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Transforming the transportation sector: Mitigating greenhouse gas emissions through electric vehicles (EVs) and exploring sustainable pathways

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ABSTRACT

Transportation-related emissions in Pakistan have been rapidly increasing in recent years. This study aims to determine how important it is to electrify road transportation in Pakistan to reduce greenhouse gas (GHG) emissions from the transportation sector. Motivated by the need to tackle the growing environmental issues related to conventional fuel-powered automobiles, this research explores the application of electrification techniques in the context of Pakistan's transportation system. During the 2019 fiscal year, the transportation industry in Pakistan consumed 23×10^6 tonnes of energy from the burning of fossil fuels and produced 52.9×10^6 metric tons of CO_2, which made up 31% of the country's total carbon emissions. In this research, different scenarios, such as business as usual, low carbon, strengthen low carbon, and Pakistan National Electric Vehicle Policy 2040, are evaluated for the transportation sector of the country. Using the LEAP model, this study projects the effects of electrification on Pakistan road transportation over 30 years. When estimating how electrification will affect road transportation in Pakistan over the next 30 years, several factors were taken into account, including policy frameworks, changing consumer behavior, technology advancements, and infrastructure improvements. The analysis covered the emission levels, adoption hurdles, and possible advantages of transitioning to electric vehicles (EVs). The outcomes illustrate that adopting EVs can produce substantial drops in fuel consumption and environmental emissions, providing a sustainable solution to mitigate global warming. This work is directly associated with various Sustainable Development Goals, including SDG3 (good health and well-being), SDG7 (affordable and clean energy), and SDG13 (climate action). The results of this study highlight the considerable potential for GHG reduction associated with the widespread adoption of EVs, offering crucial insights to stakeholders and policymakers.

I. INTRODUCTION

A public challenge that is presently being confronted globally including many developing countries is climate change.[1] Approximately 25%–30% of worldwide carbon emissions are attributed to the transportation industry.[2] The transportation industry connects several sectors, which is crucial for the growth of developing countries' economies. Despite its constructive part, transportation sector produces a major share of carbon emissions around the globe. The transportation industry, among the major sectors where

greenhouse gas emissions are still rising, contributes nearly a quarter of greenhouse gas (GHG) emissions around the globe. The transportation industry's greenhouse gas emissions are a serious environmental issue that has a substantial impact on climate change worldwide.[3] About half of all transport sector-associated greenhouse gas (GHG) comes from road transport, which is by far the prime emitter.[4] The International Energy Agency (IEA) 2018 report claims that 26% of world GHG emissions comes from transportation, which is 70% greater than that of GHG emissions in 1990.[4,5]

The worldwide transportation sector is dependent on fossil fuels, of which oil has 92% of the total share. The transportation sector contributes significantly to climate change by using fossil fuels, such as gasoline and diesel, which produce large amounts of carbon dioxide, methane, and nitrous oxide into the environment. The usage of fossil fuels can cause obvious complications, such as bad air quality due to smog and acid rain, which harms aquatic life, birds, and trees badly.[6] In both developed and developing countries, environmental pollution due to exposure to fossil fuel burning is a main environmental problem disturbing human health. Burning of fossil fuels emits pollution and creates climate change that leads to human health, early death, asthmatic diseases, heart attacks, respiratory disorders, and autism spectrum disorder. Although there are other ambient air contaminants, fine particulate matter (PM2.5) is the marker that has been studied the most and has independent impacts. According to the Global Burden of Diseases (GBD) study, long-term exposure to ambient PM2.5 caused 103.19×10^6 disability-adjusted life-years (DALYs) and 4.21×10^6 deaths globally in 2015, which is the fifth-ranking mortality risk factor, presenting 6.91% of overall world deaths and 3.90% of worldwide DALYs.[7] Table I represents the summary of transport fuel pollutants, GWP of pollutants, and their adverse impacts on human health. Effective mitigation techniques are desperately needed, as the environmental consequences affect not only the climate directly but also human health, biodiversity, and air quality. The transportation sector's contributions to climate change offer increasing environmental hazards, which must be mitigated immediately.[8]

Pakistan faces unique obstacles concerning emissions and transportation that are influenced by a combination of infrastructural, economic, and demographic issues. The demand for transportation, which is mostly dependent on fossil fuels, has increased due to rapid urbanization, population growth, migration toward cities, and the emergence of a middle class.[10] Higher emissions are a result of the nation's transportation sector's heavy reliance on outdated and inefficient cars. Furthermore, the lack of adequate public transportation infrastructure in large cities increases the cost of owning a personal automobile, which aggravates the environmental effect.[11] The adoption of cleaner technology is impeded by Pakistan's economic limitations, which make it more difficult to shift to more sustainable modes of transportation. Furthermore, the transportation industry both contributes to and is a victim of environmental degradation, making the nation susceptible to the effects of climate change.[12]

In Pakistan, the percentage of carbon emissions is growing day by day just because the number of vehicles on the roads increases vastly every year, and 31% of total carbon emissions are attributed to transportation sector.[13] With the current situation and growing energy demand in the country, GHG emissions perhaps cross 281.8 MMT by 2035.[14] In Pakistan, vehicle registration is growing at a rate of 15.1% and more than 23.54×10^6 vehicles were registered in 2018, which is 200% more than in 2011.[15] The number of vehicles made by local manufacturing companies is growing every year, and in 2018, 2 079 774 motor cars were produced locally and imported internationally.[16] The high sulfur content emitted by vehicles in Pakistan is the major contest within the transportation industry of the country's economy. In Pakistan, most fuels hold a sulfur content of 4000–10 010 parts per million, which is a particularly major cause of carbon emissions. The emission standard range of 4000–10 010 parts per million for Euro III and Euro IV vehicles is

TABLE I. Summary of fuel pollutants, GWP of pollutants, and their detrimental effects on human health and life.[9] Data sourced from Ministry of Climate Change, government of Pakistan. INDC. 2018. Available online: http://www.lead.org.pk/pakindc/aboutindc.html (accessed on 7 April 2022). "Adapted from Ministry of Climate Change, government of Pakistan. INDC. 2018. Reproduced under the terms of fair use for educational and research purposes."

Fuel type	Pollutants	Adverse effects on human health	GWP (20-years)
Gasoline	Carbon dioxide (CO_2)	Headaches, dizziness, restlessness, heart dysfunction, decline in cognitive function, calcification of the kidneys, and demineralization of the bones	1
Diesel	Carbon monoxide (CO)	Hypoxia, issues with the heart and blood vessels, poor learning capacity, and fatigue	6
CNG	Nitrogen oxides (NOx)	Lung diseases, damaged lung and liver tissues, and respiratory diseases	43
Biodiesel	Hydrocarbons (HCs)	Cancer and harming of the central nerve and respiratory systems	3–9
Ethanol	Volatile organic compounds (VOCs)	Cancer and irritation of the mucous membranes in the mouth, nose, and throat	14
	Particulate matter (PM2.5, PM10)	Permanent deterioration of respiratory function, heart diseases, and lung infection	

significantly higher.[17] Many developing countries around the globe have already adopted these emission standards to limit their carbon emission. Still, the implementation procedure is sluggish due to unknown causes in Pakistan, which caused excessive carbon emissions. Due to a lack of management and lack of policy implementation, Pakistan is now among the top ten countries in terms of excessive carbon emissions coming from the transportation sector.[18–23]

To reduce reliance on fossil fuels, Pakistan needs to revise its future environment and energy policies. Pakistan is majorly dependent on imported fossil fuels, which will cause climate change and global warming, and it is high time to address this very important socioeconomic issue. To tackle these obstacles, a diverse strategy is needed, including policy changes, funding for eco-friendly transportation options, and international collaboration to promote technological advancements.[24] This will eventually lead Pakistan's transportation sector to become more resilient and environmentally safe. Road transport is the major contributor to environmental emissions due to the usage of oil-based products; each year tons of oil is imported into Pakistan with significant obligation fees, as indicated in Fig. 1. A total of 66% of petroleum products, both imported and produced locally, was consumed by the transport sector of Pakistan. The transport sector of Pakistan contained 51% high-speed diesel, 39% motor spirit oil, 8.9% CNG, 1.1% high octane, and 0.2% light fuel during the fiscal year 2018.[14] All around the globe, specifically in developing countries, investments have been made to support green energy pledged fiscal stimulus plans, amounting to about \$181 to \$196 $\times$ 10^9 [primarily, the United States (\$66 $\times$ 10^9), China (\$45 $\times$ 10^9), and Korea (\$33 $\times$ 10^9) as per International Monetary Fund (IMF) report 2018].

