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Energy sustainability and carbon dioxide emissions mitigation options for South Africa's road transport sector

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Abstract

Background The transport sector in South Africa is responsible for around 11% of the country's carbon dioxide emissions, with road transport contributing an overwhelming 90% of this total, as noted by the South African Green Transport Energy of South Africa. As part of its commitment to global climate pacts, South Africa aims to reduce emissions from its road transport sector. Yet, studies focused on reducing energy consumption and related emissions in this sector have been sparse.

Results Utilizing a bottom-up accounting modelling framework Low Emissions Analysis Platform (LEAP), this research investigated five low-carbon transition scenarios alongside a business-as-usual (BAU) scenario for road transport. These scenarios comprised Fuel and Technology Switching (FTS), Modal Shift (MS), Logistics Improvement (LI), Energy Efficient (EEF), and a Combined Mitigation (CMT). The BAU scenario was established as a benchmark to demonstrate energy demand and emissions in the absence of changes to current practices or policies. According to our model, under the BAU scenario, there will be a 61% surge in final energy demand, from 769 petajoules (PJ) in 2020 to 1240 PJ by 2050, accompanied by a proportional increase in emissions. The study revealed that the implementation of any of the alternative low-carbon scenarios could yield a reduced energy demand by 2050. LI 21%, MS 33%, FTS 40%, EEF 48%, CMT 77%, Significantly, a combined approach, integrating multiple low-carbon policies, can achieve more substantial reductions in energy demand and Carbon Dioxide (CO_2) emissions than applying single policies separately.

Conclusions This study emphasizes the importance of crafting province-specific solutions, acknowledging that challenges and contexts vary between provinces. Furthermore, lessening energy reliance not only diminishes the nation's fuel import bills but also improves air quality and aids in achieving low emission targets.

Keywords Bottom-up accounting modelling, Business-as-usual (BAU), Carbon dioxide emissions, Emissions reduction, Energy demand, Low-carbon transition, Provincial strategies, Road transportation, South Africa

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Background

Since the advent of mechanized transport systems, energy has always fuelled movement, transforming from human and animal power to carbon-intensive petroleum fuels. Today's global transport sector accounts for significant energy consumption, with 95% of its energy derived from petroleum-based fuels, primarily gasoline and diesel (SLOCAT 2021; Oladunni et al. 2022). The finite nature of petroleum resources raises questions about the long-term sustainability of this energy source. Oil production is geographically concentrated, making oil-consuming countries vulnerable to supply disruptions due to geopolitical tensions, market volatility, or resource depletion. Moreover, the extraction, processing, and use of oil result in the emission of greenhouse gases and pollutants, contributing to climate change and air quality degradation.

The global transport sector stands as a major consumer of final energy (petroleum resources), contributing approximately 29% to total energy consumption and 65% to the world's oil products consumption (Solaymani 2019). Its CO_2 emissions amount to nearly 24% of global emissions, trailing only electricity and heat production sectors (Solaymani 2019; Agency 2003). A report by the Intergovernmental Panel on Climate Change (IPCC) in 2019 revealed that road transportation accounted for 70% of transport emissions, while aviation, shipping, and rail transport contributed 12%, 11%, and 1%, respectively (Shukla, et al. 2019).

In South Africa, a rapidly developing economy, the growth in GDP have brought about substantial changes in lifestyle patterns, including increased frequency of travel. This, combined with factors such as non-centralized economic hubs, spatial planning, and infrastructure development, has led to a considerable dependence on transportation, making passenger and freight transport a vital component of the South African economy (Christopher Zegras 2007).

The South African transport sector, comprising of passenger and freight transport across road, rail, air, and water, relies heavily on road transport, with approximately 90% of all freight moved by road and approximately only 10% of passengers are by rail (National Transport Mastereplan 2021; Green Transport Strategy 2018a; South Africa Passenger Transportation 2023). Despite its energy efficiency, the rail transport sector remains underutilized due to deteriorating infrastructure and people safety. The overall energy consumption in the transport sector in 2022 was second only to the industrial sector, mirroring global trends (Department of Mineral Resources and Energy 2018).The energy supply to the sector is predominantly petroleum liquids, making South Africa the largest CO_2-eq emitter in Africa (Oladunni et al. 2022). The transport sector in South Africa contributes approximately 11% to the national carbon dioxide emissions inventory with road transport contributing approximately 90% of that inventory according to the South African Green Transport Energy of South Africa (Green Transport Strategy 2018b).

In this context, this study aims to investigate transport energy demand and CO_2 mitigation strategies in South Africa using a long-term energy modelling framework developed by the Stockholm Environment Institute. The primary aim of this study is to evaluate the long-term technologically feasible energy demand reduction and CO_2 mitigation potentials in the South African transport sector. Specifically, the study seeks to:

- develop a technology-rich, bottom-up energy model for the South African road transport sector per province, per vehicle classification and usage.
- assess provincial energy saving potentials in the South African transport sector.
- evaluate provincial carbon dioxide mitigation potentials for the South African transport sector.

Main text

Literature review

As the arteries of the global economy, the transport sector is an indispensable component of modern life, connecting people, goods, and services across geographic borders. The sector, encompassing road, rail, air, and maritime transport, is an integral driver of economic development and societal progress. However, the overwhelming dependence of this sector on fossil fuels, primarily petroleum derivatives, casts a long shadow on its environmental sustainability. In the light of the Paris Agreement and the growing urgency to mitigate climate change, a transition towards a more sustainable and low-carbon transport sector is imperative. The Net Zero Scenario under the Paris Agreement estimates that oil dependency needs to decrease from 102EJ in 2021 to 77EJ in 2030 to be on track for the decarbonisation targets (Shif 2014).

The transition towards a sustainable transport sector is a complex task requiring concerted efforts from all stakeholders. Governments play a crucial role in steering this transition through policy measures (Newell and Mulvaney 2013). These measures include fuel economy standards, emission regulations, fiscal incentives for cleaner vehicles, investments in infrastructure, and support for research and development and as such South Africa such as a The Green Policy Review of South Africa's Industrial Policy Framework (Green Economy Policy 2020).

South Africa's transport sector, like many around the globe, is primarily fuelled by diesel and gasoline. The country's unique geographic and economic structure leads to variations in fuel use, primarily differentiated by octane levels between coastal and inland provinces. For instance, coastal provinces utilize unleaded 95 gasoline and diesel 50 parts per million (PPM) and 500 PPM, while inland provinces additionally offer the alternative of 93 unleaded fuel. Alongside these conventional fuels, electricity has begun to emerge as a uniform tariff across all provinces.

Over the past decade, from 2010 to 2020, all fuel tariffs in South Africa have seen a significant increase, with an approximate growth of 100% (Felver 2020). This dramatic surge in fuel prices has come in tandem with a growth in the transport sector's demand for energy, contributing to a rise in both fuel costs and carbon emissions.

The prevalence of manual transmission vehicles in South Africa, which account for approximately 4 5% of the market share (Williams 2022), also impacts fuel efficiency and carbon emissions. Manual cars, depending on driving habits and styles, may consume more fuel than their automatic counterparts. As such, transitioning to automatic vehicle transmissions, and potentially in the future to self-driving vehicles, could play a crucial role in South Africa's fuel consumption mitigation strategies.

