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Evaluation of transition to 100% electric vehicles (EVs) by 2052 in the United States

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Abstract

With the rising need to transition from fossil fuel consumption to renewables, the transportation industry is foreseeing large-scale adoption of electric vehicles (EVs). According to various studies, the petroleum resources will last until or around 2052. Utilizing the US Federal Highway Administration (FHWA) published data on the number of registered vehicles by each state, the profile of vehicles by 2052 was forecasted using a time series. The vehicle profile comprised vehicles by each type classified as automobiles, buses, trucks, and motorcycles. This future profile became the basis of the quantification of total EVs by the end of 2052. Based on the available fuel economy data published by the US Department of Energy, the average energy consumption per mile (kWh/mile) of each vehicle type was factored into the energy demand calculation for 100% electrification by 2052. A roof-top solar photovoltaic system is easy to install on unoccupied roof space for US house owners. Obtaining the capacity of such a roof-top solar PV system acts as a good decision-making criterion for both house owners and developers. However, for city-dwellers living in multi-family residential buildings, the potential of utilization of roof-top solar PV becomes a subject of future work when effective sharing of resources for local power generation by renewables and development of community-shared EV charging infrastructure is concerned. How well EVs performed against internal combustion engine (ICE) vehicles in terms of fuel efficiency and reduced carbon emissions is a driving factor for this transition. For energy demand calculations, a base model was framed, and results were obtained by utilizing mathematical and statistical tools. After accounting for the effects of improved fuel efficiency or reduced energy consumption by EVs over time, the model was modified to obtain revised energy demand and, thus, effective energy generation required. Accordingly, the capacity of EV charging infrastructure required by each state determined the need for preparation by utility companies and local jurisdictions. With limitations on battery size and thus increased frequency for drivers to return for charging, additional fast chargers (level 3) at existing gasoline stations become an option that requires further assessment.

Keywords Electric vehicles, Energy consumption, Energy management system

Introduction

The electric vehicle (EV) charging technology has been evolving, and thus, there is scope for improvement to the existing battery electric vehicles and their charging infrastructure. Car manufacturers have found alternatives to fossil-fueled cars by deploying cars with battery or fuel cells (Sorlei et al., 2021). The EV industry has grown from the first available electric cars during the 1830–1890s to advanced autonomous featured ones in recent years. The purpose of this research is to establish known technologies in electric vehicles and charging infrastructure, and identify the areas of improvement. Furthermore, the paper delves into preparing a transition for all existing automobiles, buses, trucks, and motorcycles to be electric, thereby obtaining overall energy demand from EVs and the need to add renewable energy resources. Although efficiency of the batteries and charging infrastructure must be considered in

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minimizing the associated energy loss, the deployment of utility-scale solar farms with battery energy storage systems appears as a promising solution. EV components-wise efficiency ranges from 81–99% depending on component being studied such inverter offers 90–96%, battery input offers 90–99%, battery output offers 93–98%, rectifier offers 96–98%, electric motor offers 81–95%, electric generator offers 82–95%, and transmission offers 89–98% (Albatayneh et al., 2020). Electric motors are proven to deliver high torque when running at low speed and torque reduces as the speed increases. Electric motors generate counter electromotive force as they pick up higher speed, which reduces the torque; thus, the torque vs speed curve falls after a certain speed is exceeded. With evolving technology in improving rotations per minute (rpm) to 20,000–30,000 for the brushless direct current motors in EVs, better torque vs speed characteristics can be obtained (Stadtfeld, 2020). Similarly, improved designs for permanent magnet synchronous (PMSM) with better speed vs torque characteristics offer excellent applications in EVs (Sankhwar, 2024a).

Major powertrain components of an EV comprise battery, motor, gearbox, and power electronics wherein battery and motor are major elements that distinguish them from conventional ICE vehicles (König et al., 2021). Energy density is a key criterion for Li-ion battery's success in EV traction applications (König et al., 2021; Tian et al., 2021). Authors have researched alternatives of battery chemistry to the current widespread use of lithium-ion (Li-ion) batteries to power EVs (Tian et al., 2021). Li-ion batteries are economically feasible and provide safe operation. Rising depletion of natural resources raises the need for alternate battery chemistry. Additionally, lithium extraction process is attributed to large water consumption, and air contamination. To compare EV performance against conventional ICE vehicles in terms of green house gas (GHG) emissions, end-of-life life cycle analysis (LCA) reports published by the U.S. Department of Energy (Tian et al., 2021) are indicators for a positive sign for large-scale use. Additionally, EV acceptance is driven by policy incentives, positive environmental impact, and affinity to technology (Wicki et al., 2023).

Li-ion batteries are consistently improving in technology, and prices continue to decrease over time (Ziegler & Trancik, 2021). Since the growth of Li-ion batteries determines the success of EVs (Ralls et al., 2023), declining battery prices and improved technology bolsters EV industry growth. Li-ion battery chemistry includes lithium–metal oxide as an electrolyte with a porous medium between the cathode and anode (Chapman, 2019). The battery equation with reduction and oxidation reactions at cathode and anode, respectively, is given by (1) (Chapman, 2019). When referring left to right battery discharges and charges vice versa.

$$\mathrm{LiC_6} + \mathrm{CoO_2} \rightleftarrows \mathrm{C_6} + \mathrm{LiCoO_6} \tag{1}$$

The types of EVs available in the market include battery, plug-in hybrid, and hybrid. Battery EVs are powered by an electric battery, and in this paper, EVs would be deemed as battery options unless otherwise noted. Plug-in hybrid EVs can utilize both gasoline and battery charging. Hybrid EVs are powered by gasoline, but assisted by electric motors which in turn are powered by a battery. Types of charging infrastructure available for EVs include Level 1, Level 2, and Level 3 (DC fast charging) (Sankhwar, 2024b). In terms of type of battery charging used, battery EVs support all Levels 1, 2, and 3, whereas plug-in hybrids support Level 2 only, and hybrid supports none. Another type of charging available is wireless charging, which allows vehicles to charge while they are being driven or parked. Although wireless charging technology is in the early stages of both research and development its implementation requires studying impacts. Some pilot deployments by state agencies in the US, such as charging while driving/parking, are promising applications. Apart from health and safety and construction challenges, charging at a fast rate of 15 min is a major challenge (Mahesh et al., 2021). Level 1 chargers allow people to charge with a maximum available option of 2.4 kW during an elongated period spent during the work shift or overnight. Level 2 chargers allow people to charge with a maximum available option of 12 kW during a short time of 3–4 h in a day. However, Level 3 chargers allow people to charge with a maximum available option of 240 kW during a shorter period ranging from 30–40 min. With a limited network of chargers in the US (Mastoi et al., 2022), about 60% population have access to the nearest public charging stations (Bestvater & Shah, 2024). Achieving 100% access to every individual requires planning and implementation prior to the depletion of crude oil resources.