The literature that is now available on global electrification initiatives emphasizes how important it is to switch to electric technology to mitigate climate change and lessen reliance on fossil fuels. The use of electric vehicles (EVs) and the development of charging infrastructure have advanced significantly in developed nations worldwide.[26,27] In contrast, the literature on developing nations emphasizes their particular prospects and difficulties, especially those in Africa, Asia, and Latin America. Significant obstacles include limited infrastructure, high initial prices, and financial limitations, even though some developing countries are making progress toward adopting electric vehicles. Research indicates that to support the shift to electric vehicles in developing countries, certain legislation, financial incentives, and international cooperation are essential.[28–30]

While many developing nations throughout the world are improving internal combustion engines, introducing advanced automobile (hybrid) models, and using better fuels, electric vehicles remain a vital answer for environmentally friendly and sustainable transportation. The adoption of electric vehicles can ensure the minimization of overall carbon impacts on the environment and decrease the major dependence on petroleum fuels. In the past few years, the importance of electric vehicles (EVs) has been rising quickly.[31] In 2018, worldwide, electric vehicles (EVs) fleet grew by five million with an intensification of 64% from the last year.[32] Compared to other world, China has significant transformation obsessed by the mass saturation of electric vehicles.[33] In 2019, China dominated the worldwide electric vehicle fleet, comprising 46% of the total, followed by Europe with 25% and the US with 21%.[34] Figure 2 depicts the trend of worldwide electric vehicle growth, illustrating the shift towards electrification in developing nations. Norway ranks among the top countries in the world for EV market share, with 38% of new cars sold there being EVs.[35] In terms of EV market share, Iceland was the second largest country globally with 18% of the EV market share and Sweden ranked the third with 9% share.[36,37] In 2018, more than 2 $\times$ 10^6 electric vehicles were sold, so the worldwide electric vehicles fleet is escalating quickly, which compared to 2017 is more than double of electric vehicles that were registered in 2018.[38] With 1.11 $\times$ 10^6 automobiles sold, China continues to lead the globe in sales of electric vehicles; there are currently 2.30 $\times$ 10^6 electric vehicles in use.[39] Leading to the rising trends in electric vehicle manufacturing and market share, many countries around the globe have set goals and made policies to fix out internal combustion engine vehicles (ICEVs).[40] By revealing a schedule to stop making internal combustion engine vehicles (ICEVs), many developing nations worldwide have approved the Paris Agreement goals and followed electrification of the transport sector, such as the UK, France, Germany, and the Netherlands, by 2040.[41,42]

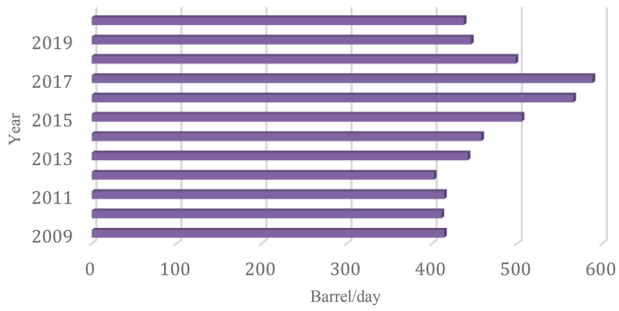

FIG. 1. Oil consumption in Pakistan.[25] Data sourced from HDIP (2021). Pakistan Energy Yearbook 2021. Hydrocarbon Development Institute of Pakistan, government of Pakistan. "Adapted from Pakistan Energy Yearbook 2021, Hydrocarbon Development Institute of Pakistan, government of Pakistan. Reproduced under the terms of fair use for educational and research purposes." Copyright HDIP.

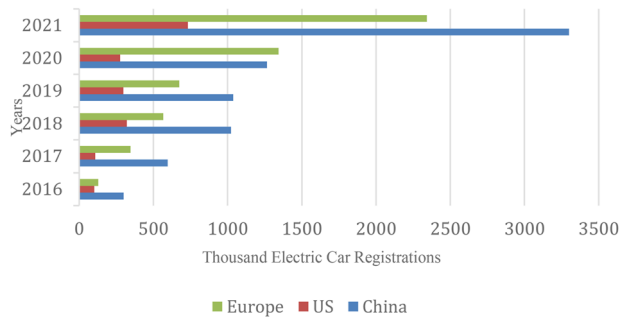

FIG. 2. Electric cars registration in China, United States, and Europe (2016–2021).[43] Data sourced from International Energy Agency (IEA). Global EV Outlook 2019; IEA: Paris, France. 2019. "Adapted from Global EV Outlook 2019, International Energy Agency (IEA), Paris, France. Reproduced under the terms of the licensed under a Creative Commons Attribution 4.0 License."

TABLE II. Policy measures to promote the adoption of EVs.[43] Data sourced from International Energy Agency (IEA). Global EV Outlook 2019; IEA: Paris, France. 2019. Adapted from Global EV Outlook 2019, International Energy Agency (IEA), Paris, France. Reproduced under the terms of the Creative Commons Attribution (CC BY) license."

Policy actions	Average	Effective	Efficiency	Possibility
Plugs lobby	4.26	4.15	4.48	4.16
Infrastructure and support built up	4.16	4.32	4.16	3.99
Management in political features	4.02	4.35	4.16	4.00
EVs initiatives	4.01	4.01	3.74	4.24
Deliver data to people	4.02	3.82	3.82	4.01
Newly developed EV requirements	3.73	4.00	3.83	3.40
Enable roaming between regions	3.64	3.85	3.72	3.32
EVs reserve on-street parking spaces	3.60	4.00	3.66	3.16
EVs toll tax relaxation	3.32	4.01	3.41	2.61
EV's promotion of citizen	3.21	3.78	3.61	2.21

To diminish the dependence on non-renewable energy sources and minimize the injurious carbon emissions formed due to the burning of fossil fuels in IC engines, many developing countries worldwide have planned policies to make the transport sector safe and sustainable. To encourage ECs in developing countries, Table II signifies the ephemeral evaluation of various incentives provided by governments. For green transportation systems, electrification of agility is a capable choice if energy generation is decarbonized by substituting non-renewable energy sources with renewables. To reduce carbon emissions, many developing countries around the globe have acknowledged transport electrification as a possible and feasible solution.[44,45] By 2030, the Sustainable Development Goals of the United Nations aim to provide a safe, reasonable, available, and sustainable transportation system, in particular through increasing the sustainability and resilience of passenger mobility. To meet SDG requirements, technological goals, and environmental safety, many European countries have been endorsing extensive implementation of ECs. Significantly, the use of Electric Vehicles (EVs) with the adaptation of SDGs in the current transport sector can assist in minimizing carbon emissions related to transportation.[46,47]

Due to the advancement of lithium batteries and charging station development, the ownership costs of electric vehicles are falling. Due to the surge of carbon emissions, penetrating competition, and recent research, electric vehicle costs are dropping day by day.[48] Since 2010, Europe has been the most dynamic area globally due to the suggestion of EC adoption. In 2019, Chinese administration made China the prime EC marketplace by giving incentives to manufacturing companies. A future way forward for freight transport is also being established by China, with inclusive estimation made on electrification as well as public transportation. In China, the standard of public transport electrification increased to 459 100 units and electric bikes touched 301×10^6 in 2018.[49] Table III shows the major automaker announcements on electrification to promote Electric Vehicles (EVs).

Pakistan, the seventh most climate-vulnerable country, needs to think about sustainable energy options.[31,51] Road transportation accounts for 18% of Pakistan's total CO_2 emissions and is dependent

TABLE III. Important electric vehicle announcement (2021–2022).[50] Data sourced from Dechamps, The IEA World Energy Outlook 2022–A brief analysis and implications. Eur. Energy Clim. J., 2023. **11**(3), 100–103. Adapted from Dechamps, Eur. Energy Clim. J., **11**(3), 100–103, 2023. Reproduced under the terms of the Creative Commons Attribution (CC BY) license."