It's worth noting that the country has begun to explore alternative transport technologies as part of its decarbonisation efforts. For example, studies have suggested the potential of battery swapping with solar-charged minibus trailers in South Africa's long-distance para-transit sector (Giliomee and Booysen 2023). However, the lack of a comprehensive plan for these new technologies, at both the government and academic levels, may impede progress in this area.

Based on future projections, transitioning to more advanced transport technologies could significantly reduce baseline greenhouse gas (GHG) emissions from motor vehicles by 19% in 2050, even while internal combustion engine (ICE) motorcars continue to contribute the majority (63%) of emissions (Tongwane and Moeletsi 2021). Yet, the successful implementation of these technologies is dependent on a multitude of factors, including energy security, affordability, and infrastructure improvements.

In a broader perspective, energy modelling provides valuable insights into the complex energy challenges South Africa is facing. It's an essential tool in informing policies, defining strategies, and setting specific targets. The available literature indicates that energy modelling in developing countries, and in South Africa specifically, is an active area of research that has produced several model types (Alison Hughes 2015). A comprehensive and integrated energy strategy, leveraging the potential of regional hydropower and other renewable resources, may provide an effective pathway to decarbonize South Africa's transport sector and economy (Arndt et al. 2016).

In other words, the economic implications of energy efficiency improvements in the South African transport sector cannot be overlooked. Energy efficiency improvements can bring significant cost savings in the long term and can contribute to economic growth by stimulating technological innovation and creating jobs in the clean energy sector. Therefore, given the dynamic and rapidly evolving global energy landscape, this study fills a significant gap in understanding the long-term technological feasible energy efficiency improvements and CO_2 mitigation potentials in the South African transport sector. Its findings could inform and shape policies, strategies, and practices towards a more sustainable and environmentally friendly transport sector in South Africa, contributing to the broader global agenda of sustainable development and climate change mitigation.

Methods

General overview of methodological framework

The research approaches the study of energy sustainability and carbon dioxide emissions mitigation methods in the South African Transport sector by creating a bottom-up, technology-rich model using the Low Emissions Analysis Platform (LEAP) modelling tool. The tool was developed by Stockholm Environment Institute (SEI). Analysing and modelling the road and rail transport industry for both freight and passenger services across all nine provinces. Provincial concentration of the model is driven by the non-uniformness of the circumstances per province. For example, some provinces have rail only for passenger transport and freight is transported by road. Using the LEAP's standard method framework, we developed a specific methodological framework presented in Fig. 1 for this study. Extracting from framework overview, the modes, technologies and demand for the transport sector are identified per province in conjunction with fuel used per mode, and an overview of the framework is presented in Fig. 2.

LEAP modelling framework

The study's framework is determined by the desired end results. Inputs on LEAP were set based on available energy information for the sector to achieve desired results. Figure 2 illustrates the road transport structure analysed in this study.

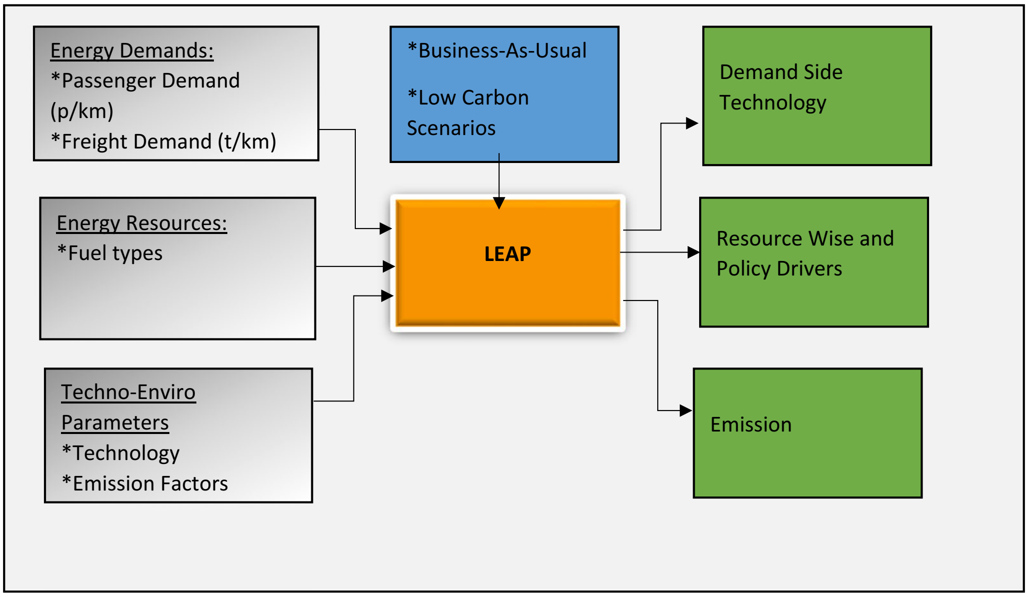

Fig. 1 Specific overview of for the methodological framework

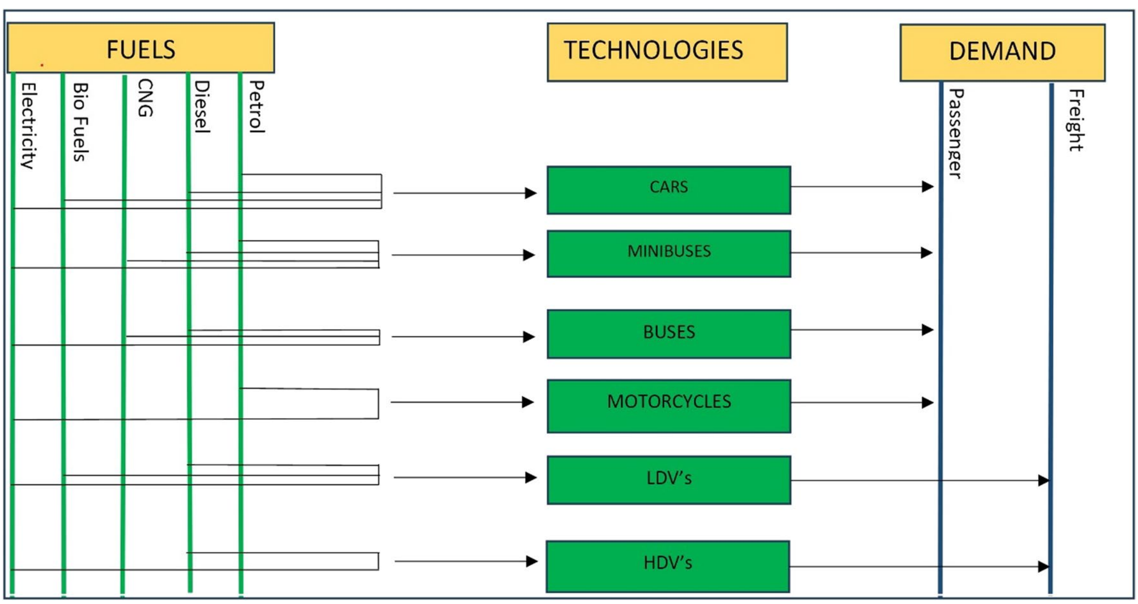

Fig. 2 Overview of transport modes and types by province with corresponding fuel utilization