Given oil reserves are diminishing every year, they might be adequate until or about 2052 (Kuo, 2019; U.S. Energy Information Administration, 2023, 2024a). The current number of internal combustion engine (ICE) vehicles require transitioning to a battery electric vehicle. There are challenges to manufacturing and supply chains to meet the increasing demand, but leading car manufacturers are aiming for large-scale production to cope with the global EV market reaching $56.7 trillion by 2050 (ETP Trends, 2023). For instance, Tesla Motors has seen an increase in production during 2023 by 35% accounting for 1.85 M units of production (Business Wire, 2024). Additionally, Government programs such as the National Electric Vehicle Infrastructure (NEVI) Formula Program have offered funds to states and municipalities to increase EV charging stations. Federal Income Tax Rebates and grants further encourage customers to buy EVs. Continued support for customers positively increases the number of electric vehicles and their use, thus increasing the need to study the required energy for electric chargers. Studies have indicated an incremental rise of a $1000 rebate offers a 2.6% rise in average EV sales (Jenn et al., 2018). Typically, in the US market, Internal Revenue Code Section 30D allows a credit of $2500 to $7500 for qualifying EVs (Sherlock, 2019). However, since February 27, 2024, the federal government has offered three tax credits starting from credit for new, and pre-owned to qualified commercial clean vehicles (Marples & Buffie, 2024). Additionally, the Inflation Reduction Act (IRA) bolsters the electrification and improving EV share in light-duty vehicles (Slowik et al., 2023).

Being responsible for the environment calls upon studying the carbon emissions from electric vehicles. Average emission from electric vehicles is estimated to be 0.22% for a gasoline-fueled vehicle (Emissions from Electric Vehicles, 2024). Per the US Energy Information Administration, US electricity generation capacity in 2022 is nearly 1160.16 million kilowatts, wherein 28.54% comes from renewables and the rest from coal, natural gas, nuclear, petroleum, and others (U.S. Energy Information Administration, 2024b). To reduce dependence on non-renewable energy resources, there is a need to increase power generation through renewable energy resources. Given energy generation by renewables has increased periodically (Yolcan, 2023), it is advisable for energy generation companies to focus on growing renewable energy power generation. Solar photovoltaic is an untapped resource when analyzing the increase in energy consumption due to large-scale EV usage by 2052. Roof-top, ground mount, and floating PV are known to be safe and reliable sources of power. For both commercial and residential areas with available unoccupied roof space, ground space, or water bodies, untapped solar potential offers reduced emissions and reduces dependence on non-renewable power resources. Energy demand increases due to climate change (Ruijven et al., 2019) and global energy demand has risen at a significantly faster rate of 2.2% in year 2023 but advanced economies have shown temporary decline (IEA, 2024). It is anticipated that advanced economies will see a rising trend by 2026 when industrial production increases together with reduced inflation (IEA, 2024).

To ensure dependency on grid power is reduced, an HEMS is a viable solution wherein users control their energy consumption and utility prepares for generation based on historic demand curves. With HEMS customers become capable of supplying power back to the grid from their captive power generation via solar PV systems, an untapped potential of storage system is readily available from EV batteries (Zafar et al., 2020). The bi-directional power flow, which is essentially a smart grid application, is worth pursuing when HEMS capabilities in monitoring, controlling, managing, logging, and detecting faults are concerned. Some researchers have put forward the challenges of HEMS when handling a large volume of data communication between home devices and smart grids as cybersecurity issues (Sankhwar, 2024c; Zandi, 2018). Additionally, scalability becomes a limiting factor when HEMS starts to interact with other buildings in the community (Zandi, 2018). Government initiatives on establishing enough protocols for communication between consumers, utility companies, and industries are key to HEMS's success. EV continues to increase its presence in smart grid applications but poses potential risks due to their stochastically charging due to traffic and user's subjective willingness (Xue et al., 2021). Addition of harmonics during charging session increases the power quality issues (Ahmadi et al., 2019). So, smart grid preparedness to power increased EV load requires analyzing the dynamics of EV use behavior as consumers start to grow. The concept of Vehicle to Grid (V2G) promises further independence of the house owners from grid power (Coban et al., 2022). When HEMS is integrated together between housing units, power grid, and governing bodies (Sankhwar, 2024c), the bi-directional energy transfer either from home battery energy storage system or electric vehicle can be enhanced. The undue burden added by EV charging equipment during existing energy peaks causes power quality issues (Lewicki et al., 2024), but communicative networking for captive power generation sources such as generator and battery energy storage systems and the power grid is further enhanced by energy management systems such as HEMS.

Solar PV panels work on the simple principle of photovoltaic effect wherein a strike of light on its film generates potential difference (open circuit voltage) at its terminals, which can drive current when a load is connected across their terminals. This generated voltage is direct current (DC) in nature whereas external loads are usually alternating current (AC). By using an inverter DC is converted to AC. Usually, Solar PV AC conductors are connected to service entrance conductors. Thus, the building has two power sources namely utility and solar PV feed. EV reduces household costs thus adding solar PV with a battery energy storage system not only offers savings, but also reliable power throughout the year (Kumar, 2022; Wu et al., 2024). Additionally, home energy management systems (HEMS) offer both utility, solar PV, and battery storage systems operating in a collaborative manner, offering savings to homeowners by switching loads to the cheapest option available at a given time of the day. Utility companies implementing TOD (time-of-day) tariffs provide an excellent opportunity for homeowners to limit their costs of energy. Roof-top installations on warehouses and factories have enormous potential for reducing energy costs for low-income residential homes (Stanford Report, 2024). Roof-top PV parking lots add to another prospect of harnessing solar energy (Osório et al., 2021).

Solar PV system application at commercial level often calls upon a detailed study on some of the parameters on type of panel, optimal tilt, wind and snow loads, shading effects, heating effects, and costs (Yao & Zhou, 2023). Often these are mounted on a flat roof with horizontal or zig-zag placement, on a pitched roof with parallel-to-roof placement, and on a curved roof with curved placement (Yao & Zhou, 2023). Residential homes often have a pitched roof, whereas commercial buildings have either flat, pitched, or curved roofs. It is the zig-zag mounting pattern that allows customizing the tilt angle. Around the US a total of 87,510 sq-feet roof-top building surface is available with a potential of 1432 TWh (Gagnon et al., 2016). Heavy capital costs with large-scale solar PV adoption have been a limiting factor, but return on savings promises a bright future (Lee et al., 2014; Mangiante et al., 2020).

Modern transportation system by roadways is primarily focused on the reduction of accidents (Retallack & Ostendorf, 2019) and thus improve the driver experience. EVs have seen increased adoption by several US public agencies, and thus, there are multiple programs that develop charging infrastructure along the highways. Without compromising driver safety, manufacturers have launched EVs with safety features in autonomous driving. At the transportation management level, improvement in driver safety by the implementation of intelligent traffic management has enormous opportunities when fully integrated autonomous vehicles with traffic controls are developed. Large-scale adoption of EVs is driven by the availability of frequent charging infrastructure wherein drivers recharge the batteries before fully running out. Developing batteries with increased mileage and reduced charging time is a question for both manufacturers and researchers. Ultra-fast chargers and charge while-in-motion on the roadway are some solutions for offering reduced charging times. With current trends in reduced traffic congestion hours and improved charging times with ultra-fast chargers, the EVs promise not only an energy-efficient solution but also feasibility for large-scale adoption. Cost of EVs is another driving factor, but with time and an increasing supply chain system, the costs may tend to decrease. And with fossil fuel running out, alternatives to EVs would be limited to fuel cell-based vehicles. Some biofuel-fueled vehicles may offer alternate solutions but will heavily rely on the production of such biofuels on a large scale. For instance, ethanol-blended gasoline is a practical solution to slow down gasoline consumption, but large-scale availability depends on agricultural infrastructure.