Carmaker	Date of announcement	Objectives
Toyota	2021	By 2030, 3.50×10^6 car sales annually and the rollout of 30 BEV models
Volkswagen	2021	To exceed 70 and 50% of European, Chinese, and US sales of EVs by 2030 and 100% to be ZEVs
Ford	2022	By 2030, Europe will sell one-third of electric automobiles
BMW	2021	50% of new cars sold in 2030 will be all-electric
Volvo	2021	To establish an all-electric automotive firm by 2030
Geely	2021	20% of new automobile sales will be electrified by 2025
Mercedes	2021	By 2030, all newly introduced vehicles will be entirely electric
General Motors	2022	By 2025, North America will be able to produce 1×10^6 BEVs and 30 EV variants

on non-renewable energy sources.[52] Air pollution is the primary cause of 310 000 deaths in the nation each year, highlighting the severe environmental conditions that citizens must endure.[53] The government's focus on electric vehicles (EVs) as an environmentally beneficial alternative was prompted by growing air pollution concerns and their link to road transportation.[31] According to recent media reports, the Pakistani government wants to switch 90% of its fleet of vehicles to electric power by 2040.[54–56]

There is a sizable market for imported hybrid cars in Pakistan, including Honda Fit, Toyota Prius, and Honda Vezel.[57] Although there are a few electric cars on the road, such as Plug-in Hybrid Toyota Prius, Audio e-Tron, BMW, Nissan Leaf, and Tesla Model S, precise statistics regarding the number of electric cars in Pakistan are not yet accessible.[58] The data indicate that Pakistan is not just a developing market for automakers but also that policymakers should give careful consideration to developing frameworks and regulations that support the decrease in emissions and the use of fossil fuels.

There are several significant gaps in the literature that need to be filled to fully understand electrification in Pakistan. There is limited knowledge regarding the socioeconomic and cultural aspects that impact the uptake of electric vehicles (EVs) and the transportation sector's general electrification in Pakistan. Examining these factors is essential to customizing methods and regulations that appeal to the community and make the shift to sustainable transportation easier. Moreover, further investigation is needed into the economic and environmental effects of electrification in Pakistan. In a developing nation, such as Pakistan, an analysis of the long-term sustainability and economic viability of electrification initiatives is also necessary.

The air quality of major industrial cities of Pakistan is hazardous because of transportation.[59] Therefore, Pakistan policymakers should properly plan and execute energy-saving and sustainable energy policies. To achieve its aim of an emission-free Pakistan, the government of Pakistan has created targets for improving the air quality index for the transportation sector. These goals include rationalizing safe driving, transportation costs, road networks, industrial cities, and the connection of provinces. Pakistan government has made a "National Transportation Policy (NTP)" based on Vision 2025, which includes numerous transport sector expansion ingenuities.[60] The prime aim of this NTP is to deliver harmless transport services. The government must deal with actual implementations of this approach. The Pakistani government has implemented rapid transit systems based on the NTP plan immediately in three major cities.[61] In the transport sector, to save the environment and energy, Pakistan needs emission-free transport, and policymakers should move toward modern technologies, such as EVs to reduce carbon emissions from the transport sector.

The urgent need to address the nexus of transportation, sustainability, and climate change, especially in the local context of Pakistan, motivates the conduct of this research. Public health and welfare are seriously threatened by the growing air pollution problem, which is mostly the result of transportation that is dependent on fossil fuels. The goal of this research is to support the worldwide effort to combat climate change and the aim of sustainable development, which are intrinsically linked to larger socioeconomic and environmental imperatives. Various scenarios of Pakistan for transport division have been established and evaluated in terms of environmental perspectives. This research is both timely and novel in light of the severe global climate problem and the urgent need for sustainable transportation solutions. This research directly addresses current policy issues and the critical need for practical strategies to mitigate climate change in the context of Pakistan's increasing urbanization and expanding emissions from the transportation sector.

II. METHODOLOGY

The Long-Range Energy Alternatives Planning (LEAP) system is utilized in this study's scenario-based modeling technique to evaluate the possible effects of electric vehicle (EV) adoption on greenhouse gas (GHG) emissions and reduction probability in Pakistan's transportation sector. LEAP was selected because of its extensive use in research evaluating energy and environmental transitions, as well as its ability to accurately capture the complexities of energy systems. With the help of the LEAP model, it is possible to analyze various scenarios dynamically and simulate different levels of EV adoption, changes in energy sources, and governmental interventions over time. An extensively used and adaptable software tool for energy policy analysis and climate change mitigation evaluation is the Long-Range Energy Alternatives Planning (LEAP) model. Utilizing a variety of data sources, the simulation-based model LEAP projects future possibilities related to energy use, emissions, and policy effects.[62]

The World Bank and the UNEP provided financing for the Boston-based Stockholm Environment Institute to create the LEAP model, a long-range examination model used for energy modeling and planning, and several developing nations use LEAP to compile national climate change reports.[63] The LEAP energy model is used in ~195 countries for assessing GHG emissions, environmental impacts, energy demand, and energy generation. Globally, the LEAP model is a standard tool for energy forecasting, planning, and development that is used for future energy demand prediction.[64,65] The benefits of using the LEAP energy modeling software involve easily manageable time frames, less initial data requirements, and user-friendliness. LEAP predicts the energy consumption, demand, and environmental consequences of energy zones to compare energy demand and consumption in detail, which estimates the advantages of every scenario.[66] To examine the removal and consumption of energy resources across various economic sectors, LEAP offers a user-friendly, scenario-based modeling approach. The LEAP model is suitable for Pakistan's transportation modeling framework due to low initial data requirements and built-in technology.

Several scenarios relating to Pakistan's road transportation electrification were simulated and projected using the LEAP model. The methodology framework includes the key parameters that were incorporated into the LEAP model, including the composition of the vehicle fleet, the mix of conventional and electric vehicles, infrastructure development, policy interventions, and existing energy consumption patterns. The LEAP model provided insights into the economic and environmental consequences of different electrification scenarios by allowing the investigation of possible future trajectories through the manipulation of these parameters.

The first stage is gathering and entering data into the LEAP model, including the amount of energy that is currently consumed in the transportation sector, the distribution of both conventional and electric vehicles, and the policies that are now in place. A wide range of variables, including the rate at which electric vehicles are adopted, prospective technological advancements, the development of infrastructure, and policy implementation, are taken into account while creating scenarios. The goal of these scenarios is to capture a variety of positive outcomes for Pakistan's electrification of road transportation. Over the 30-year projection period, a deep understanding of the possible outcomes is made possible by the dynamic simulation of interactions between the defined scenarios by the LEAP model. To provide insights into the environmental effects of various electrification options, the LEAP model computes the greenhouse gas emissions related to each scenario.

Carbon emission reduction policies and measures were quantified as LEAP input measures using data from Pakistan's road transportation. This research is based on the transportation sector of Pakistan's fuel consumption. Five different data sources were used for the base year (HDIP, PAMA, IEA, yearly Energy Book, and OGRA). To obtain a clearer picture of fuel consumption, data were then disaggregated and discrete scenarios were created. The LEAP tree model is shown in Fig. 3. Four different mitigation scenarios were developed and analyzed, including the BAU scenario. Therefore, the energy demand for each sector of the transport industry using the LEAP model is considered based on different constraint value sets under various scenarios to measure the emission outcomes by multiplying different pollutant emission factors. Data on carbon emissions from all sectors of Pakistan were obtained from the International Energy Agency, the Federal Institutes of Pakistan, and the World Bank. Data on the quantity of registered automobiles for Pakistan were attained from the Finance Ministry GOP and Economic Survey 2018, which is a useful parameter to know about transport sector emission analysis and future recommendations. To make a baseline scenario, these data are required for LEAP tree progress and future energy/fuel demand forecasting. The accuracy of the mitigation scenarios is directly related to the data used for BAU for emission forecasting quality.

In this study, outcomes were estimated and proved through the available statistics using appropriate emissions standards for different fuel types. Using LEAP, four different scenarios, including BAU, LC, SLC, and National Electric Vehicle Policy (NEVP) 2040 scenarios, were created and examined for the transportation sector of Pakistan. For the year 2019–2050, various measures on energy consumption and emissions were evaluated and all scenarios were also instantaneously compared.

Many developing nations around the globe have developed long-term transportation plans for energy-environment planning using LEAP. A LEAP model based in Nigeria was discussed with various pathways, such as BAU, electric vehicles, GDP-evolution, and public transport for utilization of EVs.[62] In Korea, Sungjun Hong using LEAP analyzed Korea's GHG reduction related to transportation. For reducing GHG emissions by 32% by 2030, Korea has established specific regulations.[67] Ling–Yung worked on policy initiatives to reduce harmful greenhouse gas emissions associated with China's transportation industry. These included integrating and examining many approaches that included electric vehicles (EVs) using the LEAP model.[65] Using LEAP forecasting of transportation in Malaysia, Musharraf Azam analyzed emission estimation.[68] A detailed review of earlier studies related to transportation and energy usage is shown in Table IV.

To gain a better understanding of policy measures, the electric vehicle policies of various states, such as China, the UK, the USA, and Norway, were considered, which caused better implementation of electric vehicles in these regions. This study's outcomes will support the extensive literature survey carried out for the adoption of electric vehicles in Pakistan.