Data collection and input parameters

Step 1:

Vehicle registration data in South Africa per vehicle type and per province was collected from the National Traffic Information System (NaTIS) (Live vehicle population 2021). Data are available from the years 1999–2005, 2010, 2014–2020; we interpolated to determine the gaps in order to create a uniform number sequence that assisted in projection up to 2050 as per Eq. 1.

$$y = y_1 + (x - x_1)\frac{(y_2 - y_1)}{(x_2 - x_1)} \tag{1}$$

Step 2:

To determine the growth in number of vehicles from 2020 to 2050; the product of available GDP and population projections to 2050 was calculated to produce GDP/Capita to 2050 and rate of change of GDP/capita will directly contribute towards the growth of the country's vehicle count. The product of the rate of change of income and the vehicle elasticity produces the rate of change of elasticity that the vehicle population increases. Using this method, we project each vehicle class per province to 2050.

Step 3:

LEAP has a guideline formula that it applies in calculation of energy intensities (Insitute 2020). The data requirements for achieving the desired LEAP inputs as tabulated in Tables 1 and 2 include load factor, average distance travelled by vehicle type per year and fuel consumption per car type in South Africa. The fuel technology and percentage distribution referred to in Table 1 and the average distances, load factor and relative fuel consumptions in Table 2.

Vehicle Stock Turnover is calculated as per Eq. 2.

$$Stock_{tyv} = (Sales_{tv} * Survival_{t,y-v}) \tag{2}$$

$$\sum\nolimits_{y-0V} Stock_{y,v,t}$$

where t is the type of vehicle (i.e. the technology branch), v is the vintage (i.e. the model year), y is the calendar year, T is the number of types of vehicles, *Sales* is the population of vehicles added in a particular year: entered as an expression. *Stock* is the number of vehicles existing in a particular year: either entered as an expression for current accounts or calculated internally based on historical sales. *Survival* is the fraction of vehicles surviving after a number of years: entered as a lifecycle profile. V is the maximum number of vintage years: determined automatically from the survival lifecycle profile, with a maximum of 30 years.

Secondly, to calculate fuel economy using the formula (Eq. 3):

$$FuelEconomy_{t,y,y} = FuelEconomy_{ty} * FeDegration_{t-yy} \tag{3}$$

where *Fuel Economy* is fuel use per unit of vehicle distance travelled (i.e. l/km), entered as an expression. *FeDegradation* is a factor representing the decline in fuel economy as a vehicle ages. It equals 1 when y = v, entered as a lifecycle profile.

To calculate mileage, we use the formula (Eq. 4):

$$Mileage_{t,y,y} = Mileage_{ty} * MlDegration_{t-yy} \tag{4}$$

where *Mileage* is the annual distance travelled per vehicle, entered as an expression. *MlDegradation* is a factor representing the change in mileage as a vehicle ages. It equals 1 when y = v, entered as a lifecycle profile.

These are calculated on LEAP when developing the current accounts of the baseline by inputting the product and sums as per Table 3.

Using results of all the information above, energy consumption is calculated using the formula (Eq. 5):

$$EnergyConsumption_{tyv} = Stock_{tyy} * Milesge_{t,y,v} * FuelEconomy_{t,y-v,p} \tag{5}$$

Distance-based pollution emissions is calculated using the formula (Eq. 6):

$$Emission_{t,y,y,p} = Stock_{tyy} * Mileage_{t,y,y} * EmissionFactor_{t,v,p} * EmDegration_{t,y-v,p} \tag{6}$$

Table 1 Vehicle type, technology, and technology share percentage

Vehicle type	Vehicle technology	Technology percentage (%)
Motorcars and Station Wagons	Gasoline	50 (Taviv et al. 2008)
	Diesel	50 (Taviv et al. 2008)
Minibuses	Gasoline	100 (Taviv et al. 2008)
Buses	Diesel	100 (Taviv et al. 2008)
Motorcycles	Gasoline	100 (Taviv et al. 2008)
LDVs	Diesel	100 (Taviv et al. 2008)
HDVs	Diesel	100 (Taviv et al. 2008)

Table 2 Vehicle type, annual mileage, load factor and fuel consumption

Vehicle type	Average distance travelled/year (km)	Load factor	Fuel consumption (l/pas-km)
Motorcars and Station Wagons	16,630 (Merven et al. 2012)	1.4 (Stone et al. 2018)	0.065 (Vehicle Fuel Economy in Major Markets 2021)
Minibuses	32,000 (Merven et al. 2012)	14 (Stone et al. 2018)	0.0085 (Vehicle Fuel Economy in Major Markets 2021)
Buses	22,072 (Merven et al. 2012)	25 (Stone et al. 2018)	0.0142 (Vehicle Fuel Economy in Major Markets 2021)
Motorcycles	8300 (Merven et al. 2012)	1.1 (Stone et al. 2018)	0.0490 (Vehicle Fuel Economy in Major Markets 2021)
LDVs	25,000 (Merven et al. 2012)	0.5 (Stone et al. 2018)	0.6 (Vehicle Fuel Economy in Major Markets 2021)
HDVs	50,000 (Merven et al. 2012)	2.5 (Stone et al. 2018)	0.162 (Vehicle Fuel Economy in Major Markets 2021)

Table 3 LEAP calculated data input requirements

	Calculating passenger-KM	Input values
A	Car Use (billion veh-km)	17.1
B	Load Factor (pass-km/veh-km)	1.4
C = A*B	Total Vehicle (Car) Pass-km	72.31
D	Bus (billion veh-km)	0.2
E	Load Factor (pass-km/veh-km)	25
F = D*E	Total Bus Pass-km	4.6
G = F + C	Road Passenger-km	76.91
H	Rail Passenger-km	0.1
I = G + H	Total Passenger-km	55.1
Calculating energy intensities		
J	Car Fuel Economy (l/pas-km)	0.065
K	Load Factor (pass-km/veh-km)	1.4
L = 1/(J*K)	Energy Intensity (litres/pass-km)	52.6
M	Bus Fuel Economy (l/pas-km)	0.049
N	Bus Load Factor (pass-km/veh-km)	25
O = 1/(M*N)	Energy Intensity (litres/pass-km)	

where P is any criteria air pollutant. *Emission Factor* is the emissions rate for pollutant p (e.g. grammes/ veh-mile) from new vehicles of vintage v, entered as an expression. *EmDegradation* is a factor representing the change in the emission factor for pollutant p as a vehicle ages. It equals 1 when y = v, entered as a lifecycle profile.