The existing research was mainly focused on improving electric motor designs, traction electrification, and present needs for 100% electrification (Haghani et al., 2023). Some researchers have established the benefits of EVs in reducing emissions and proposed a solution for rising fuel prices (Ahmad et al., 2022); whereas, many authors have found no clear advantages of EVs when comparing the emissions from EVs with ICE vehicles (Albrechtowicz, 2023). Moreover, the energy mix of a country determines how much emission reduction is possible by EVs (García & Casals, 2024). Grid overloading with increased energy demand from EVs requires investments in both decarbonization and the ability to manage intermittent loading (García & Casals, 2024). The government's support in improving the charging infrastructure is crucial while technological innovations continue to flourish. However, the preparation of utility companies and governing bodies in 100% transition to electric is in the developmental stages. Additionally, EV technology innovation has been a researched topic from equipment, battery, electric motor, and so on perspectives. However, there is no significant research that established forecasting based on available data resources for commercially available electric vehicles.

The scientific aim of the work is to establish a model to calculate energy demand and capacity of charging infrastructure required by each state. This paper delves into quantifying values of additional required energy generation and the capacity of charging infrastructure to allow both utility and government bodies to start a transition plan before the energy crisis is at its peak. The paper begins with modeling the average requirement of power for supporting an EV for residential buildings. And, it then analyzes the detailed vehicle profile for both public and privately owned automobiles, buses, trucks, and motorcycles to predict the total number of EVs by 2052. Thus, determining the annual energy production required to meet the increased EV demand load. Effects of reduced traffic congestion and improvement in EV energy consumption from improving technology or other factors were factored into the modified model to obtain energy demand. This article brings an innovative approach less known from existing literature, in many areas such as: forecasting the future electric vehicle profile in the United States, presenting untapped potential available for utilizing solar energy and energy management systems, technology application of charging infrastructures in level 1, 2, and 3, and utilizing publicly available data base for forecasting future energy needs. The research paper has been organized in the following manner: section "Solar photovoltaic system model" describes a simple solar photovoltaic model and energy management systems. Section "Obtaining EV energy demand" obtains a forecasted vehicle profile, energy demand, and capacity of EV infrastructure. Section "Power generation capacity required by state to power EV infrastructure" covers power generation required by each state and base model. Section "Comparison of EV with ICE vehicles for performance" covers the comparison of EVs with ICE vehicles. Section "Optimization of the performance of EVs by 2052" covers the optimization of the performance of EVs. Section "Obtaining improvement in energy consumption by EV" covers obtaining results from optimized EV. Section "Modified model and results" presents the modified model. Sections. "Conclusion", "Practical implication", "Discussion and future scope" cover the conclusion, practical application, and future scope, respectively.

Solar photovoltaic system model

Methodology

Non-renewable energy resources for charging an EV defeat the fundamental principle of switching over to green or clean energy resources. So, to become more responsible towards energy consumption, a residential home-owner must utilize roof-top solar PV to curb additional energy demand added to the grid because of EV ownership. Addition of a HEMS—being a nascent stage—offers a coordinated operation between home and grid. Figure 1 depicts a solar PV (without battery storage) integrated with residential electrical service.

Suppose an average car owner in Maryland purchases a Tesla Model 3 with a battery wattage of 80 kW and drives an average of 13.5 K miles yearly; energy demand was calculated based on typical energy consumed by an EV per mile. To develop a holistic model, as presented in Fig. 1, to power the EV car from solar PV, capacity of required solar PV system was calculated using NREL System Advisor Model (SAM). For homeowners, roof-top mounted solar panels let them go off-grid to meet EV charging demands. To power an EV in Randallstown, Maryland, an average energy of 3373 kWh per year is required. Using the NREL System Advisor Model, the required size of the roof-top PV system is 2.8 kW for individual house owners. A total of 7 × 400W panels occupying a 159 sq feet rooftop will generate nearly 3838 kWh yearly (Fig. 2).

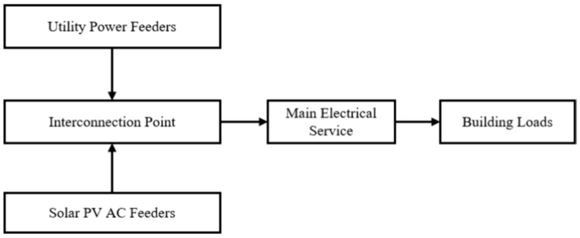

Fig. 1 Residential building with solar PV

Since solar irradiance values vary depending on location, similar calculations can be performed to obtain PV system size in kW at any given location. For residential applications, (120/240)V Solar PV Feeders may be tied to service entrance point directly from AC side of the Inverter. However, a battery storage system added to store the energy allows prolonged usage time periods. For commercial (277/480)V systems, a similar methodology becomes viable. The design criterion is governed by local buildings, and electrical codes and standards. For example, the National Electrical Code and International Building Code are examples of some of the applicable codes and standards; whereas means, methods, and workmanship are defined per the standard technical specifications per owners' requirements such as Division 26 (Electrical).

For commercial applications similar modeling would significantly reduce the dependence on grid power for meeting EV charging demand. Many applications for solar PV systems include integrating with microgrids to facilitate captive power generation and thus provide the ability to go on or off the grid. Deployment of energy management systems as depicted in Fig. 2-3 allows microgrids to stay cost-effective, resilient, and sustainable (Lan et al., 2021). Typical building loads are powered at (277/480)V, or (120/240)V, with major loads comprising a heating and mechanical ventilation system, plumbing, lighting, and receptacles. With the capabilities of the local switching of loads to solar or other local renewable energy sources based on live tracking of local generation, and loading offers an effective energy management solution.

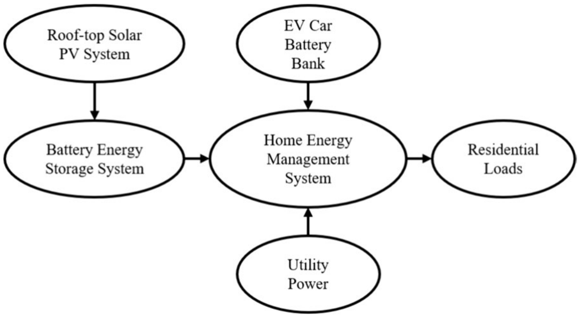

Fig. 2 Home energy management system

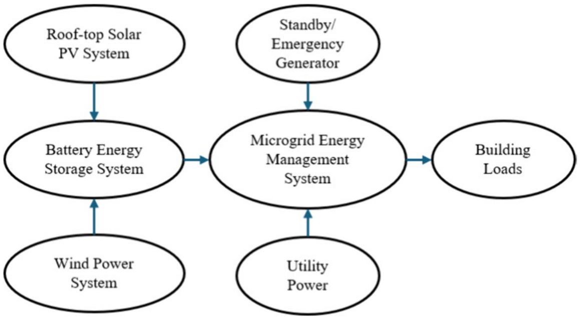

Fig. 3 Commercial building microgrid energy management system

Obtaining EV energy demand

Methodology

Using the US Federal Highway Administration (FHWA) published data (US Department of Transportation Federal Highway Administration, 2023) on the number of registered vehicles by each category, namely automobiles, buses, trucks, and motorcycles for both public and private use by each state, the existing vehicle profile was established from the year 2000 to the latest available year 2022 in Figs. 5, 6, 7, and 8. To project the figures for the next 30 years until 2052, 2000 to 2022 vehicle profiles were compared, and relationships for each state's growth or decline were used to forecast the 2052 profile. Although there is an overall dip in the number of automobiles based on the forecast, buses/trucks/motorcycles continue to see a rising trend. Figure 4 shows the model for quantification of energy generation required by 2052.