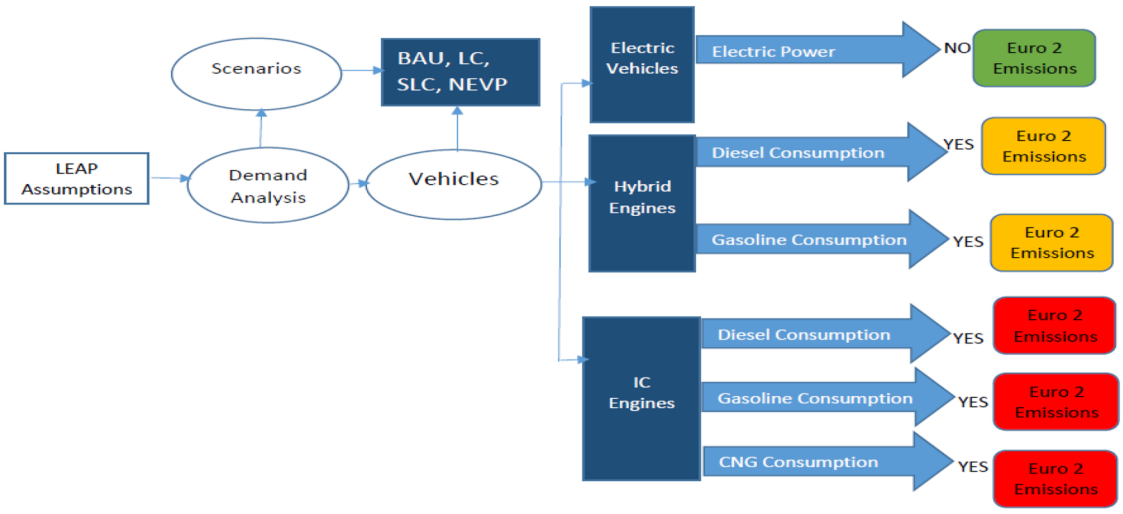

FIG. 3. Pakistan's transport sector LEAP tree diagram.

TABLE IV. Summary of previous research on energy usage and transportation.

Authors	Country	Time frame	Method	Major findings
Verdezoto *et al.* (2019)	Brazil	2010–2016	LEAP model	Due to the purchase of new hydropower plants, hydel energy will be available in 2030, at 63512 GWh, which is 3.26 times more energy than in 2011 and was predicted to save 15×10^6 BOE
Asim *et al.* (2022)	Pakistan	2019–2035	LEAP model	Diverse scenarios are examined, and outcomes are predicted for 17 years. The outcomes of the study reflect that EV implementation can cause a substantial drop in transportation emissions
Raza *et al.* (2019)	USA	1973–2015	HWT	The outcomes illustrate that electric vehicles (EVs) have a significant impact on carbon emissions over the short, long, and medium terms
Gao *et al.* (2012)	China	1985–2015	Decoupling elasticity index model	The findings show that there is a weak decoupling (54.19%) between the development of the industry and overall electric mobility
Zhang *et al.* (2019)	China	Train time table	Bi-level model	Results show that the EC is pointing upward by more than 7.6%
Aized *et al.* (2018)	Pakistan	2011–2030	LEAP model	This work is based on four scenarios, with the transportation sector's EC increasing from 13.30 Mtoe in 2012 to 64.61 Mtoe in 2030
S. Hong *et al.* (2016)	Korea	2011–2050	LEAP model	The South Korean government declared its intention to cut national GHG emissions by 30% by 2020
Wang *et al.* (2022)	China	2020–2025	LEAP model	Under the baseline scenario, emissions from transportation increased at a rate of 20% yearly, while emissions expressively reduced under the LC scenario and the SLC scenario
Naveed Ahmed Unar *et al.* (2022)	Pakistan	2011–2030	Load growth model	In Pakistan, the total energy demand for EVs was 24.61 GWh in 2020 and climbed to 2873.64 GWh in 2030
Musharraf Azam *et al.* (2015)	Malaysia	2012–2040	LEAP model	Key findings demonstrate that the NGV scenario, followed by BIO and HEV, contributes to the biggest reduction in road transport energy usage

III. OVERVIEW OF EMISSIONS FROM PAKISTAN'S TRANSPORTATION SECTOR

A. Fuel consumption of Pakistan's transportation

The annual growth rate of Pakistan is 7.98%, and Pakistan's transportation energy consumption has increased significantly over the past few years. Pakistan's transport sector emitted 40.81 MMT of CO_2 and discharged about 17.91×10^6 tonnes during the fiscal year 2018. Due to a surge in energy usage by domestic, commercial, industrial, and transportation sectors, Pakistan's energy consumption in 2018 was 9.8% higher than the last year. In the fiscal year 2018, gasoline and diesel consumption increased due to newly installed transportation structure and local manufacturing companies with an ACGR of 16.91% and 7.12%, respectively.[69]

In Pakistan, due to insufficient infrastructure, machinery, extraction localities, and oil refineries, fossil fuels produced locally are not enough to fulfill Pakistan's demand for petrol and diesel. So, to fulfill its energy demand, Pakistan spends billions of dollars every year. In recent years, due to the ongoing CPEC project development, rapidly growing residents, and increasing demand for cars, an extension of highways has subsidized to a quick rise in fuel use. Figure 4 illustrates the energy usage from 2003 to 2018 in Pakistan's transport sector.

B. Various types of fuel consumption

Pakistan's transport sector is heavily dependent on oil. The majority of medium-scale vehicles are petrol-motorized, while freight transport is high-speed diesel-powered. Since 2012, CNG

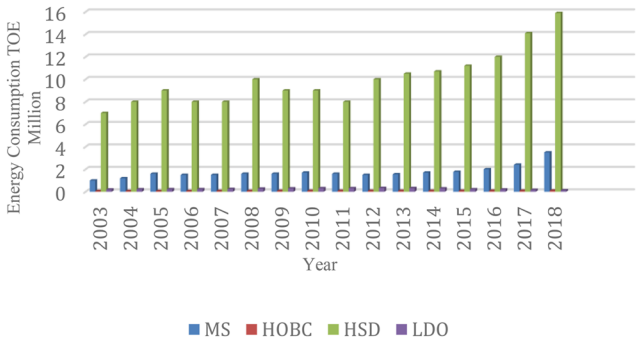

FIG. 4. Fuel usage of Pakistan's transport sector.[70] Data sourced from Pervaz, Pakistan Energy Yearbook 2017. Inf. téc. Islamabad: Ministry of Energy (Petroleum Division), Hydrocarbon Development Institute of Pakistan, 2018. "Adapted from Pakistan Energy Yearbook 2017, authored by Pervaz, published by the Ministry of Energy (Petroleum Division), Hydrocarbon Development Institute of Pakistan, Islamabad, 2018. Reproduced under the Author, licensed under a Creative Commons Attribution 4.0 License."

consumption in Pakistan's transportation has been incessantly dropping due to irregular surges in cost. Due to the induction of advanced diesel engines, specifically in the farming sector and other sectors, LDO consumption has decreased in recent years and now relies on HSD. Due to the accumulation of advanced and environmentally safe engines in vehicles, high-octane blending component (HOBC) demand increased, for example in Euro 3&4 engines. The challenges posed by RON 87 gasoline, which can cause severe knocking issues in engines, have been addressed by European cars as well as some of the newest prototypes of Pakistani factory-made vehicles. The minimum quality fuel allowed for petrol engines in Pakistan is 92 RON, as regulatory bodies have developed guidelines to address this matter. The purpose of this solution is to ensure the smooth operation of gasoline-powered vehicles and reduce knocking issues in internal combustion engines. Figures 5(a)–5(e) illustrate various types of fuel consumption demand in Pakistan.

C. Fuel mix of Pakistan transport sector

Pakistan's road transport plays a major role in the economic structure. Road transport indirectly subsidizes economic development by linking manufacturing markets to consumption markets and by enabling the travel of the public. Pakistan's major income comes from the agricultural sector, also known as an agriculture-based economy, and a majority of its freight is moved by rail and the road transport system. In Pakistan, the most used HSD for transportation has the highest percent share among all other fuels. During the fiscal year 2018, Pakistan used CNG to produce 9 632 741 tons of high-speed diesel, 7 736 017 tons of gasoline, 12 100 tons of light diesel, 129 382 tons of high octane blending component, and 1 558 648 tons of energy equal to oil.[14] As the number of vehicles is uninterruptedly growing at a similar speed, the numbers are predicted to increase every year at an estimated rate of 14.1%. Figure 6 shows Pakistan's fuel mix through a pie chart.