And similarly, energy-based emissions using the formula (Eq. 7):

$$\begin{aligned} Emission_{tyv} = & EnergyConsumption_{tyy} \\ & * EmissionFactor_{t,y,p} \\ & * EmDegration_{t,y-v,p} \end{aligned} \tag{7}$$

Scenario description

Baseline scenario—BAU

The baseline scenario of this study is the "frozen scenario" which is described as a Business-As-Usual (BAU) scenario, data as from 2020, using the same fuel without any energy conservation or emissions reduction measures. It projects the energy demand for the transport sector from 2020 up to 2050 if growth is constant relative to GDP and there are no significant changes in fuel and technologies in the sector.

Fuel and technology switching—FTS South Africa proposed a major leap towards green transportation with a new electric vehicle (NEV) promotion policy offering subsidies to manufacturers and buyers to drive up the supply and demand of NEVs. The policy seeks to achieve a forecasted 40% of new electric vehicles by 2030 and for that number to reach 80% by 2040 (Auto Green Paper 2021). The policy is not specific on vehicle category therefore this study assumes the targets are across all passenger categories since there have been a pilot of imported vehicles by different manufacturers yet none in the road freight vehicle categories. This scenario uses an average EV consumption in South Africa from the IEA data as tabulated below (IEA 2022). Sedans are known to be the most efficient by consumption at 0.26 kWh/km (Database 2015). As specified in Table 4, a case study of Malaysia also achieved better electrical buses consumption of 1.35 kWh/km, similar to the Chinese recorded consumption of 1.3 kW/h (Beckers et al. 2021; Saadon Al-Ogaili et al. 2020). An assumed 50% of buses to be using electricity as means of fuel by 2050 is used for the study combined with CNG buses.

With the drive from government especially in the buses industry after introducing CNG buses pilot programme in Johannesburg, Tshwane, and Cape Town, an estimated growth of the country's 50% buses and minibuses is to be CNG fuelled by 2050. Since the South African data are still in its pilot stage, the study uses consumption as tabulated in Table 5 of similar buses tested in real driving conditions using CNG and the consumption in Table 5 was achieved for both bus types (Prati et al. 2022).

South Africa has experienced a growth in using motorcycles post the 2020 pandemic (Giliberto et al. 2019). Considering the lifespan of motorcycles, it is easier to drive an electrical bikes initiative by government that can result in all motorcycles using electricity in 30 years. For this vehicle type, an assumption that all motorcycles will be electrical by year 2050, a case of equal 33.3% increases per decade. All other factors such as road freight vehicle categories remained unchanged from the BAU scenario for the FTS scenario.

Table 4 FTS scenario electrical vehicles consumption

Vehicle type	Consumption (kWh/km)
Sedan	0.26 (Database 2015)
Minibuses	1.49 (Database 2015)
Buses	1.35 (Database 2015)

Table 5 FTS scenario CNG vehicles consumption

Vehicle type	Consumption (g/km)
Minibuses	355 (Prati et al. 2022)
Buses	470 (Prati et al. 2022)

Modal shift—MS The Modal Shift strategy is a strategy that can be applied in cases where public and private transport coexists and travels common areas; it is applied to shift private transport users to public or shared transport such as buses, trains, ship and plane in order to reduce use of private cars. In South Africa, a study highlights that the choice and shift between using public transport versus private is associated with level of income, physical access and affordability (Venter et al. 2013). For passengers the modal shift scenario assumes a shift from private cars to minibuses and buses, especially with the visual evidence of bus rapid transport (BRT) in metropolitan areas in the country. For freight transport; this study considers that approximately 87.5% of freight in South Africa is transported by road and the Department of Environmental Affairs reported an initiative to create a modal shift with a split of 70% market share by 2043 and constant share thereafter with rail transporting 70% on a high uptake, 50% on medium uptake and 30% on a low uptake (Shif 2014). Developing countries such as Pakistan have also studied and modelled that instead of the current Pakistan split of 4% rail freight to 96% road freight, freight transportation could be more optimal with a split that utilizes more rail than freight with a modal split of 97% rail and 3% road freight transportation (Ali et al. 2022). This study assumes the medium uptake of achieving a 50% split by year 2043 and keeping a 50% market share split thereafter for freight from road to rail, decreasing the passenger car usage to 10% of total billion passenger kilometres (BPkm) by shifting the loads to buses in order to reach a share of 45% by 2050 and minibuses 30% by 2050.

Logistics improvement—LI In South Africa, most road transport is responsible for freight transportation from different sources of production to process and sale destinations across the country (Merwe et al. 2022). Most freight transport uses a single-trip transport method, from the loading point to delivery destination without a return load resulting in empty running time (McKinnon and Ge 2006). A shift towards rail transport for long-distance, dense corridors might yield environmental, financial and social benefits (Merwe et al. 2022). Using the two trips-to-one load ratio, an assumption that 50% of trips are empty loads but contribute significantly on the kilometres travelled, fuel consumption and carbon emissions. Studies in developing countries such as Nigeria have been conducted assuming that if efficient logistics management is implemented, a reduction of empty running time can reduce the annual tonne mileage by 40% in year 2050 (Dioha and Kumar 2020). A current development of a bimodal rail train is in its pilot stage by Transnet Rail Engineering (TRE) in partnership with RailRunner South Africa (RRSA), a redesigned bogie and trailer technology will transport specific freight that will achieve two-way loads (Merwe et al. 2022). Considering that empty loads consume lesser fuel compared to a loaded truck, this study assumes that if South Africa starts the process of logistics improvement immediately and achieve 5% reduction in 5 years and reach 50% reduction of annual tonne kilometres travelled by freight vehicles by year 2050.

Energy Efficient—EEF The Energy Efficient scenario is based on efficient fuel prioritization and utilization; in 2005 the South African government embarked on an initiative towards fuel efficient vehicles by proposing a policy the Energy Efficiency Strategy of South Africa which aimed at making sure vehicle dealerships introduces fuel efficient vehicle, even though there were no actual targets (Energy Efficiency Strategy 2005). Therefore, for modelling purposes this study assumes an improvement of 50% fuel efficiency by the year 2050 in without an introduction of any new fuel technologies. The assumption is modelled in both passenger and freight vehicle classes.

Combined mitigation scenario—CMT The mitigation scenario combines all scenarios, exploring a more robust approach if all scenarios are implemented in parallelism to achieve the most energy demand reduction and CO_2 emissions mitigation.

Results

Final energy demand projections

Figure 3 illustrates the total energy demand projections for both the Business-As-Usual (BAU) scenario and all low energy demand scenarios. In the BAU scenario, characterized by a lack of technological advancements, the final energy demand is projected to exhibit an upward trend. Starting at 769PJ in the base year 2020, it is anticipated to surge dramatically by 61%, reaching a staggering 1240PJ by the year 2050. Comparing all scenarios, we observe that the Logistics Improvement (LI) scenario projects the second-largest energy demand in 2050, totalling 978PJ. While this still represents an increase from the base year, it reflects a notable reduction of 262PJ compared to the BAU scenario. Furthermore, both the Modal Shift (MS) and Fuel Technology Switching (FTS) scenarios project similar energy demands, standing at 821PJ and 819PJ, respectively. These values signify a modest 7% increase per scenario compared to the base year.