The relationship between annual energy consumption (E) with number of vehicles (n), annual average miles driven (m), and energy consumption (e) in kWh/miles is given by (2):

$$E = n.m.e. \tag{2}$$

The total quantity of both public and private vehicles continues to increase every year, but some diminishing trends by category type are indicators of how well the industry would grow or decline in times when energy crises are at their peak. Although breakdown based on the exact make/model of vehicles is not considered in this modeling, the total count of vehicles by each category was input for market trend indication.

Using average miles driven by each category as available from the US Department of Energy, the projected total travel miles for all categories was 19.62 trillion.

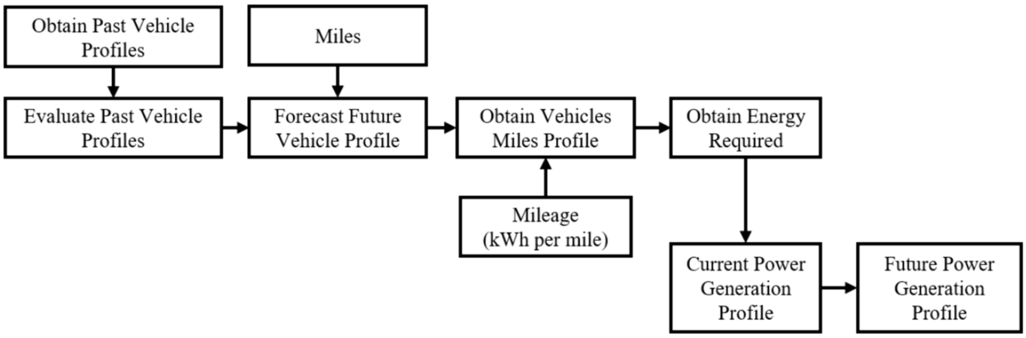

Fig. 4 Modeling quantification of energy generation

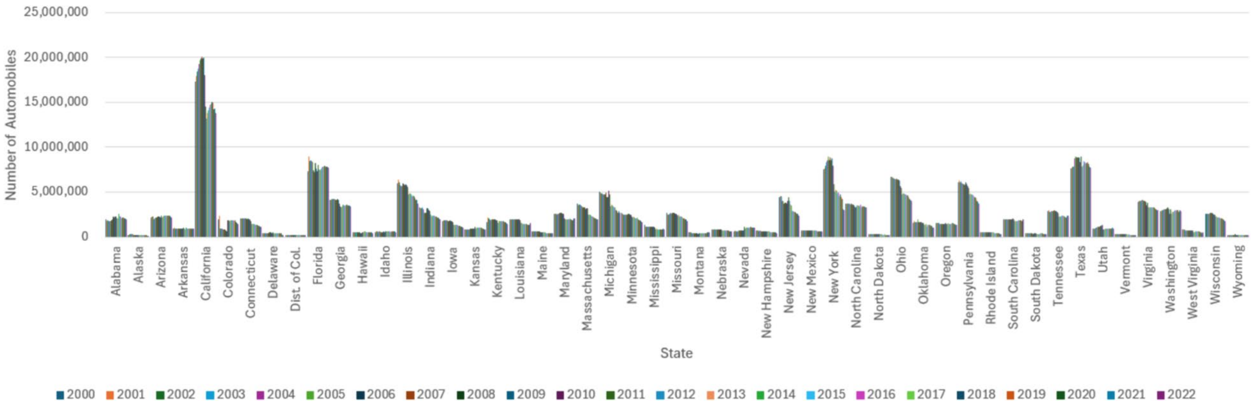

Fig. 5 Vehicle profile for automobiles (US Department of Transportation Federal Highway Administration, 2023)

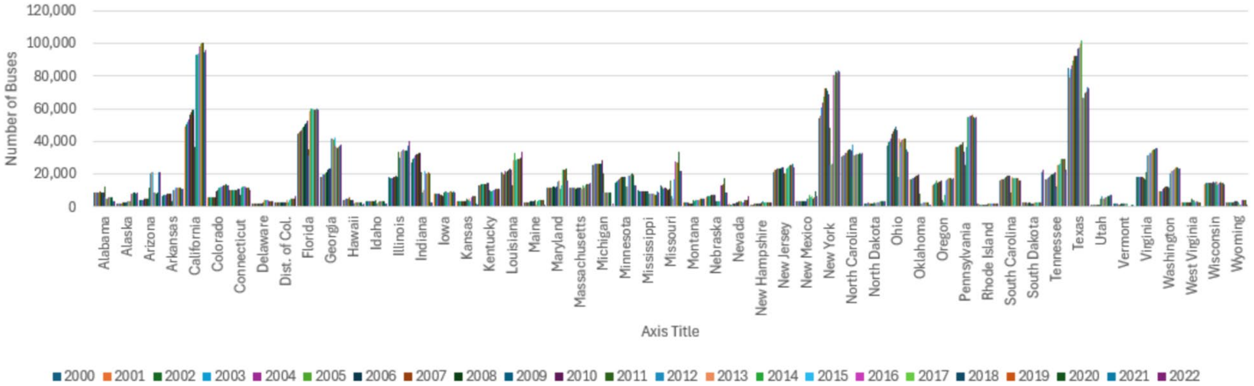

Fig. 6 Vehicle profile for buses (US Department of Transportation Federal Highway Administration, 2023)

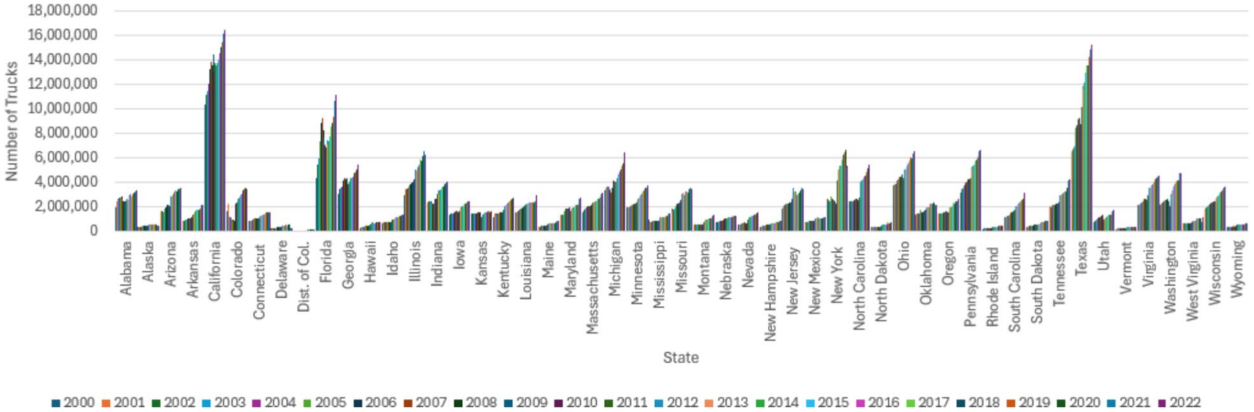

Fig. 7 Vehicle profile for trucks (US Department of Transportation Federal Highway Administration, 2023)

