 2030 to 38–42% by the 2040s, while fossil cars decline from 61% in 2025 to around 12% by 2040. In *Kubaya*, fossil passenger cars remain dominant throughout the entire period (43–61%), with electric cars never exceeding 2% of total demand, reflecting the scenario's limited private vehicle electrification. In *Kujilewa*, electric car demand grows more gradually, only becoming substantial from 2040 onwards (18%), compared to *Hatua Binafsi* where the shift is already underway by 2030. Buses account for a notably larger share of material demand in *Kunawiri*, where mass transit is favoured, representing 13.5% of total demand in 2025 (13.2% electric, 0.3% fossil), rising to 32% by 2035 as the BRT fleet builds out, and shifting to 23% of solely electric buses by 2050. Electric freight vehicles contribute a smaller but growing share in *Hatua Binafsi* and *Kunawiri*, reaching around 5% of total material demand by 2050, while remaining absent in *Kubaya* and negligible in *Kujilewa*.

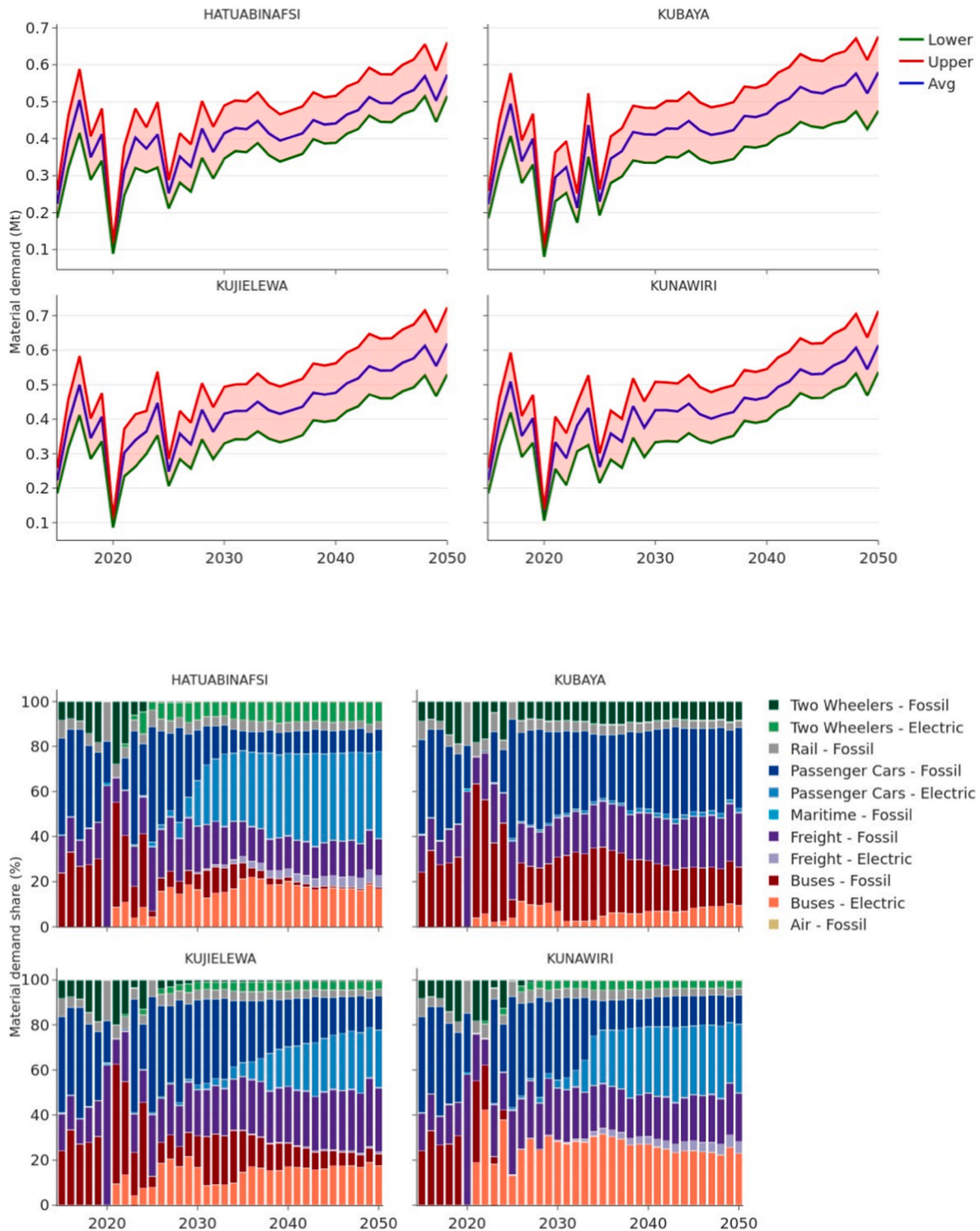


Fig. 5. Total material demand with upper and lower bounds estimated with Mat-dp database (top) and material demand shares (bottom) by scenario.