In contrast, the Energy Efficiency (EFF) scenario emerges as the first scenario to reduce energy demand in comparison to the base year. It achieves a positive reduction of 124PJ in 2050 relative to the 2020 energy

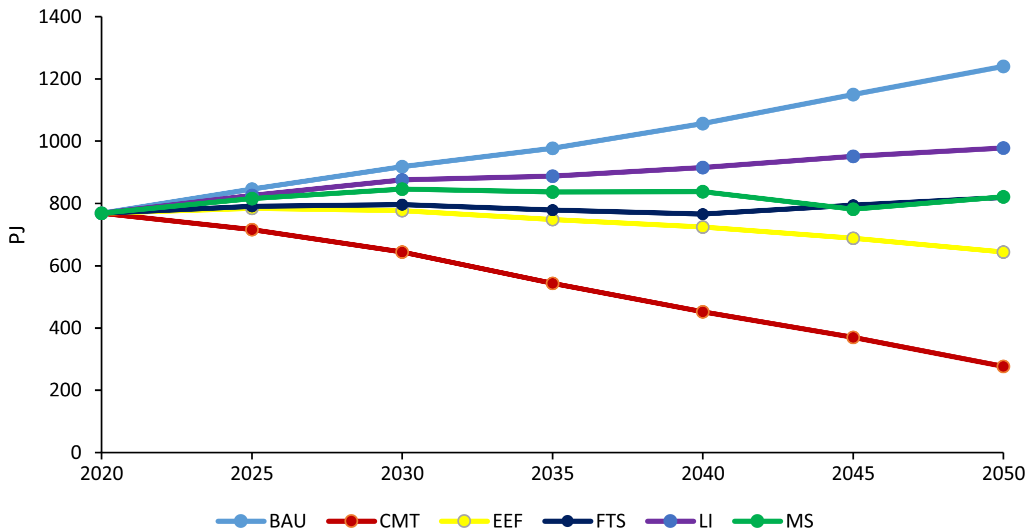

Fig. 3 Final energy demand projections for all scenarios

demand. This corresponds to an impressive 51% reduction in energy demand compared to the BAU scenario. To further enhance the potential for implementing diverse strategies, a combined scenario was developed as a robust strategy. The results demonstrate a substantial reduction in energy demand, reaching 543PJ and 276PJ in 2030 and 2050, respectively. These figures signify a 44% reduction in 2030 and an even more significant 78% reduction in energy demand by 2050 when compared to the BAU scenario.

Figure 4 provides a visual representation of the final energy demand distribution across various vehicle categories in each scenario. In the base year, across all scenarios, cars account for the highest energy demand, constituting approximately 38% of the total energy demand, while heavy-duty vehicles (HDVs) also represent 38%, light-duty vehicles (LDVs) make up 12%, minibuses contribute 6%, motorcycles account for 5%, and buses contribute 2% to the total energy demand.

As we project into the future, by 2050, the energy demand distribution in the Business-As-Usual (BAU) scenario undergoes slight changes. Cars' share of the energy demand increases to 43%, while the share of HDVs decreases by 6% to 32%. It's important to note that

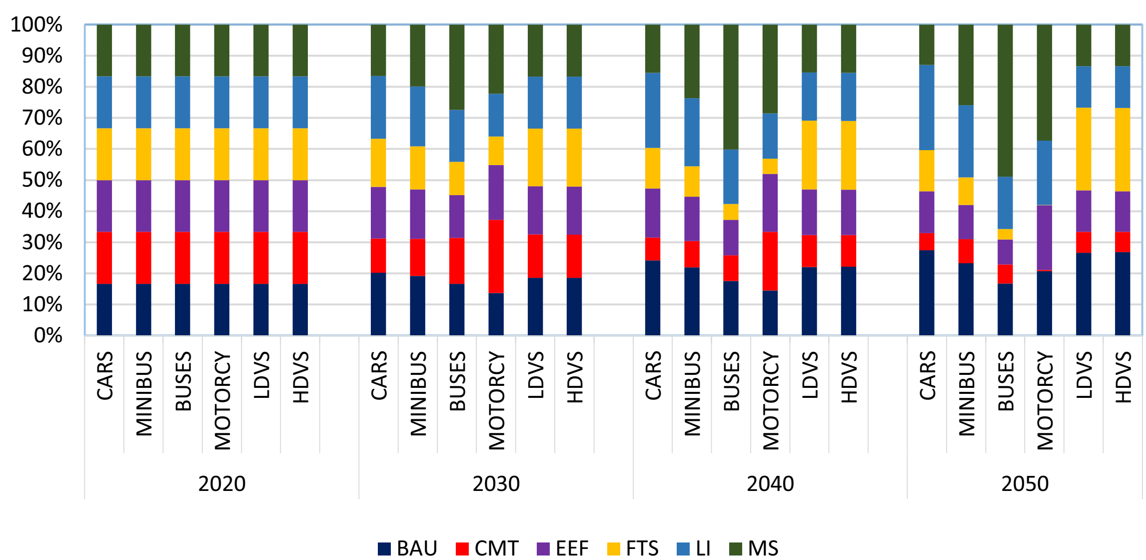

Fig. 4 Share of final energy demand by vehicle types for all scenarios

these changes in the BAU scenario are primarily influenced by GDP projections.

In the context of all alternative low energy demand scenarios, distinct variations in energy demand growth patterns emerge across different vehicle categories. These variations are attributed to the policy and technological inputs and changes specific to each scenario. Notably, when we examine cars, we observe the following energy demand shares: 32% for the Fuel Technology Switching (FTS) scenario, 55% for the Logistics Improvement (LI) scenario, 41% for the Energy Efficiency (EEF) scenario, 32% for the Fuel Technology Switching (FTS) scenario again, and 31% for the Modal Shift (MS) scenario. It's worth noting that the actual energy demand for cars in all scenarios either matches or falls below the Business-As-Usual (BAU) scenario in 2050. The LI scenario, in particular, sees higher energy demand shares for cars due to substantial reductions in energy demand for other vehicle types.

For a more detailed breakdown, Fig. 5 presents the total energy demand projections by some vehicle types across all scenarios. Notably, due to the implementation of various policies, restrictions, and technologies, cars in both the BAU and LI scenarios share targeted demand projections. Similarly, for minivans, buses, and motorcycles, the BAU scenario shares the projected energy demand target with the Modal Shift (MS) scenario. These scenarios are projected to reach 86PJ for buses, 89.94PJ for minivans, and 130PJ for motorcycles by the year 2050. In contrast, cars exhibit the highest total energy demand projections in the BAU scenario, reaching 535PJ, while minivans and buses reach their highs of 86PJ and 89PJ, respectively. These variations are influenced by factors such as the number of passengers per kilometre travelled ratio.