D. Vehicle fleet in Pakistan

In Pakistan, there were about 23.58×10^6 automobiles registered as of 2018, and this number is expanding at a pace of 13% annually.[31] In Pakistan, most cars, motorbikes, and tractors are locally factory-made, while public transport buses and freight vehicles are imported in big numbers with every passing year. With every passing year, due to modernization, the need for vehicles is increasing rapidly in Pakistan; consequently, automotive industry is expanding more rapidly than other manufacturing sectors. Since the past decade, Japanese automakers, such as Honda, Toyota, and Suzuki, as well as Korean automakers, such as Hyundai and Kia, have become significant market shareholders. JDM automobiles have significantly increased in number on the roads in recent years; in addition, European luxury car and SUV producers, such as Audi, BMW, Porsche, and Mercedes Benz, have also experienced growth in Pakistan.[14] Since domestic businesses produce the majority of the two- and three-wheelers in Pakistan, the automotive manufacturing industry has contributed to the country's economy's expansion. Figure 7 illustrates the registered automobiles in the country. The public's reaction to the adoption of electric vehicles has fallen short of expectations because of the recently established NEVP and a lack of information among the general public regarding EV adoption and its effects on the environment.

E. CO_2 emission from fuel consumption

Pakistan generated about 181 MMT of CO_2 through the burning of fossil fuels, according to the IEA 2019 study. Currently, 31% of Pakistan's yearly carbon emissions are attributable to the transportation industry.[72] The overall trend for transportation-related CO_2 emissions in developed nations, such as the US and UK, is 17%–20%.[73] In 2018, Pakistan produced 47.8 MMT of CO_2 through the production of heat and electricity, 2.51 MMT through industrial applications, 49.53 MMT through goods production sectors, 56.61 MMT through the transportation industry, and 25.62 MMT through other industries.[14]

Figure 8 shows the sector-wise emissions due to the burning of fossil fuels in Pakistan. Pakistan has seen a consistent increase in CO_2 emissions over the past ten years. Pakistan has a lot of potential in terms of sustainable energy and reducing carbon emissions. The transition toward green and clean energy will open the door for electric cars in Pakistan, which will reduce emissions in upcoming years. Figure 9 shows the CO_2 emitted from fuel combustion.

IV. RESULTS AND DISCUSSION

A. Business as usual (BAU) scenario

Globally, the transport sector contributes 20%–25% of CO_2 and other GHG emissions. The transportation sector in Pakistan, which is one of the fastest-growing industries, uses 17.69×10^6 TOE of fossil fuel energy and releases 58.88 MMT of CO_2 and other harmful emissions.[14] According to the BAU scenario, in the current socioeconomic situation, GHG emission levels will rise by 2050 if such conditions continue to exist. According to LEAP calculations, under the BAU scenario, energy consumption in Pakistan's transportation sector will increase by 153.8×10^6 and 1904.0×10^6 TOE in 2035 and 2050, respectively. The BAU scenario results also indicate that if there is no specific change in the price of oil globally, Pakistan's expenditures on importing fossil fuels will increase with the same trend as the fuel values. This is because Pakistan's transportation sector depends more on imported fuels. As per existing

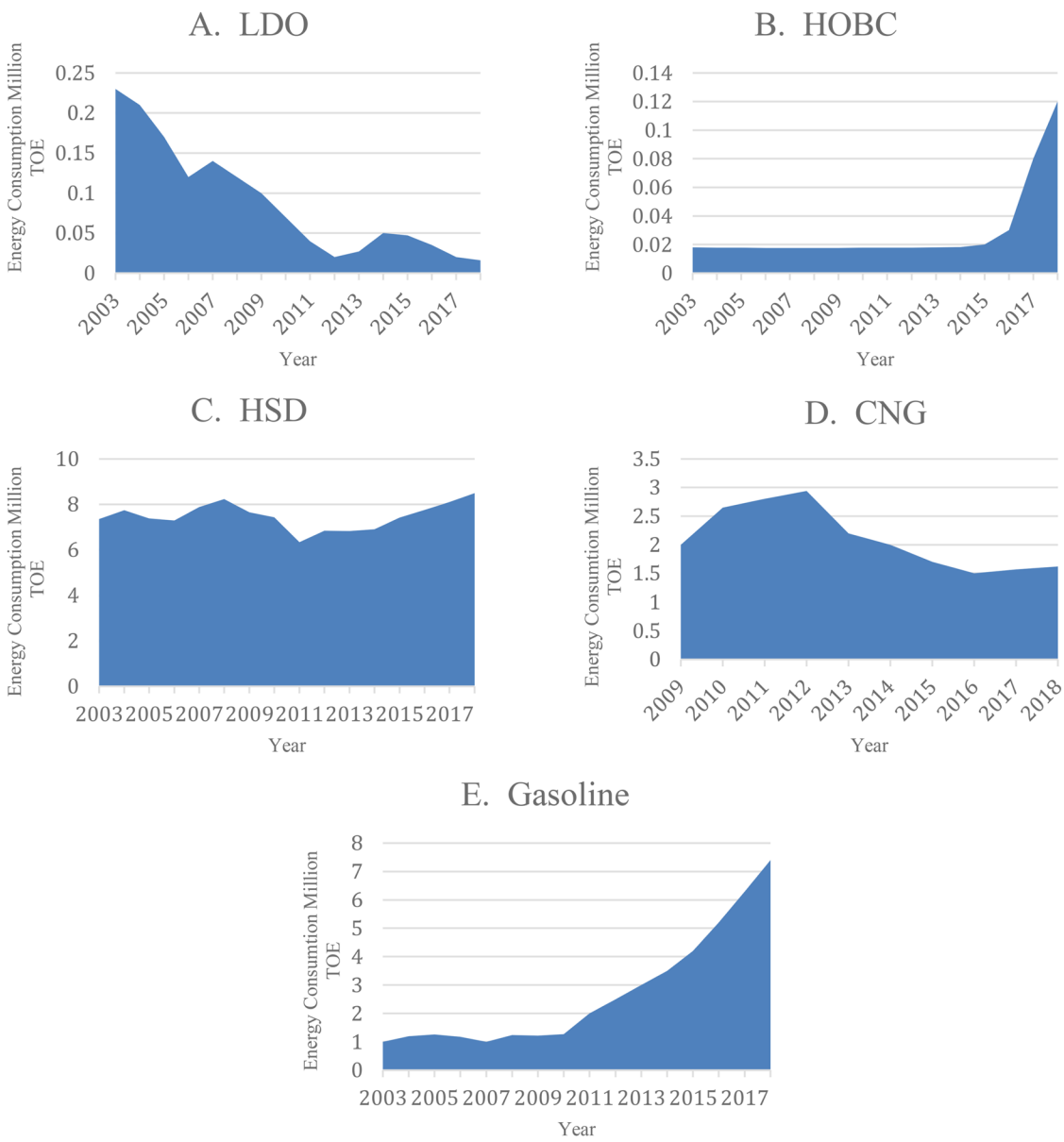

FIG. 5. (a) Light diesel oil, (b) blending component, (c) high-speed diesel, (d) CNG, and (e) motor spirit.[70] Data sourced from Pervaz, Pakistan Energy Yearbook 2017. Inf. téc. Islamabad: Ministry of Energy (Petroleum Division), Hydrocarbon Development Institute of Pakistan, 2018. "Adapted from Pakistan Energy Yearbook 2017, authored by Pervaz, published by the Ministry of Energy (Petroleum Division), Hydrocarbon Development Institute of Pakistan, Islamabad, 2018. Reproduced under the Author, licensed under a Creative Commons Attribution 4.0 License."

circumstances, the transport sector's emissions in Pakistan will total 453.6 MMT by 2035 and 6192.1 MMT by 2050. There is a strong recommendation for rapid decarbonization and restriction of fossil fuel usage as per trends attained from the BAU scenario. Figure 10(a) indicates an elaborative energy demand forecast for Pakistan from 2019 to 2050, and Fig. 11(a) indicates GWP of 100 years: carbon dioxide emissions from different vehicle categories under the baseline scenario until 2050.