3.2. Material demand by material type

Fig. 6 shows the material demand shares and totals for the two material types of interest: bulk and critical.

Bulk material demand rises steadily after 2025 for all scenarios ranging from 0.45 to 0.51 Mt by 2050. *Kujielewa* and *Kubaya* reach the highest bulk demand at approximately 0.51 Mt in 2050, followed closely by *Kunawiri* at 0.49 Mt. The lowest bulk material demand is for the *Hatua Binafsi* scenario which only reached 0.45 Mt in 2050, reflecting its

dominance of lighter electric two-wheelers which require comparatively little material per vehicle. The highest bulk material demand is due to Metals & Alloys with 60–72% of total demand in the period studied in all scenarios. Metals and Alloys include steel and iron which are notorious for being required in large quantities for transport technologies [2]. Plastics have a consistent second place as a total share of bulk material demand with between 10 and 16% over the time period studied in all years. Fibers and Insulation form a notable third category at 6–8% of demand by 2050. It is noticeable that the trends for bulk materials are

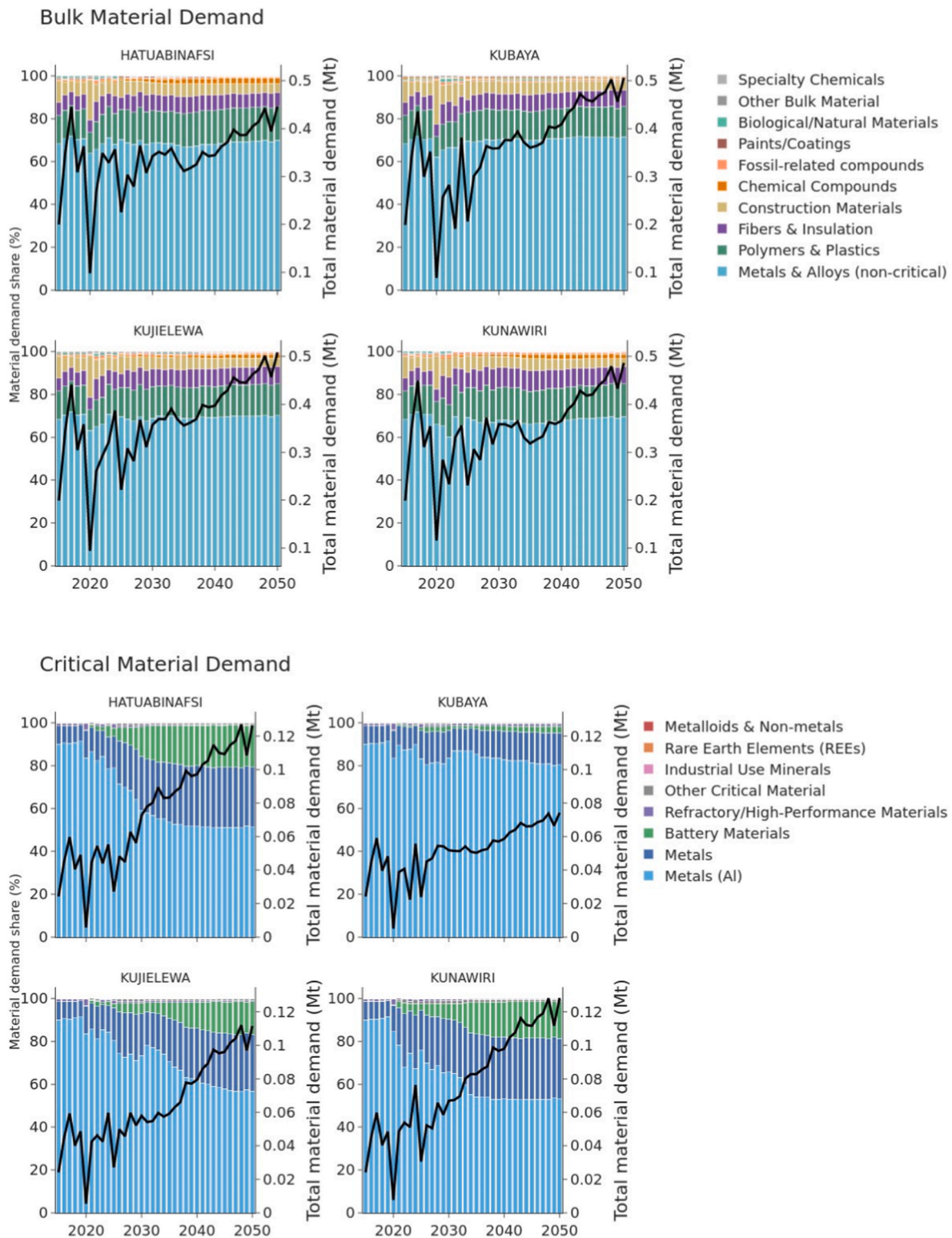


Fig. 6. Share (in bars) of bulk (top) and critical (bottom) material demand and total bulk and critical material demand (in lines) for each scenario and year. Note that Aluminium was shown separately in the Metals category given its large share.

somewhat similar in all scenarios considering shares, with only small differences observed in the category Chemical Compounds which reaches up to 3% in scenarios with higher electrification (*Hatua Binafsi*, *Kunawiri*) compared to a consistent 0.7% in *Kubaya*, reflecting its connection to fleet electrification, e.g., dimethyl carbonate, a solvent used in lithium-ion battery electrolytes.

Critical material demand grows the most for the *Hatua Binafsi* and

Kunawiri scenarios, reaching 0.13 Mt by 2050. The *Kubaya* scenario, where the least electrification occurs, has the lowest critical material demand with only 0.07 Mt required by 2050. The materials requiring the largest demand in all scenarios are Metals, among them aluminium has the largest shares (starting at 91% of critical material demand and decreasing over time to 51–57% by 2050 in electrifying scenarios) but its demand decreases over time as other materials grow in importance.