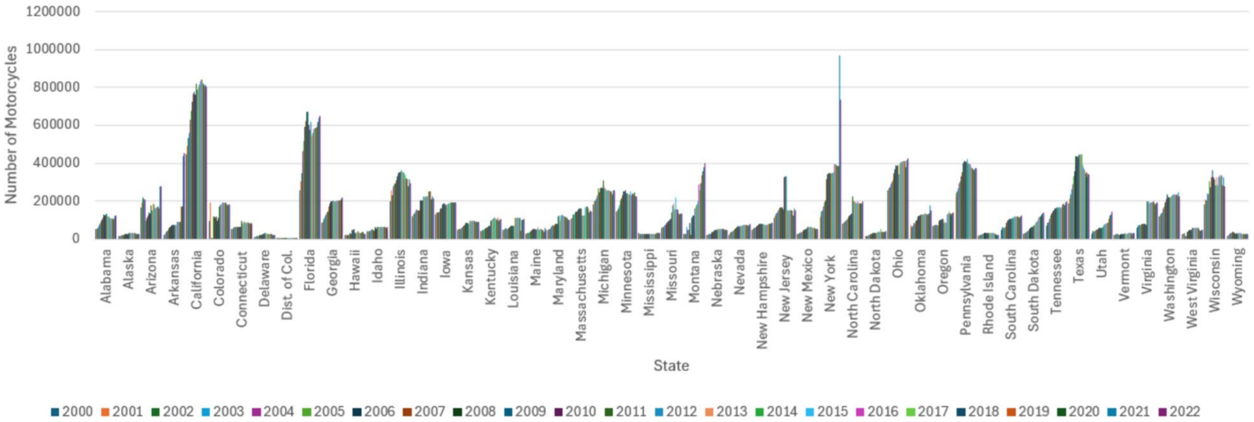

Fig. 8 Vehicle profile for motorcycles (US Department of Transportation Federal Highway Administration, 2023)

After accounting for the mileage of commercially available electric cars, buses, trucks, and motorcycles, the total annual energy required is 38.15 M GWh. Additionally, the generation required by each state was obtained with the assumption that the average miles driven by drivers in each state remained the same.

The current generation profile from the US Energy Information Agency (EIA) indicates around 1.16 million

GW capacity (U.S. Energy Information Administration, 2024b); thus, an additional infrastructure to power 38.15 M GWh annually will be required when large-scale EV adoption is concerned. Thereby projecting a total energy generation capacity to be increased from current installed capacity by a minimum of 0.37% by 2052 to meet the rising EV demand.

Existing vehicle profile

A comparison of FHWA's 2000 to 2022 number of registered automobiles, buses, trucks, and motorcycles is presented in Figs. 5, 6, 7, and 8.

Forecasting vehicle profile

Maryland

Using time series forecasting starting in 2022 and ending in 2052 with a timeline range taken from 2000 to 2052 and detecting seasonality, the Maryland vehicle profile is plotted in Fig. 9. Using forecasting tools, Maryland automobiles data from 2000 to 2022 projected a declining number of vehicles towards 2052 in Fig. 9.

Using forecasting tools Maryland buses data from 2000 to 2022 projected a rising number of vehicles towards 2052 in Fig. 10.

Using forecasting tools Maryland trucks data from 2000 to 2022 projected a rising number of vehicles towards 2052 in Fig. 11.

Using forecasting tools Maryland motorcycles data from 2000 to 2022 projected a rising number of vehicles towards 2052 in Fig. 12.