B. Low carbon (LC) scenario

After the natural increase in automobiles, a study of the world-wide market for new energy vehicles found that the low carbon (LC) scenario involves an extension toward clean road traffic and a decline in the use of internal combustion engines in public transit. To meet the emission limits outlined in COP 21, 22, 23, and 24, it is projected that 30% of all IC engine cars will be electrified

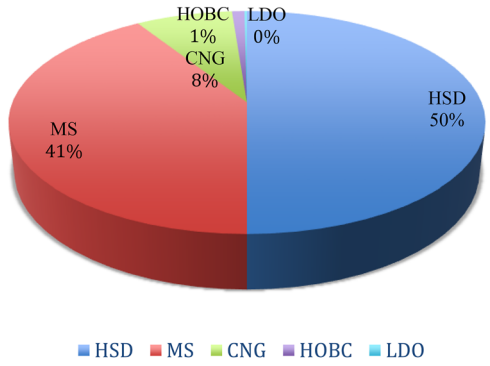

FIG. 6. Pakistan transport sector's fuel mix 2018.[70] Data sourced from Pervaz, Pakistan Energy Yearbook 2017. Inf. téc. Islamabad: Ministry of Energy (Petroleum Division), Hydrocarbon Development Institute of Pakistan, 2018. "Adapted from Pakistan Energy Yearbook 2017, authored by Pervaz, published by the Ministry of Energy (Petroleum Division), Hydrocarbon Development Institute of Pakistan, Islamabad, 2018. Reproduced under the Author, licensed under a Creative Commons Attribution 4.0 License.

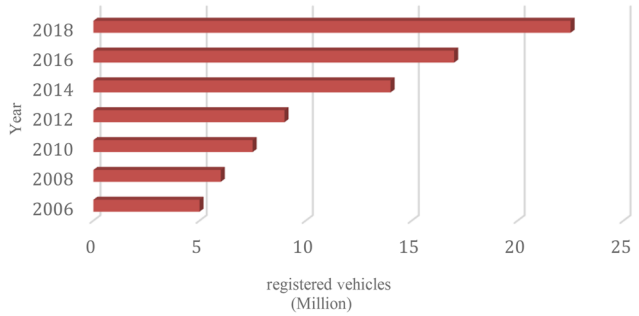

FIG. 7. Vehicle registrations in Pakistan between 2006 and 2018.[71] Data sourced from GOP, 2020. Pakistan Economic Survey 2019–20. Ministry of Finance, Govt. of Pakistan, Pakistan. Adapted from Pakistan Economic Survey 2019–20, published by the Ministry of Finance, Government of Pakistan, in 2020. Reproduced under the, licensed under a Creative Commons Attribution 4.0 License.

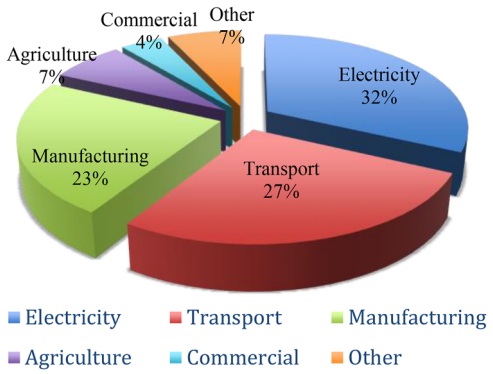

FIG. 8. Pakistan sectorial CO_2 emissions 2018.[71] Data sourced from GOP, 2020. Pakistan Economic Survey 2019–20. Ministry of Finance, Govt. of Pakistan, Pakistan. "Adapted from Pakistan Economic Survey 2019–20, published by the Ministry of Finance, Government of Pakistan, in 2020. Reproduced under the, licensed under a Creative Commons Attribution 4.0 License."

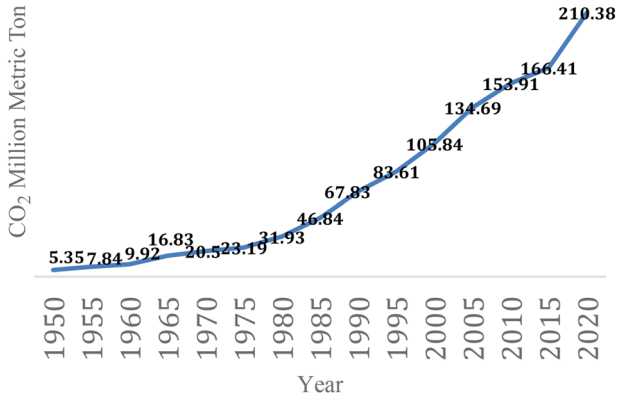

FIG. 9. Pakistan's fuel consumption-related CO_2 emissions.[25] Data sourced from HDIP. (2021). Pakistan Energy Yearbook 2021. Hydrocarbon Development Institute of Pakistan, Government of Pakistan. "Adapted from Pakistan Energy Yearbook 2021, Hydrocarbon Development Institute of Pakistan, Government of Pakistan. Reproduced under the terms of fair use for educational and research purposes."

globally during the next 12 years as per the International Energy Agency (IEA) report. The International Energy Agency V30 drive has predicted that the expansion of electric car (EC) chargers will boost the interest of automobile manufacturer companies in the development of electric cars (ECs) to raise awareness of the importance of using ECs in the future. By creating efficient regulations for charging stations and other incentives under the LC Scenario, transportation policy research is being ramped up to increase EV use in the country. In this scenario (LC) to electrify 30% of the fleet of vehicles, a LEAP model is built for demand analysis by using IEA V30 conditions utilizing 2018 data for projecting energy demand and emission results using the base year circumstances until 2050 for Pakistan's transportation sector. According to the findings, the energy demand in 2035 under the LC scenario is 102.4 × 10^6 TOE, as opposed to 153.8 × 10^6 TOE under the baseline scenario, and in 2050, it is 1371.9 × 10^6 TOE as opposed to 1904.0 × 10^6 TOE under the baseline scenario. In 2035 and 2050, the related CO_2 emissions under the LC scenario are 302.7 and 3050.5 MMT, respectively, as opposed to 453.6 and 6192.1 MMT under the BAU scenario. Figure 10(b) indicates an elaborative demand prediction for Pakistan from 2019 to 2050, and Fig. 11(b) indicates GWP of 100 years: emissions of different vehicle categories under the LC scenario until 2050. The LC scenario emphasizes encouraging the use of substitute fuels and improving fuel efficiency. To achieve the LC scenario requirements, major hurdles are the cost of alternative fuels, the deficiency of fueling infrastructure, the lack of funding, and the need for noteworthy reserves to expand the fuel efficiency of existing vehicles.

C. Strengthen low carbon (SLC) scenario

This scenario emphasizes long-range planning and development for the accomplishment of environment-friendly and clean transportation in Pakistan and competitive milestones achieved by