The other metals included in the category include battery-related ones such as copper and smaller amounts of nickel and cobalt which rise over the time period studied going from 15–18% to 26–28% in electrifying scenarios. The second largest growing category is Battery Materials, whose demand rises over time with fleet electrification, covering 15–20% of total critical demand in 2050 for all but the *Kubaya* (2.9%) scenario. Together, non-aluminium Metals and Battery Materials have a growing share of total critical material demand, rising from approximately 19–22% in 2025 to 42–48% in 2050 for *Hatua Binafsi* and *Kunawiri*. In contrast, these two categories only reach 18% in 2050 in the *Kubaya* scenario.

3.2.1. Sensitivity analysis of lorries

The key category with a mismatch between Mat-dp and TEAM is medium lorries in TEAM which is assigned to small lorries in the analysis (see SI). To study the effect of such category mapping, we conduct a one-at-a-time sensitivity analysis to bound this uncertainty by estimating material demand under two alternative assumptions: (i) mapping Medium rigid lorry to Small rigid lorry (16t), representing a lower-bound assumption on material content, and (ii) mapping to Large rigid lorry (28t), representing an upper bound.

Fig. 7 shows the additional material demand relative to the baseline (which excludes these vehicles) under the two mapping assumptions. Mapping Medium rigid lorries to Small rigid lorry (16t) would increase total material demand by approximately 1.4–3.8% across scenarios at key modelled years. Mapped to Large rigid lorry (28t) instead, the increase rises to 1.7–4.8%. The difference between the two assumptions is modest: 0.4–1.1 percentage points (pp), reaching a maximum of 1.1 pp under *Kunawiri* by 2050. *Kunawiri* is consistently the most sensitive scenario (+4.8% under Large lorry by 2050), followed by *Hatua Binafsi* (+4.3%). Both are the scenarios where medium rigid lorry fleet growth is greatest. *Kubaya*, which has the slowest overall freight fleet growth, is least affected (+2.4%). The spread across scenarios is roughly double from least to most affected, but all remain below 5% at key modelled years regardless of the mapping assumption.