The scenarios mentioned above each focus on specific, isolated cases to explore various approaches for achieving policy objectives. In contrast, the mitigation scenario consolidates all these individual scenarios into a robust

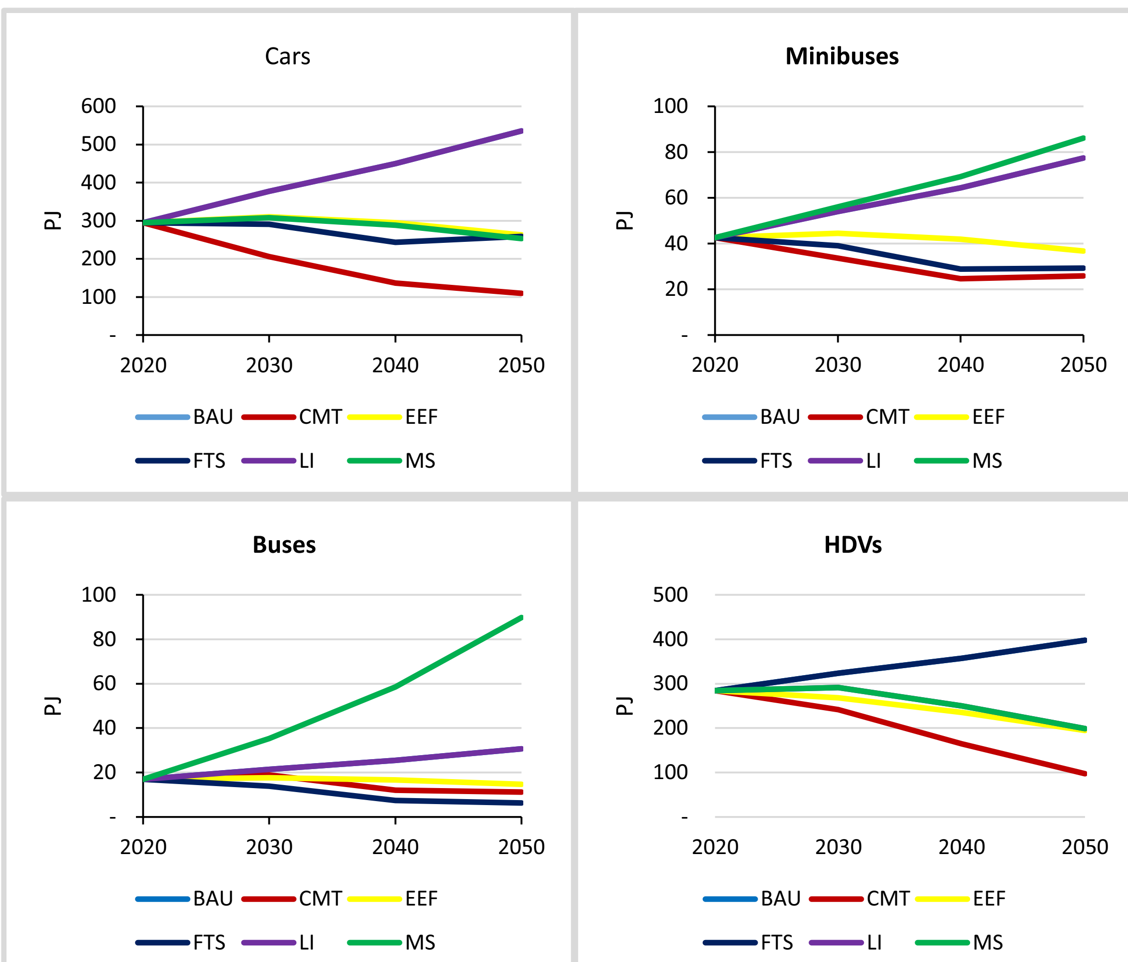

Fig. 5 Final energy demand by vehicle types for all scenarios

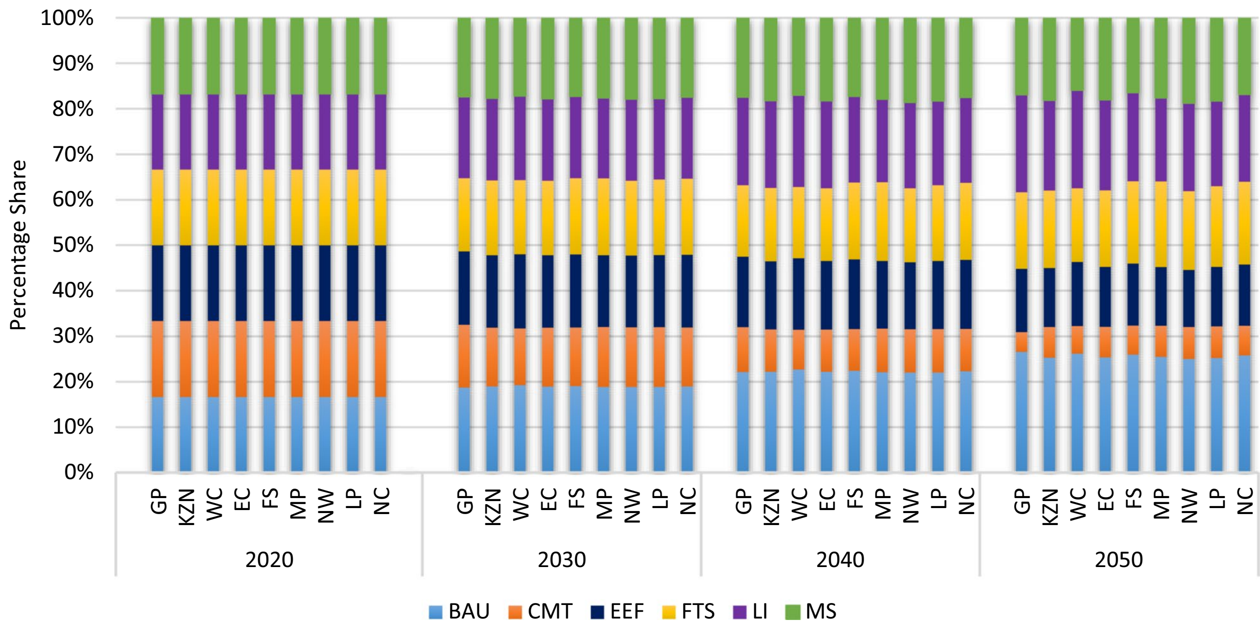

Fig. 6 Share of final energy demand by province for all scenarios from 2020 to 2050

framework that combines their elements into a single policy approach. Within the model, this combined scenario appears to be the most effective, delivering substantial reductions in energy demand. By 2025, it achieves an equivalent reduction of 15%, which further increases to an impressive 77% by the year 2050.

Additionally, when examining the metropolitan provinces of Gauteng, Western Cape, and Eastern Cape, they exhibit similar model profiles as presented in Fig. 6. In these provinces, the demand for gasoline surpasses that of diesel, unlike the other six provinces characterized by industrial economies, farming, and mining activities. In the latter group of provinces, the demand profile reverses, with higher diesel demand compared to gasoline demand.

GHG emissions projections

The greenhouse gas (GHG) emissions data input utilized in the model is based on a default dataset that comes preset with the LEAP model. This study relies on the default emission factors provided by the IPCC tier 1 for the fuels used. It's important to note that electric vehicles in this analysis produce zero emissions, with all production-related emissions accounted for during the production stages rather than as part of fuel emissions analysis in this study.