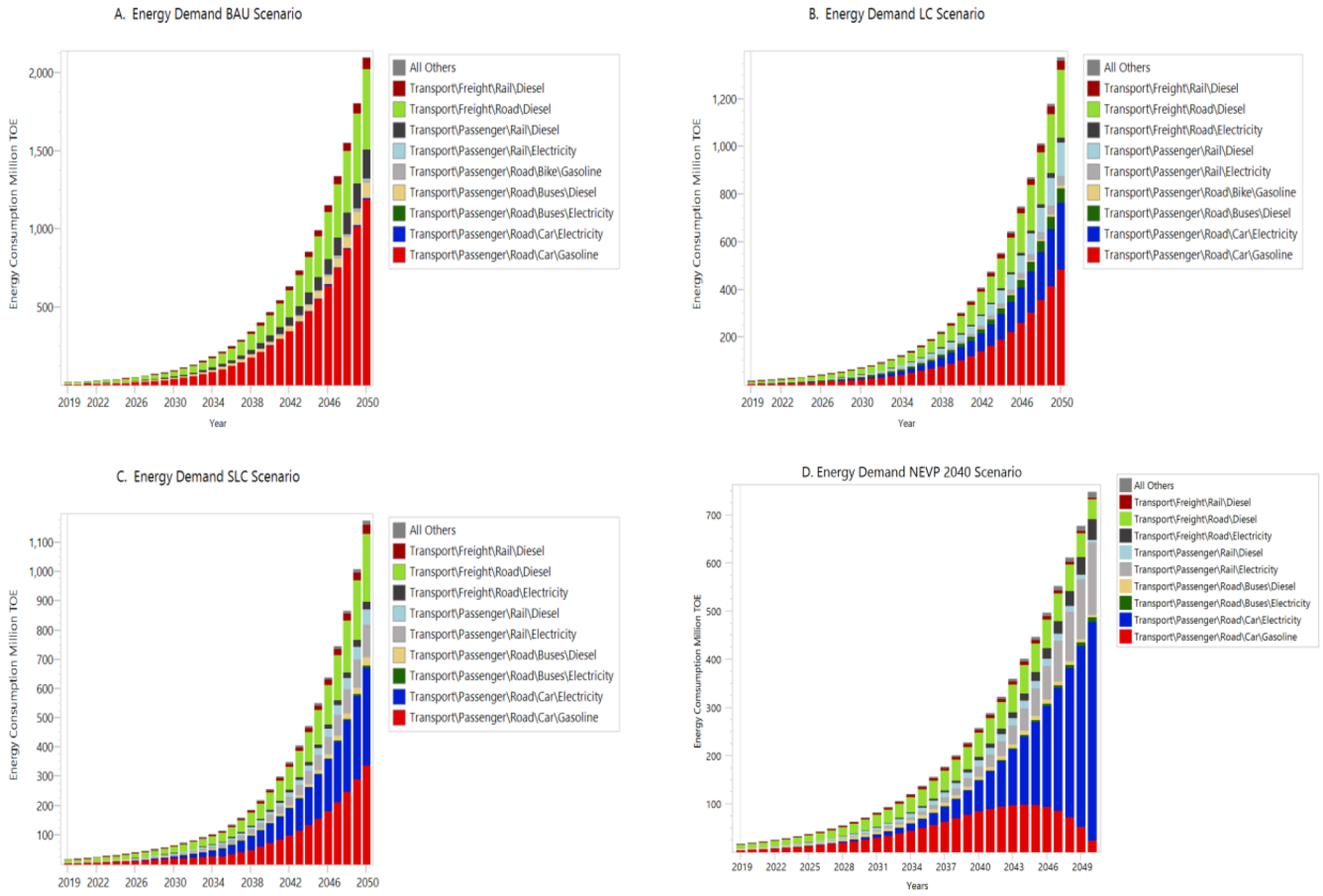

FIG. 10. (a) Energy demand related to BAU scenario, (b) energy demand related to LC scenario, (c) energy demand related to SLC scenario, and (d) energy demand related to NEVP 2040 scenario.

a 50% transition from IC engines to EVs by 2050. Many developing nations, including those in Europe, have developed effective plans to lessen the consequences of the severe pollutants and emissions due to the burning of fossil fuels. One such plan is to encourage the use of electric cars (ECs) in the transportation sector to cut emissions. In this scenario, in addition to the LC scenario, a new feasibility policy of energy for the transport sector of Pakistan is further proposed based on the development and placement of electric vehicles. The SLC scenario is an improved version of the Low Carbon (LC) scenario that emphasizes clean road traffic, banning internal combustion engines in public transit, introducing electric and hybrid vehicles, and implementing new energy exchange regulations for the transportation industry. By keeping the global temperature increase to within 2 °C, the SLC scenario achieves all the requirements to implement the policies specified by the European Union and Paris Agreement. By 2050, global GHG emissions should be 80% lower than they were in 1990, according to the SLC scenario. Applying these requirements to Pakistan's transportation industry under the SLC scenario suggests the potential for rapid decarbonization.

In 2035, the SLC scenario predicts an energy demand of 82.3×10^6 TOE as compared to 153.8×10^6 tons of oil equivalent under the baseline scenario. In the same way, the demand for energy in 2050 will be 1102.9×10^6 tons of oil equivalent as compared to 1904.0×10^6 tons of oil equivalent in the BAU scenario. Results show that the transport sector contributed 202.7 MMT of CO2 emissions in 2035 under LSE conditions, related to 452.6 MMT under the baseline scenario, and 1872.7 MMT in 2050, compared to 6192.1 MMT in the BAU scenario. Under the SLC scenario in terms of fossil fuels usage, a significant reduction in energy demand and emissions under such recommendations is achievable. Figure 10(c) indicates an elaborative energy demand forecast for Pakistan from 2019 to 2050, and Fig. 11(c) indicates GWP of 100 years: carbon emissions of different vehicle categories under the SLC scenario until 2050.

The main objective of the SLC scenario is to decrease emissions coming from transportation by encouraging use of electric vehicles and sustainable energy sources. To achieve the SLC scenario, key hurdles are the high cost of electric vehicles, charging station infrastructure, and the related significant investments and the

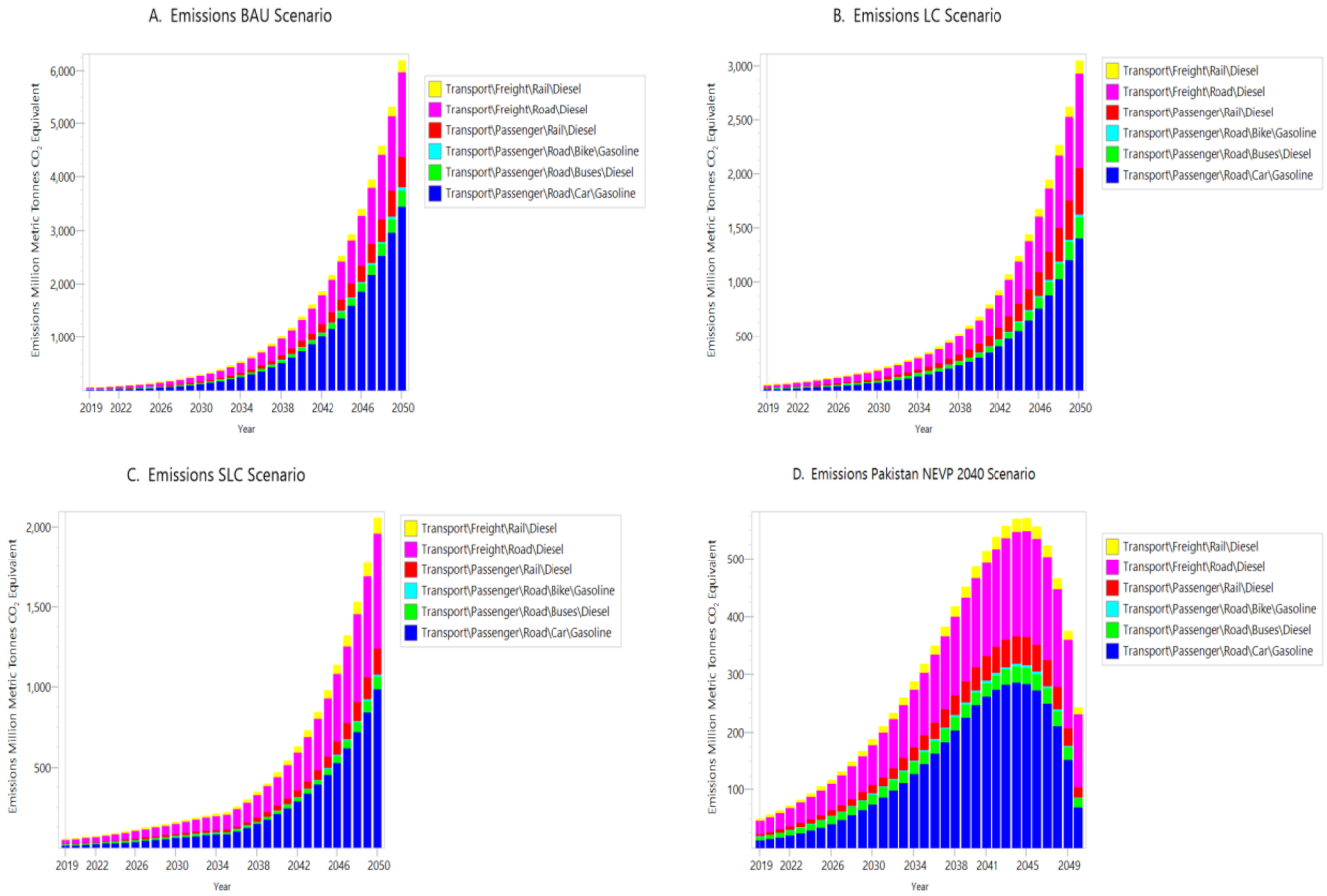

FIG. 11. (a) Carbon emissions related to BAU scenario, (b) carbon emissions related to LC scenario, (c) carbon emissions related to SLC scenario, and (d) carbon emissions related to NEVP scenario.

requirement for a steady and reliable power supply from renewable energy sources.

D. Pakistan national electric vehicle policy (NEVP) 2040 scenario

To cut emissions from the transportation sector, Pakistan's government eventually created its first Electric Vehicle (EV) regulation in late 2019. As per Pakistan's NEVP 2030 goals, the government of Pakistan intends to have the following percentages of electric vehicles on the roadways by 2030: 30% automobiles, 51% 2–3 wheelers, 49% buses, and 30% trucks. Under the NEVP 2040 scenario, 90% of IC engine vehicles are expected to be replaced by EVs by 2040. According to NEVP 2040 conditions and policy changes, there can be considerable short- and long-term reductions in energy use and related emissions over the long run in Pakistan's transportation industry. Under NEVP 2040, outcomes have revealed a minimum energy demand and related emissions that are 670×10^6 TOE and 243.4 MMT, which are lower than all other scenarios in 2050. Figure 10(d) indicates an elaborative energy demand forecast for Pakistan from 2019 to 2050, and Fig. 11(d) indicates GWP of 100 years: emissions of different vehicle categories under the NEVP scenario until 2050.