The absolute additional material demand by 2050 ranges from 11 to 23 kt/year (Small lorry) to 14–30 kt/year (Large lorry) across scenarios, with a gap of 3–7 kt/year between the two assumptions. The Small rigid lorry (16t) produces lower total material demand than the Large rigid lorry (28t) overall, meaning the baseline (which excludes Medium rigid lorries entirely) represents a conservative lower bound on total demand, acceptable for this study's focus on demand forecasting. Critical minerals are negligibly affected under either assumption.

In absolute terms, the dominant contributions under the upper-bound mapping at 2050 are approximately 6–13 kt/year of cast iron and 5–11 kt/year of steel. Cast iron shows the highest relative sensitivity, increasing by 8–32% depending on scenario and mapping

assumption, due to its high content in rigid lorries (3080 kg/vehicle for the 16t class; 4740 kg/vehicle for the 28t class). The most pronounced asymmetry between the two mapping assumptions is GFRP: the Small rigid lorry entry includes 1000 kg of GFRP per vehicle while the Large rigid lorry entry contains none, producing a 14–41% increase in GFRP demand under the Small lorry mapping and no change under the Large lorry mapping, equivalent to 1.3–2.8 kt/year at 2050. Synthetic rubber also shows moderate sensitivity (4–9% under the Large lorry mapping). Steel increases by 1–4% across all scenarios and both assumptions. Critical minerals are minimally affected: aluminium increases by up to 1.4% (Large lorry mapping) and copper by less than 1% under either assumption.

3.3. Emissions from material production and transport

Fig. 8 shows the emissions for both bulk and critical materials as shares on the left-hand side axis and as totals for each scenario on the right-hand axis (both the total material emissions and the total direct emissions). Material emissions are overall lower than direct emissions, with embodied bulk emissions reaching 1.8–2.3 Mt CO_{2e} by 2050 and critical embodied emissions reaching 1.0–1.3 Mt CO_{2e}, compared to direct emissions of 10–25 Mt CO_{2e}. The largest material emissions are for the *Kunawiri* scenario (with both critical and bulk material emissions increasing by 2050 at 2.3 Mt and 1.3 Mt respectively). *Hatua Binafsi* has the lowest bulk material emissions (1.8 Mt in 2050) while *Kubaya* has the lowest critical material emissions (0.98 Mt in 2050). The *Kubaya* scenario relies more heavily on bulk material emissions, with bulk embodied CO₂ approximately double its critical embodied emissions by 2050 (2.1 Mt vs 1.0 Mt), reflecting the dominance of ICE vehicle materials in its fleet. Bulk material emissions are the highest overall and are driven by aircrafts and buses which require large amounts of for fibres and insulation categories (which account for 55–62% of bulk embodied CO₂ by 2050 across all scenarios) which include glass and CFRP (which has a particularly high GWP). Metals and alloys follow as the second largest contributor at 32–38% of bulk embodied CO₂ in 2050, while polymers and plastics account for only 5–7%. Critical material emissions are almost entirely driven by aluminium, which accounts for 78–92% of embodied CO₂ across scenarios in 2050 (highest in *Kubaya*, where no electrification occurs). Copper is the next most significant contributor, growing from around 7% in *Kubaya* to 17% in *Hatua Binafsi* and *Kunawiri* by 2050, reflecting the copper-intensive nature of electric motors and charging infrastructure. Cobalt accounts for less than 1% of critical material embodied CO₂. Notably, battery materials such as graphite and lithium carry negligible embodied emissions relative to the other metals, confirming that the critical material emission challenge is dominated by aluminium rather than battery chemistry. As for total direct emissions, the *Kubaya* scenario has the highest amongst all scenarios, reaching approximately 25 Mt CO_{2e} by 2050. *Kubaya* is also the scenario where no low-carbon transition is observed as emissions grow over the time period studied instead of peaking and decreasing as in other scenarios.

The results show that from a direct emissions perspective, the introduction of mass transport (specifically in the *Kunawiri* scenario) brings the greatest benefits, with direct emissions falling to approximately 10 Mt CO_{2e} by 2050, the lowest of all scenarios. However, the trade-off is having the highest critical material demand (0.13 Mt by 2050) driven by battery requirements for its large BEV bus fleet. *Hatua Binafsi* offers two advantages: the prevalence of electric two-wheelers leads to having the lowest total bulk material demand of all scenarios (0.45 Mt by 2050) with similarly low direct emissions. The lowest overall benefits are in the *Kubaya* scenario, where a delayed transition to electric mobility combined with higher adoption of passenger cars leads to the highest direct emissions by 2050 (~25 Mt CO_{2e}, and still growing). While *Kubaya* incidentally requires the fewest critical minerals due to minimal electrification, this reflects a lack of transition rather than an advantage, and comes with continued fuel import dependency and growing bulk material demand for ICE vehicles.