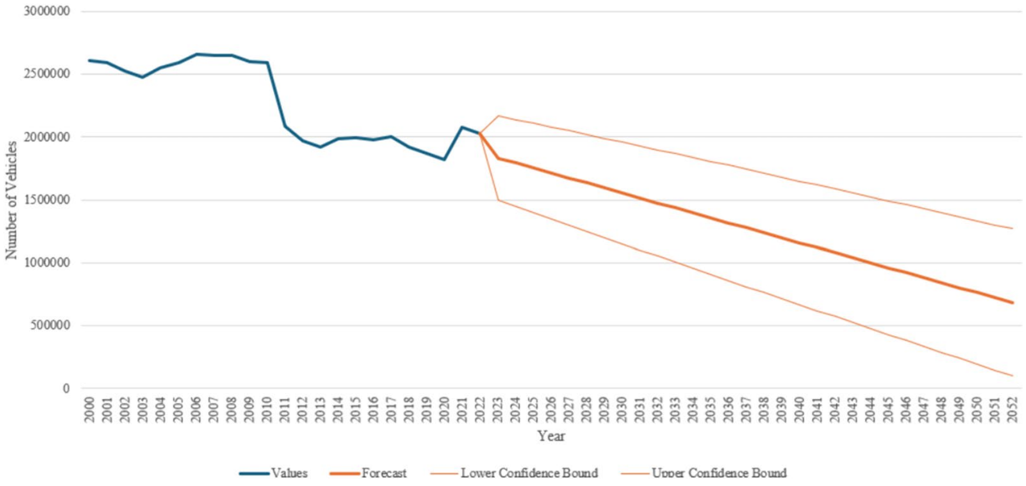

Fig. 9 Vehicle projections for MD—automobiles

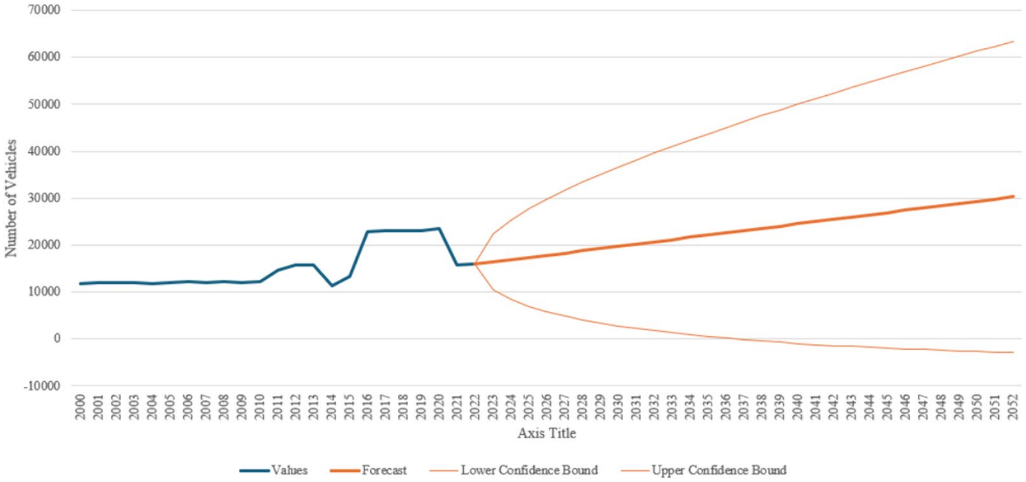

Fig. 10 Vehicle projections for MD—buses

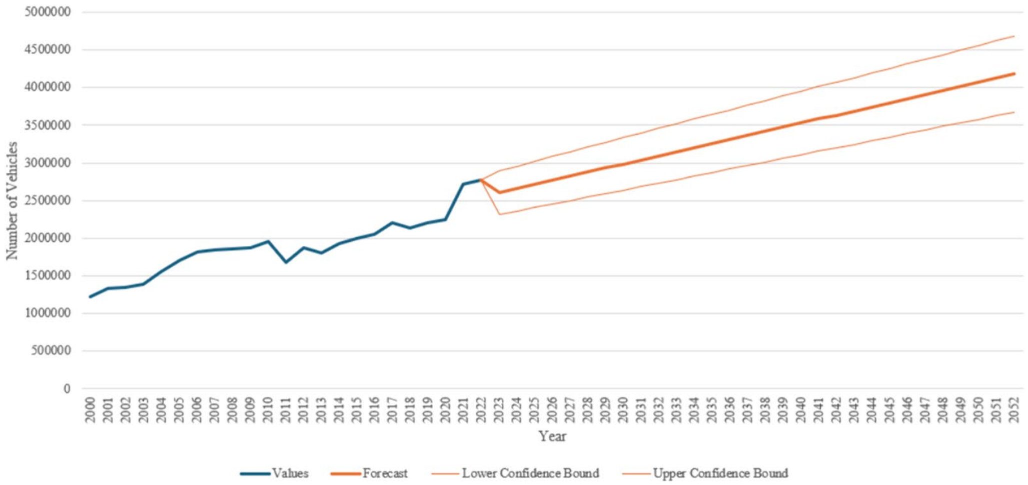

Fig. 11 Vehicle projections for MD—trucks

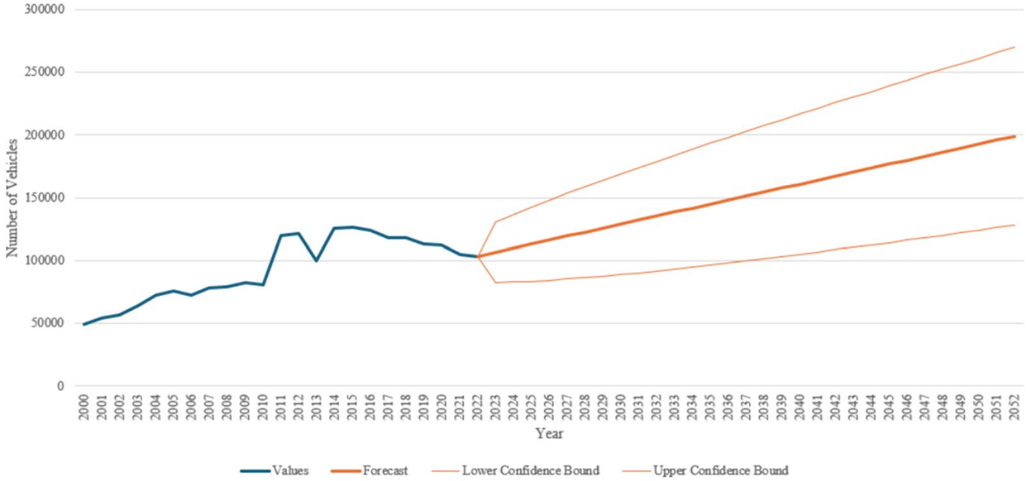

Fig. 12 Vehicle projections for MD—motorcycles

Similarly, all state data were utilized to project the number of vehicles of each category by 2052 for the corresponding state. Based on individual growth/decline by each vehicle category between 2000 and 2022, Fig. 13 was obtained with projections for total vehicles (inclusive of all categories) by 2052.

Energy consumption

By grouping the vehicles by each category type, total miles driven were used to obtain the required energy in GWh and presented in Fig. 14. Majority of energy is required for trucks, followed by automobiles, buses, and motorcycles. Based on the analysis presented in Fig. 18, the average energy consumption (kWh/mile) offered by the automobile category was taken as 0.39 kWh/mile. Leading models for electric buses provided by MAN and IC Bus offered an average energy consumption of 0.42 kWh/mile (Editorial, 2024). Semi-trucks from Tesla offered below 2 kWh/mile (Tesla 7, 2024). Based on Zero-motorcycles electric motorcycles offered 0.087 kWh/mile (Zeromotorcycles, 2024).

Figure 15 shows average energy consumption by each state and Fig. 16 shows average capacity of charging infrastructure required by each state.

Power generation capacity required by state to power EV infrastructure

Individual house owners, and private and public commercial buildings must prepare for adding renewable energy systems with battery storage systems to meet

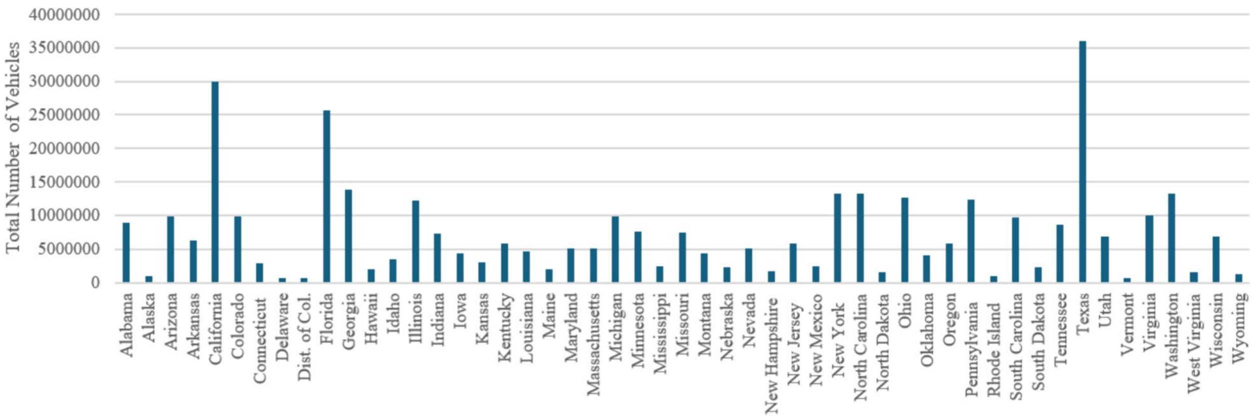

Fig. 13 Vehicle projection by 2052

the energy needs of EV charging. With a known total of 38,154,284 GWh energy required, a minimum of 4355 GW infrastructure is required. Figure 16 shows the required generation capacity (GW) by each state.

Comparison of EV with ICE vehicles for performance

Methodology

EV comparison with ICE vehicles is necessary for customers, businesses, and government agencies before planning to fully transform existing vehicles into electric ones. In this section, vehicular fuel consumption, safety, cost, and GHG emissions were taken as comparison criteria.

Vehicular efficiencies

Comparison of the reciprocating movement of the piston in ICE is considered less efficient when compared with EV, which has an absence of this reciprocating movement. Based on fuel economy a significant amount of energy is lost in various inefficiencies in ICE and comparatively EV significantly lesser (Kirk, 2024).