Figure 7 provides an illustration of emissions projections resulting from energy demand across all scenarios. In the Business-As-Usual (BAU) scenario, emissions are expected to rise from 54.5 $MtCO_2eq$ in 2020 to 87.68 $MtCO_2eq$ in 2050, signifying a substantial 60.08% growth over 30 years. The Logistics Improvement (LI) scenario is projected to have the second-highest emissions, with a 25% increase, which is significantly different from the Modal Shift (MS) scenario's lowest positive reduction of 6% compared to the base year. Meanwhile, the Energy Efficiency (EEF) and Fuel Technology Switching (FTS) scenarios are both anticipated to achieve emissions levels below the base year, with reductions of 9 and 11.53 $MtCO_2eq$, respectively.

The South African fuel price structure results in standard prices for coastal provinces, while inland provinces experience higher prices due to increased logistical activities. As a result, the energy demand profile projection varies slightly for each vehicle type and province. Additionally, the quantities of vehicle types per province contribute to shaping the energy demand and its environmental impact differently. Figure 8 provides a visual representation of the variations in emissions across all scenarios in different provinces.

For instance, in Gauteng, emissions in the Business-As-Usual (BAU) scenario increase from 20.86 $MtCO_2eq$ in 2020 to 33.21 $MtCO_2eq$ in 2050. Conversely, the Fuel Technology Switching (FTS) scenario decreases from 20.86 $MtCO_2eq$ to 15 $MtCO_2eq$ between 2020 and 2050, marking a significant 50% reduction between these two scenarios. A similar trend is observed in KZN, where emissions in the BAU scenario increase from 7 $MtCO_2eq$ in 2020 to 12 $MtCO_2eq$ in 2050, and the FTS scenario reaches 6 $MtCO_2eq$, reflecting a comparable percentage

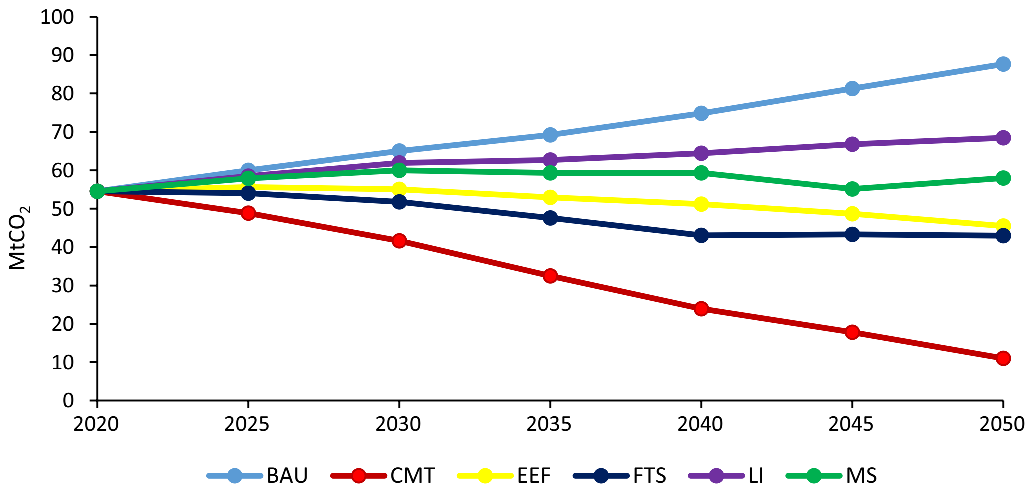

Fig. 7 CO_2 emissions projections for all scenarios

difference to the Gauteng scenario between the highest and lowest emissions scenarios.

In Mpumalanga, the province's unique profile, characterized by a significantly higher proportion of trucks relative to other vehicle types, positions the Energy Efficiency (EEF) scenario as the most effective in reducing carbon emissions. In this case, emissions in the BAU scenario range from 4.73 $MtCO_2eq$ in 2020 to 7.23 $MtCO_2eq$ in 2050.

Discussion

The model generated provincial-specific results to delineate the focus areas within South Africa's transport sector. This approach involved tailoring measures that are relevant to each province's unique characteristics. For instance, when we consider the vehicle population, it's evident that the Northern Cape has a relatively smaller fleet of freight vehicles compared to Johannesburg. Consequently, the government in the Northern Cape should prioritize initiatives that specifically address changes in energy demand and CO_2 emissions pertinent to the province. In contrast, provinces like KwaZulu Natal and Mpumalanga exhibit a higher prevalence of trucks, primarily due to their mineral mining activities and shared export corridors. Given this context, scenarios geared towards freight transport, which includes these trucks, should be accorded higher priority in these provinces. By customizing strategies based on provincial disparities, South Africa can better address its energy and environmental challenges in the transport sector and make more effective use of available resources.

The FTS scenario involves the adoption of various fuel technologies through phased policy implementations. Metropolitan areas across all provinces have embraced Bus Rapid Transit (BRT) systems, driven by population growth and currency instability (HOLDINGS C 2022). This trend has led to more people choosing buses for their urban commute. A pilot project in Pretoria, Johannesburg, and Cape Town is exploring the transition to Compressed Natural Gas (CNG) for buses, signalling the introduction of policies that encourage sustainable green energy demand and enhance energy security in South Africa. According to our model, when considering Tier1 fuels, the use of CNG buses will significantly reduce CO_2 emissions, contributing to international targets for emissions reduction. Given South Africa's offshore gas reserves, this solution could soon become a viable option for implementation.

The Energy Efficient scenario is a robust approach that requires strong policies to introduce vehicles with 50% lower fuel consumption by 2050, phasing out higher consumption vehicles. Initially, a policy introduced the practice of manufacturers displaying energy consumption information on new vehicles (Auto Green Paper 2021). To achieve uniform energy consumption levels across the country, further inputs and limitations can be integrated into this scenario. This approach should be implemented continually until the entire vehicle population aligns with the established targets. In a country where rail transport has deteriorated, the surge in heavy-duty vehicles (HDVs) and light-duty vehicles (LDVs) has resulted in a higher number of vehicles on the roads. This increase has amplified energy demand and, concurrently, carbon dioxide emissions from road freight transport. The modal shift scenario explores possibilities for reducing energy demand and emissions in both HDVs and LDVs.