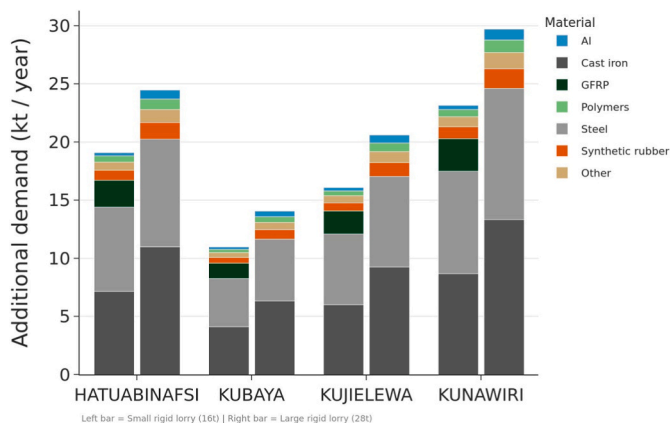


Fig. 7. Sensitivity analysis including additional demand by material from using small and large lorries instead of medium-sized.

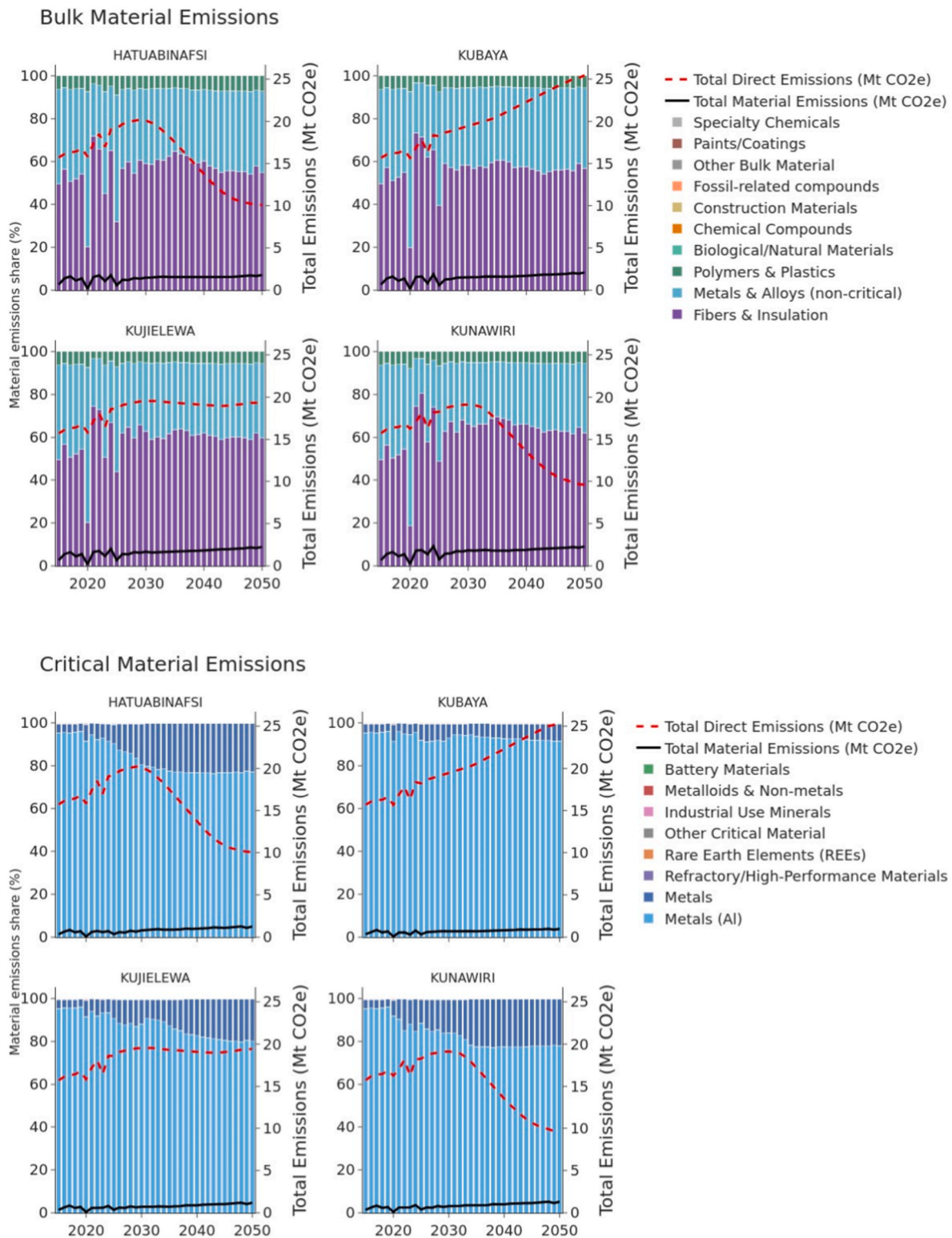


Fig. 8. Material emissions for bulk (top) and critical (bottom) as shares for each subcategory (primary y axis) and showing the totals (secondary y axis) for each scenario.

3.4. Contrasting import dependencies

Fig. 9 shows the import expenditures for fuels and batteries. The fuel imports as indicated by Dixon et al. [8] showed that “the most fossil fuel-dependent scenario, *Kubaya*, produced 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.” Battery imports estimated in this study result in a modest additional import burden. Under the moderate battery price scenario, annual battery pack expenditure in 2050 reaches approximately \$0.5 bn in the highest e-mobility scenarios (*Hatua Binafsi* and *Kunawiri*) and \$0.3 bn in

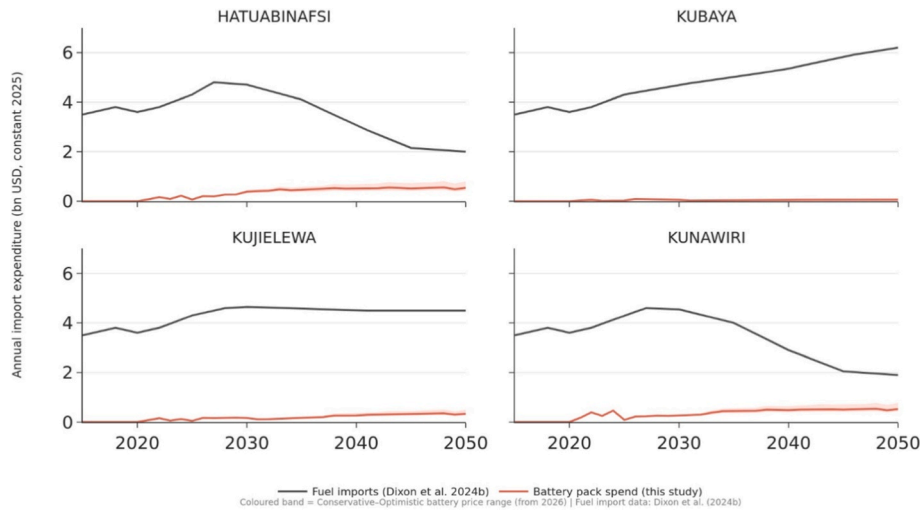


Fig. 9. Import expenditures on fuel and batteries per scenario.

Kujielewa, while *Kubaya* (with minimal EV uptake) incurs less than \$0.1 bn. Even under conservative battery price assumptions (slowest cost reduction), these figures reach at most \$0.8 bn by 2050. The combined annual import exposure (fuel plus battery packs) in 2050 therefore remains below \$2.6 bn in the high e-mobility scenarios, compared to approximately \$6.3 bn for *Kubaya*, a net reduction of roughly 59%. The battery pack cost offsetting the fuel import saving amounts to at most \$0.5–0.8 bn against a fuel saving of \$4.2 bn, meaning electrification replaces a \$4.2 bn annual fuel dependency with a battery import cost of 12–19% of that value. Therefore, a fossil fuel import dependency is not substituted for an equivalent battery or mineral dependency under the higher electrification scenarios modelled.

3.5. Policy implications for Kenya

The results presented provide Kenya with clear pathways to foster sustainable transport-energy futures, highlighting actions aligned with each scenario's outcomes and challenges. From the analysis presented, we present eight policy recommendations.