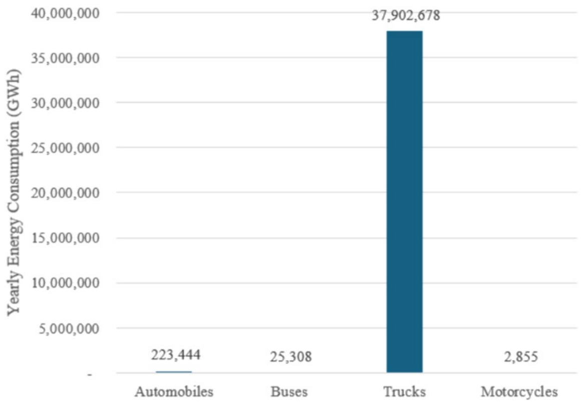

Fig. 14 Annual energy consumption by each category

Distance driven vs fuel consumption Per Department of Energy the Gasoline Gallon Equivalent (GGE) for 1 kWh of electricity is given by following relationship (3) (US Department of Energy, 2024):

$$1\text{kWh} = 33.33\ \text{GGE}. \tag{3}$$

Tesla Model 3 offers up to 29 kWh per 100 miles, and BMW 3 Series up to 36 miles per gallon. Using GGE, the EV Tesla Model 3 performed 3.2 times better than ICE BMW 3 Series. Even after comparing with other commercially available passenger ICE engine cars with EV cars, EV cars offered better fuel economy or lower energy consumption.

Safety and cost

Per the US Department of Defense, EVs are considered safer than ICE based on their ability to catch fire (Office of the Under Secretary of Defense for Acquisition & Sustainment, 2023). Additionally, most light-duty EVs were cheaper when comparing the total cost of ownership (Office of the Under Secretary of Defense for Acquisition & Sustainment, 2023).

GHG emissions

The life cycle analysis indicates EVs emit significantly lower carbon emissions than ICE (Kelly et al., 2020).

Shortcomings of EVs

Many concerns with EVs include limited battery size, greater charging time, battery life, and charging infrastructure issues. To improve the charging infrastructure, one of the simple solutions is for house owners to install level 1 chargers at their home. However, for buses and

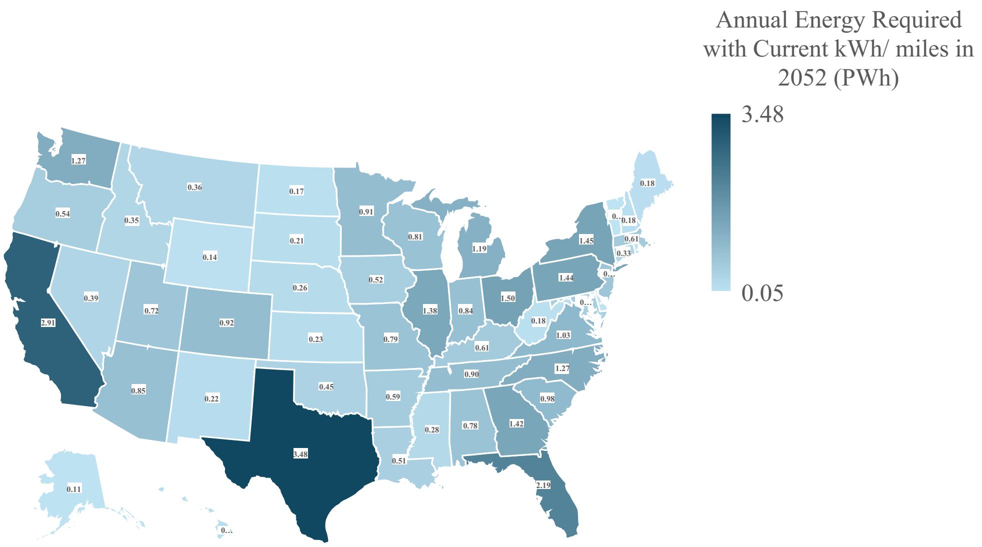

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Fig. 15 Annual energy consumption by state (PWh)

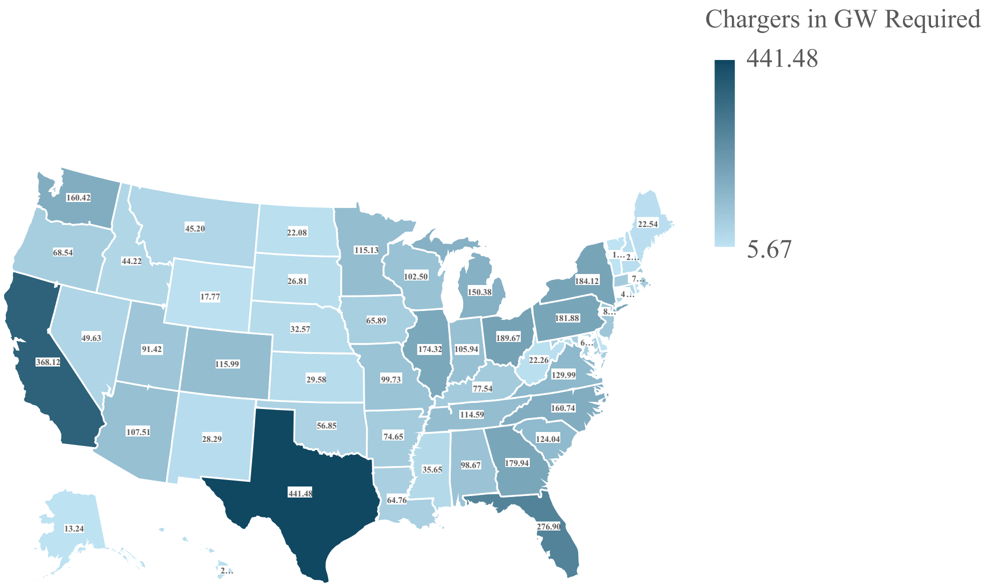

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Fig. 16 Charging infrastructure required by each state (GW) trucks, a plan is required to install a mixture of level 2 and 3 chargers that can offer charging while they park overnight or within a few hours with fast chargers. Based on the frequency of charging required for a trip, it is advisable to have fast chargers readily available, at least at all existing gasoline stations. A roadmap on the size of EV charging infrastructure required for charging automobiles, buses, trucks, and motorcycles is shown in Fig. 16.

Given EV drivers must return to charging stations frequently for charging due to limited battery size, and thus spend three to four times as much they spend for refueling ICE, many retail gasoline stations must plan for adding DC fast chargers (level 3) at least three to four times the existing number of gasoline or diesel dispensers. This is based on an average time spent by a driver as 10 min for ICE refueling and 30–40 min spent for EV charging.

Electric vehicles act as a huge source of stored energy, and with evolving technologies in smart charging with bidirectional power flow options, it is possible to harness this potential and improve grid resilience to power outages. With EV ownership, there will be increased power consumption; thus, power generation companies must prepare for increasing their power generation by renewable energy resources.

There are several studies published that document diminishing fossil fuels and present the need for transitioning to renewable energy. However, this research is based on a past number of vehicle data available from FHWA and energy usage of EVs per DOE. Thus, analyzing these data and the results presented were intended to prepare generation companies to start planning for rising demands from EV transition, as EV transition is pressing in the transportation sector. With projected figures for generation required, each state can prepare to start developing guidelines and plans for both EV purchases and Solar PV systems installation. Additionally, generation companies are required to use the untapped potential of renewable energy to meet the rising energy demand.