The combined mitigation scenario demonstrates the most significant benefits, with the lowest energy demand

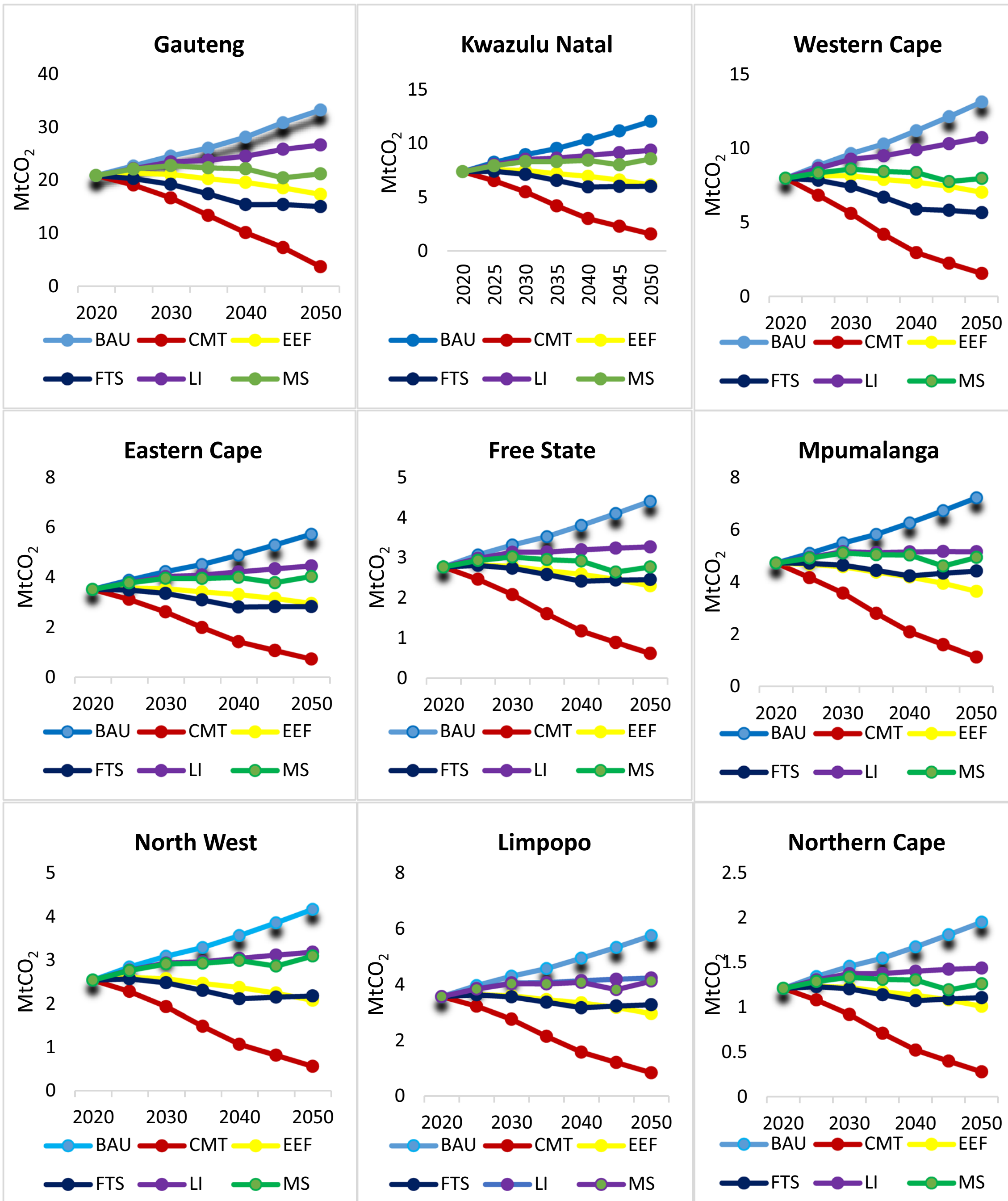

Fig. 8 Environmental effects and Carbon Dioxide emissions by fuel per province

in all provinces, increasing from the 2020 baseline to the final projection year in 2050. This model's results suggest that implementing various methods on a smaller scale can yield substantial reductions in energy demand and CO_2 emissions in the transport energy sector (Shabbir and Ahmad 2010). In the Energy Efficient scenario, the fuel technology switching scenario, and the combined mitigation scenario, CO_2 emissions drop below the 2020 level of 50 million metric tonnes. This reduction is directly linked to the use of low-carbon-emitting fuels such as electricity and CNG.

This study has highlighted gaps in energy studies and implementation plans in South Africa. While the government has proposed hybrid vehicle targets, there is a lack of corresponding implementation plans, including infrastructure development, such as fuel stations or alternatives. Moreover, there is a gap in recorded data from reputable institutions like universities, hindering continuous studies. It is crucial for South Africa, facing energy stability and security issues, surges in imported energy prices, energy economics, diverse energy sources and generation, alternative energy options, provincial solutions for industry, electrification, and transportation, to conduct further energy studies and modelling to address these challenges comprehensively.

Conclusions

In our study, we explored the potential outcomes if the government maintains its existing policies, technologies, and strategies without any intervening actions—a scenario commonly referred to as Business-As-Usual (BAU). We utilized this BAU scenario as the baseline and developed five additional scenarios based on current energy demand trends across various vehicle types, as documented in the South African National Administration Traffic Information System (NaTIS). Our analysis projected energy demand trends for the transport sector from 2020 to 2050 across all nine provinces.

From our study, several key conclusions can be drawn. Firstly, if transformative policies are not implemented by the government, stakeholders, and end-users, South Africa's Road transport sector is poised to witness significant increases in both energy demand and environmental emissions up to the year 2050. The research suggests that South Africa has the potential to align with its energy demand and greenhouse gas reduction targets, as stipulated in its commitments under the Paris Agreement. Achieving these targets would necessitate the development and implementation of tailored policies. It's important to note that these policies may not be universally applicable and must be adapted to suit each unique case study. Granting provinces, the autonomy to devise strategies tailored to their specific infrastructure and conditions is crucial in collectively reaching the country's 2050 goals.

Moreover, our study focused exclusively on road transport. Expanding the research to encompass other modes of transport, such as air, marine, and rail, would provide a more comprehensive understanding of South Africa's progress towards its low-carbon transportation objectives or the need for potential revisions. Additionally, it's essential to recognize that our study did not account for economic, social, and political factors. Their inclusion could introduce varying behaviours and outcomes in the policy scenarios developed, further enriching our understanding of the complex dynamics at play in South Africa's pursuit of its decarbonization goals.

Abbreviations

BAU	Business-as-usual
BPkm	Billion passenger kilometres
BRT	Bus rapid transit
CMT	Combined mitigation (scenario)
CNG	Compressed natural gas
CO2	Carbon dioxide
CO2-eq	Carbon dioxide equivalent
EEF	Energy efficiency (or Energy Efficient based on context)
EJ	Exajoule
FTS	Fuel technology switching (or fuel and technology switching based on context)
GDP	Gross domestic product
GHG	Greenhouse gas
HDVs	Heavy-duty vehicles
ICE	Internal combustion engine
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LEAP	Low emissions analysis platform (or long-range energy alternatives planning system based on context)
LDVs	Light-duty vehicles
LI	Logistics improvement
MS	Modal shift
NaTIS	National Traffic Information System (or South African National Administration Traffic Information System based on context)
NEV	New electric vehicle
PJ	Petajoule (unit of energy)
PPM	Parts per million
RRSA	RailRunner South Africa
SEI	Stockholm Environment Institute
TRE	Transnet rail engineering

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Author contributions
MNN carried out the modelling, validated the results, managed data curation, and drafted the original manuscript. ACC supervised the project and participated in manuscript review and editing. FMM supervised the project. DREE supervised the project, reviewed the work for intellectual content, ensuring the scientific rigor and merit of the work, and contributed to manuscript review and editing. MOD assisted in the study's conceptualization and methodology design, supervised the research project, and contributed to manuscript review and editing. All authors gave final approval of the version to be published and agreed to be accountable for all aspects of the work, ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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