1. Prioritise electrified mass transit to advance equitable and clean transport, as per the *Kunawiri* scenario, including prioritising renewable energy generation. The *Kunawiri* scenario demonstrates that strong government commitment to public transport infrastructure and accessible financing can reduce per-passenger material demand and emissions, shifting demand toward collective infrastructure, and reducing fuel import dependence. Kenya should therefore accelerate investments in electrified mass transit such as the Nairobi BRT, leveraging international climate finance where possible to reduce the fiscal burden on Kenyan citizens. The transport electrification would have lower emissions if renewable energy is also prioritised. Policies enforcing stricter emissions standards for second-hand vehicle imports, combined with subsidies for electric bus/matatu fleets, will enable the realisation of the benefits in the *Kunawiri* scenario. This contrasts sharply with the *Kubaya* scenario, where minimal government intervention results in higher emissions and increased reliance on polluting passenger cars. However, emissions standards on second-hand imports should be phased in progressively, tied to milestones in mass transit expansion and affordable EV availability, to avoid restricting access before alternatives are in place.
2. Build domestic manufacturing capacity as a precondition for supply chain resilience and job creation. The rise in vehicle demand across all scenarios represents an opportunity for domestic assembly and component manufacturing. However, Kenya's current industrial base

characterised by an 84% vehicle import share and a manufacturing utilisation factor of approximately 20% (see Section 1.4) is not yet positioned to absorb this demand. Targeted industrial policy is therefore needed to create the conditions for viable local production before import restrictions can be tightened without reducing fleet affordability. Concretely, this means tax incentives for EV assembly, investment in technical skills development, and structured partnerships with global manufacturers. These actions directly align with the manufacturing pillar of Kenya's Big Four Agenda [59] and would generate local employment benefits, particularly in the higher-electrification scenarios where fleet turnover is greatest. Strengthening this capacity is also a prerequisite for the progressive tightening of second-hand vehicle import standards since restrictions imposed before competitive domestic alternatives exist risk reducing fleet affordability rather than driving a transition. The strategies highlighted would also help mitigate the fuel import challenges highlighted in *Kubaya* and increase resilience in the face of fluctuating global markets.

3. Accompany assembly ambitions with upstream material supply security. Domestic vehicle assembly is only as resilient as the supply chains feeding it. Since bulk materials such as aluminium and, to a lesser extent, steel are largely imported, scaling up local production without securing long-term supply agreements for processed metals risks replicating the same import vulnerabilities the transition is intended to reduce. Kenya should therefore pursue long-term bilateral or regional supply contracts for key processed materials in parallel with any domestic manufacturing push. Over time, as end-of-life EV volumes grow, recycled materials could increasingly supply local component production, gradually reducing raw material import dependence and shifting Kenya toward a more circular manufacturing economy. The large 2-wheeler fleet projected under *Hatua Binafsi* will generate particularly substantial e-waste volumes as batteries reach end of life; introducing a mandatory Extended Producer Responsibility (EPR) framework for EV batteries is therefore an early and practical step toward capturing these materials for reuse in local production, and one that can be implemented well in advance of domestic manufacturing reaching the scale needed to absorb them.
4. Build regional supply chain competitiveness for critical battery metals. Pathways with high EV uptake project rising demand for cobalt, nickel and copper. National initiatives such as the Africa E-Mobility Alliance [60] should be supported by analysis of regional competitiveness in mineral refining and component manufacturing, with policies targeted toward refining, component production,

vehicle repair, or recycling as appropriate, to reduce vulnerability to global supply chain disruptions.

5. Include transport material emissions in future projections and country targets so emission reduction strategies have visibility on the role of new technologies and are well prepared to address them. With energy and transport electrification and mass transport futures, the increased material emissions for aluminium, copper, cobalt, graphite and other minerals underscore the need to prioritise low-carbon production of these materials. This is especially important if local manufacturing increases.
6. Leverage green financing to enable inclusive access to transport. The *Hatua Binafsi* scenario assumes high access to finance leading to rapid private EV uptake, but risks exacerbating inequality and congestion if public transport provision does not keep pace. Green financing must therefore be directed not only toward private vehicle adoption but toward inclusive transport access. Kenya should expand green financing schemes targeting informal and lower-income transport operators, including matatu owners and boda riders, ensuring that the benefits of electrification are not concentrated among higher-income private vehicle owners.
7. Institutionalise Non-Motorised Transport (NMT) infrastructure. NMT infrastructure is a key feature in *Kujielewa* and *Kunawiri*. Kenyan countries should institutionalise requirements for pedestrian and cycling lanes in all urban road developments, drawing from Nairobi's NMT masterplan successes [61]. These low-cost interventions can partly offset the financing challenges seen in *Kujielewa* while supporting the sustainable transport vision of *Kunawiri*.
8. Strengthen coordinated planning and governance to avoid lock-in to increasingly uncompetitive fossil technologies. The *Kubaya* scenario warns of the consequences of fragmented planning and weak government involvement, which lead to higher emissions and inefficient transport systems. To avoid this, Kenya needs to enhance institutional capacity for integrated transport-energy planning at national and county levels, fostering cross-sector collaboration through forums like the Africa Sustainable Transport Forum [62]. This would support the realisation of outcomes seen in *Kunawiri* and *Kujielewa*, where better coordination leads to improved transport provision and environmental benefits.