The NEVP 2040 scenario focuses on encouraging the implementation of EVs and intends to attain a 30% share of EVs in the country by 2040. To achieve the NEVP 2040 scenario, key hurdles are the lack of supportive policies and timely policy implementation, the cost of EVs, and insufficient charging station infrastructure. In addition, to guarantee a reliable and constant power supply for electric vehicles, there is a requirement for significant investments in sustainable energy resources.

E. Comparison of BAU, LC, SLC, and NEVP 2040 scenarios

It is perceived that the BAU scenario has the maximum fuel/energy demand and related CO2 emissions values in the long term (1904.0×10^6 TOE energy demand and 6192.8 MMT emissions in 2050). The actions of many governments under the BAU scenario included several economic growth initiatives, such as energy infrastructure projects, which will directly affect the transportation fleet, energy usage, and associated emissions of the transportation

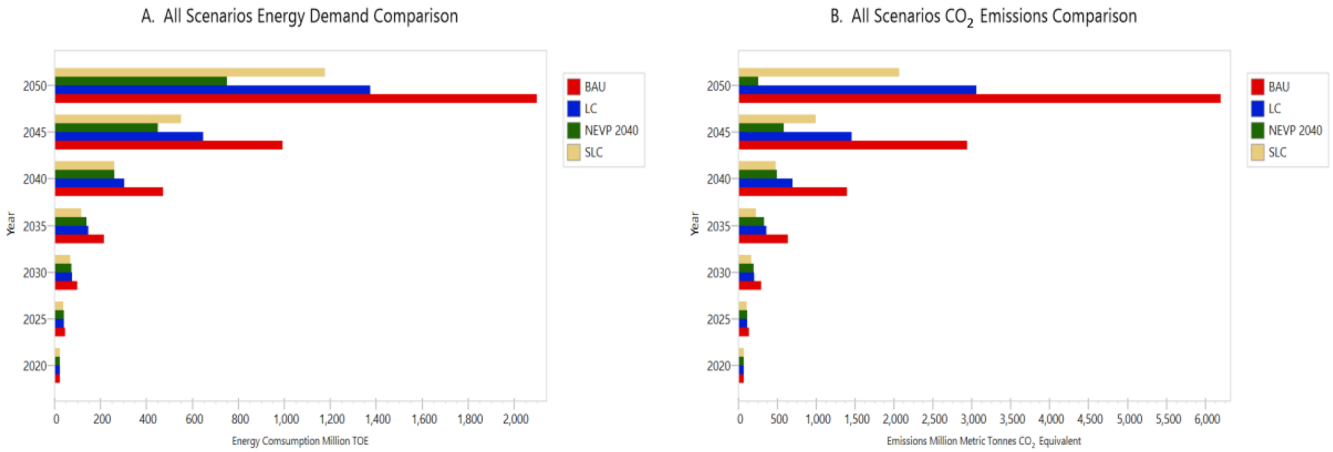

FIG. 12. (a) Energy demand comparison of all scenarios and (b) CO_2 emission comparison of all scenarios.

sector. The LC scenario is the second scenario in descending order, which anticipates an energy demand of 152.7 × 10^6 TOE and CO_2 emissions of 453.6 MMT in 2035. The baseline scenario, which comes in the first place in the ranking, is predicted to have an energy requirement of 1371.9 × 10^6 TOE and CO_2 emissions of 3050.5 MMT in 2050. Energy usage can be significantly reduced both temporarily and permanently, along with the emissions related to the transportation sector of Pakistan as per NEVP 2040 conditions and policies. Under the NEVP 2040 scenario, results have shown the minimum energy demand and emissions, which are 670 × 10^6 TOE and 243.4 MMT, lower than all other scenarios in 2050. Figure 12(a) indicates an elaborative evaluation of the energy consumption in various scenarios, and Fig. 12(b) indicates an elaborative comparison of CO_2 emissions in all scenarios.

V. LIMITATIONS AND FUTURE RECOMMENDATIONS

The reliability and quality of the input data are key factors in the Long-Range Energy Alternatives Planning (LEAP) scenario-based modeling approach's accuracy. The precision of our estimates could be affected by variations in data sources and possible mistakes in historical data. The LEAP model's forecasts are inevitably reliant on the assumptions made regarding potential future advancements, including improvements in technology and policy changes. In addition, the study mainly addresses environmental issues; more comprehensive socioeconomic factors related to electric vehicles may be investigated in future studies.

Future studies should aim to improve forecast accuracy by improving data quality and investigating different modeling approaches to overcome these limitations. Future research might include a more thorough analysis that takes into account social acceptance, economic implications, and potential obstacles to EV adoption in the Pakistan setting to increase the study's scope and relevance. Engaging in partnerships with various stakeholders, such as government agencies, industry leaders, and advocacy organizations, can provide significant benefits and improve the relevance of future studies to practical policies and practices.

VI. CONCLUSION

Among all sectors in Pakistan, the transportation sector is the one with the largest energy use. As a result, it ranks highly among the GHG pollutant emitters in the country, having a significant impact on both air pollution and climate change. This study's main goal was to shed light on the transportation sector's GHG emissions in Pakistan and how those emissions might alter in response to four different mitigation options. In this study, using the LEAP model, by gathering data of Pakistan's transportation sector, emission levels in several scenarios were calculated in detail from 2019 to 2050. Time series trends are developed and authorized in Pakistan based on accurate statistics given by the government of Pakistan and various international organizations (UN, UNFCCC, and IEA). These statistics cover particular fuel consumption (gasoline, HOBC, HSD, LDO, and CNG), emissions from the burning of fossil fuels, and the number of locally made and registered vehicles. To endorse zero-emissions agility by looking at Pakistan's available energy resources, renewable energy potential, worldwide transport flexibility, and regulatory procedures, a comprehensive literature review was presented based on sustainable and clean transport scenarios and policies. Four different scenarios (BAU, LC, SLC, and Pakistan NEVP 2040) were developed and evaluated in the LEAP software for forecasting energy and associated emissions up to 2050. Outcomes specify that from 2019 to 2050, the total road transport sector energy consumption will increase by about 3.7 times due to the persistence of present patterns and the absence of new policy initiatives. We can see under the BAU scenario that Pakistan's road transportation sector would continue to produce significantly more CO_2 emissions to fulfill future, stringent traffic demands. The findings indicate that Pakistan's energy demand and associated emissions are highest under the BAU scenario, while they are lowest under the NEVP 2040 scenario for the country's transportation sector.

This study offers an evidence-based method for policy formulation, which makes a substantial contribution to the existing research. Policymakers may predict the possible effects of different levels of EV adoption and make well-informed decisions by using

the dynamic platform that the LEAP scenario-based modeling offers for simulating various future scenarios.

The potential for producing electricity in Pakistan from renewable resources is enormous. Many renewable energy-based electricity generation projects in Pakistan are nearing completion, and many more are now under construction, which will improve the adaptation of EVs. Based on renewable energy projects, Pakistan will become self-sufficient in the production of electricity in the upcoming years. In addition, there will be sufficient electricity to run effectively the country's policy regarding electric vehicles. To capitalize on the renewable energy potential and implementation of EV policies, major challenges for policymakers in the country are the lack of infrastructure, limited access to investment, political instability, lack of technological advancements, and optional changes. This study suggests some policy implications for Pakistan's transport sector based on these key findings to reduce CO_2 emissions. In the upcoming years, an eco-friendly transportation system based on electric vehicles (EVs) should be implemented, and logistics operations in Pakistan should promote environmental consciousness among the public and commercial sectors. More commanding and effective policies are required to accomplish the global SDG targets for lowering GHG emissions in the transportation industry. The analysis and results show that adopting EVs will significantly improve Pakistan's transportation sector's ability to sustain energy use while lowering emissions. To devise the emission reduction targets across many economic sectors, this research would be helpful for the government officials for policy making. This research can be utilized as a guide for planning and policy-making to reach mitigation potentials and promote the spread of more EVs.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Rohan Kumar: Conceptualization (equal); Data curation (equal); Writing – original draft (equal). **Ammara Kanwal**: Data curation (equal); Writing – review & editing (equal). **Muhammad Asim**: Methodology (equal); Project administration (equal); Writing – review & editing (equal). **Mohsin Pervez**: Validation (equal); Writing – review & editing (equal). **M. A. Mujtaba**: Software (equal); Writing – review & editing (equal). **Yasser Fouad**: Funding acquisition (equal); Writing – review & editing (equal). **M. A. Kalam**: Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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