4. Conclusions

This study provides the first nationally focused assessment of material demands for transport-energy transitions in Kenya, linking detailed vehicle fleet projections under four co-developed socio-technical scenarios with quantified bulk and critical material requirements, their associated emissions and batter costs. By applying the TEAM-Kenya transport-energy model in combination with the Mat-dp tool, we estimate the scale and composition of critical and bulk minerals and materials such as lithium, cobalt, aluminium, and steel needed across different transport futures.

We have shown that material demand varies significantly by scenario and is shaped by both the pace and mode of electrification. In *Hatua Binafsi*, where rapid private vehicle and two-wheeler electrification is projected, electric cars grow from 21% of total material demand in 2030 to over 41% by 2050, and battery-critical minerals such as lithium, cobalt, and copper reach their highest levels across all scenarios. In *Kunawiri*, where investment in mass transit is prioritised, buses account for 13.5% of total material demand in 2025, rising to 32% by 2035 as the BRT fleet builds out; bus demand is almost entirely attributable to electric vehicles by 2030, and this scenario drives the highest aggregate demand for bulk materials, particularly steel and aluminium, associated with large vehicle fleets. *Kubaya*, characterised by minimal electrification and slow infrastructure development, maintains fossil passenger car dominance at 43–61% of total demand throughout the period, resulting in lower critical mineral demand but continued exposure to fuel import costs and stranded-asset risk from an ageing fossil-fuel fleet. *Kujielewa*

follows an intermediate trajectory, with electric car demand becoming substantial only from 2040 onwards. Across all scenarios, embodied emissions from material production scale broadly with material demand volumes, underscoring the importance of developing low-carbon production capacity for key materials, alongside circular economy approaches such as battery recycling and material recovery.

This work underscores the strategic importance of aligning Kenya's climate and industrial policy goals. Local EV assembly, battery recycling, and the development of supportive regulatory frameworks could both manage material supply risks and build domestic capabilities. Achieving this will require coordinated planning, investment in infrastructure and strong governance to guide technology choices and industrial development.

By demonstrating the utility of open-source tools and transparent data, we offer a replicable and scalable approach for other low- and middle-income countries navigating similar transitions.

Based on this study, we recommend the following pieces of future work:

1. Circular economy assessment: Develop scenarios for vehicle and EV battery recycling to quantify the extent to which recovered materials could offset future primary material demand under each pathway.
2. Supply chain resilience assessment: Evaluate the criticality of key minerals across transport futures, including Kenya's potential to locally source or substitute materials and the concentration risk of international supply chains that could constrain the realisation of desired pathways.
3. Material footprint of infrastructure quantification: Model supporting infrastructure transport projections and combine them with material requirements for infrastructure, including transport networks (i.e. roads, railways, ports, or BRT), and EV charging infrastructure.

CRedit author statement

Karla Cervantes Barron: Conceptualization, Methodology, Software, Data Curation, Investigation, Validation, Writing - Original Draft, Writing - Review & Editing, Visualization. James Dixon: Conceptualization, Writing - Review & Editing. Joshua Oduor: Writing - Review & Editing. Dominic Kemei: Writing - Review & Editing. Ignatius Maranga: Writing - Review & Editing. Patrick Mwanza: Writing - Review & Editing. Elena Pierard: Writing - Review & Editing. Christian Brand: Software, Writing - Review & Editing. Fatima Afifah: Writing - Review & Editing. Jonathan M. Cullen: Conceptualization, Funding acquisition, Supervision.

Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.esr.2026.102291>.

Data availability

Data behind the models is available open-source but for anyone interested in any other information, data will be made available upon request.

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