Optimization of the performance of EVs by 2052

Alter modern roadway transportation pattern

Transportation is focused on the reduction of costs, improving safety, and ensuring surplus supply. For most passengers, commute is mainly governed by cost and safety factors. The occurrence of accidents is mainly attributed to vehicle speed, weather conditions, congestion, and a number of vehicles on the road (Retallack & Ostendorf, 2019). Drivers' safety is proven to improve when vehicle speed and number of vehicles are controlled. The majority of trucks are purposed for the transportation of goods. Buses are mainly for public transportation and often fall into factors that make them safe and cost-effective. For instance, in a large metro city such as New York City, the majority of public transportation is by subway trains and many other cities have bus services. With the presence of buses for public transportation consumers tend to refrain from using personal cars. This effect of how consumers behave with the presence of large-scale public transportation systems is a topic of research as it may result in decreased customers for automobiles.

Implementing park-and-ride options, improving traffic light management, diversion of traffic by alternate routes, and public transportation systems are known methods in improving smoother traffic movement. Some methods, such as engaging a coordinated drive among all semi-autonomous EVs on the road, ensure driver safety and reduce travel times. For instance, entire road transportation systems become one integrated system where all vehicles know their relative position, and so does the traffic light management system.

Modeling a transportation system wherein the majority of consumers rely on public transportation systems promises reduced consumption of EVs, thereby reducing energy consumption and, thus, demand. So, a modern transportation system must goal towards energy efficiency by growing means of sharing the resources. Studies have shown that buses and trains can reduce GHG emissions by two-thirds times per capita (Welle et al., 2023). Ensuring smooth traffic flow by solving traffic congestion problems further improves fuel economy (Fig. 17).

Improvement of efficiency by traffic pattern improvement

With current infrastructure in place between FY2009 to FY2019 per FHWA, a reduction of average of 0.57 h was observed for urban areas (US Department of Transportation Federal Highway Administration, 2024). So, from 2022 to 2052, with existing strategies in place, a drop to 1.81 h is possible. Total urban area in the US comprises of 3% of land area and 80.7% population (America Counts

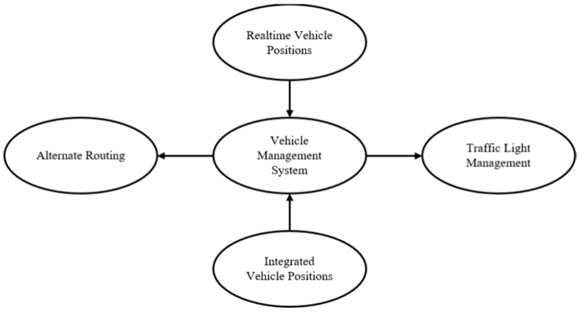

Fig. 17 Improved traffic management

Staff, 2017). So, the energy demand may be adjusted to account for this; whereas with a modified model for obtaining energy demand for EVs, the mentioned congestion hours would approach zero as there is the likelihood of least traffic congestion. However, the modified model accounted for EV improving energy consumption (kWh/mile) based on EPA data published data on fuel economy for EVs. Effects of fuel economy based on improved traffic congestion were not considered in the modified model.

Evolving EV technology

The battery EVs are evolving every year, and the efficiency of both power train and lithium-ion batteries has improved over the last decade. The overall conversion of available battery power in an EV to rotational motion is 90%. And with the missing piston movement of a traditional ICE vehicle, EVs promise improved dynamics on the road. Li-ion battery efficiency depends on charge current, state of charge, and temperature. From 2022 to 2052, with improved vehicles launched by several manufacturers, an energy consumption efficiency of 39% is possible. So, the energy demand was adjusted to account for this in the modified model.

Obtaining improvement in energy consumption by EV

Per the US Department of Energy Fuel Economy (Fuel Economy, 2024), the electric cars available in US market from 2000 to 2024 are depicted in Fig. 18 for amount of their energy consumption (in kWh/mile). Figure 19 shows energy consumption (in kWh/mile) profile for EVs available in the year 2024. Figure 20 provides with average kWh/mile each year.

Annual energy generation of 38.15 M GWh by each state converts to 4355 GW of generation capacity, and 15.06 M GWh to 1719 GW. Each state's required capacity charging infrastructure was calculated by assuming a 90% efficiency through either Level 1/2/3 type charger at rated power in kW. Figure 14 shows when energy consumption is 38.15 M GWh and Fig. 24 shows when energy consumption is 15.06 M GWh. The existing installed capacity of electric charging infrastructure was accounted per EVAdoption (EVAdoption, 2021).

Considering the 2014 to 2024 period, the average energy consumption per mile for cars will increase up to 0.53 kWh/mile in 2052 as per Fig. 21 projections. However, when EVs from one manufacturer (Tesla Motors) were considered, it was observed that kWh/mile reduced from 0.298 kWh/mile to 0.061 kWh/mile during the same duration from 2014 to 2024, as seen in Fig. 22. Hence, the forecast from Fig. 21 was discarded. Whether the technology has the potential to reduce the energy consumption per mile to the extent seen in Fig. 22 is questionable, given there will be operational challenges with the optimization of electric motors and batteries. However, an educated judgment allows the author to utilize the year 2038 values (0.18 kWh/mile) until the end of 2052 for the modified model. When this 0.18 kWh/mile in 2052 compares with the average of 0.298 kWh/mile in 2024, a 39.47% improvement is observed. With this 39.47% improvement between 2024 and 2052 in EV fuel efficiency, an educated judgment is to apply this to the entire automobile industry, given they have similar EV principles of operation. Additionally, the vehicles were assumed to operate at the same energy consumption per mile during any trip, irrespective of city or highway.

Modified model and results

Factoring improvements because of improved EV technology and thus improved energy consumption (kWh/mile) and improved transportation pattern, Fig. 23 shows a modified model for obtaining energy required and hence required generation. Improvements because of modified transportation patterns were not accounted for in the modified model.

Projected energy demand reduces to a cumulative of 15,059,496 GWh in Fig. 24. This marks a 60% reduction from projected in the previous model. Figures 25 and 26 show modified energy generation and charging infrastructure capacity required by each state, respectively.

Conclusion

Preparedness for EV transition

EVs are the future of transportation and being prepared for associated challenges drives this research work. The global energy reserves for petroleum resources are supposed to last long enough to support demands until 2052. Vehicles in the US will continue to grow every year per the forecast model. However, a drop in the automobile category is visible between 2012 to 2022, indicating similar trends for upcoming decades. Buses, trucks, and motorcycles were seen to grow during the same time, indicating similar trends for upcoming decades. Thus, the total number of projected figures for vehicles by each category was 374,820,943. Since the current share of EVs is significantly low, a quantification of energy required to support 100% EVs by 2052 was obtained. Thus, the quantified vehicles and energy required to support them prepare us for planning the future.

Solar PV system installation

Solar PV systems offer ease in meeting rising power demand from an EV. A residential owner can easily install at least 7 × 400W modules requiring 159 sq. of roof space to support one EV at home located in Randallstown,

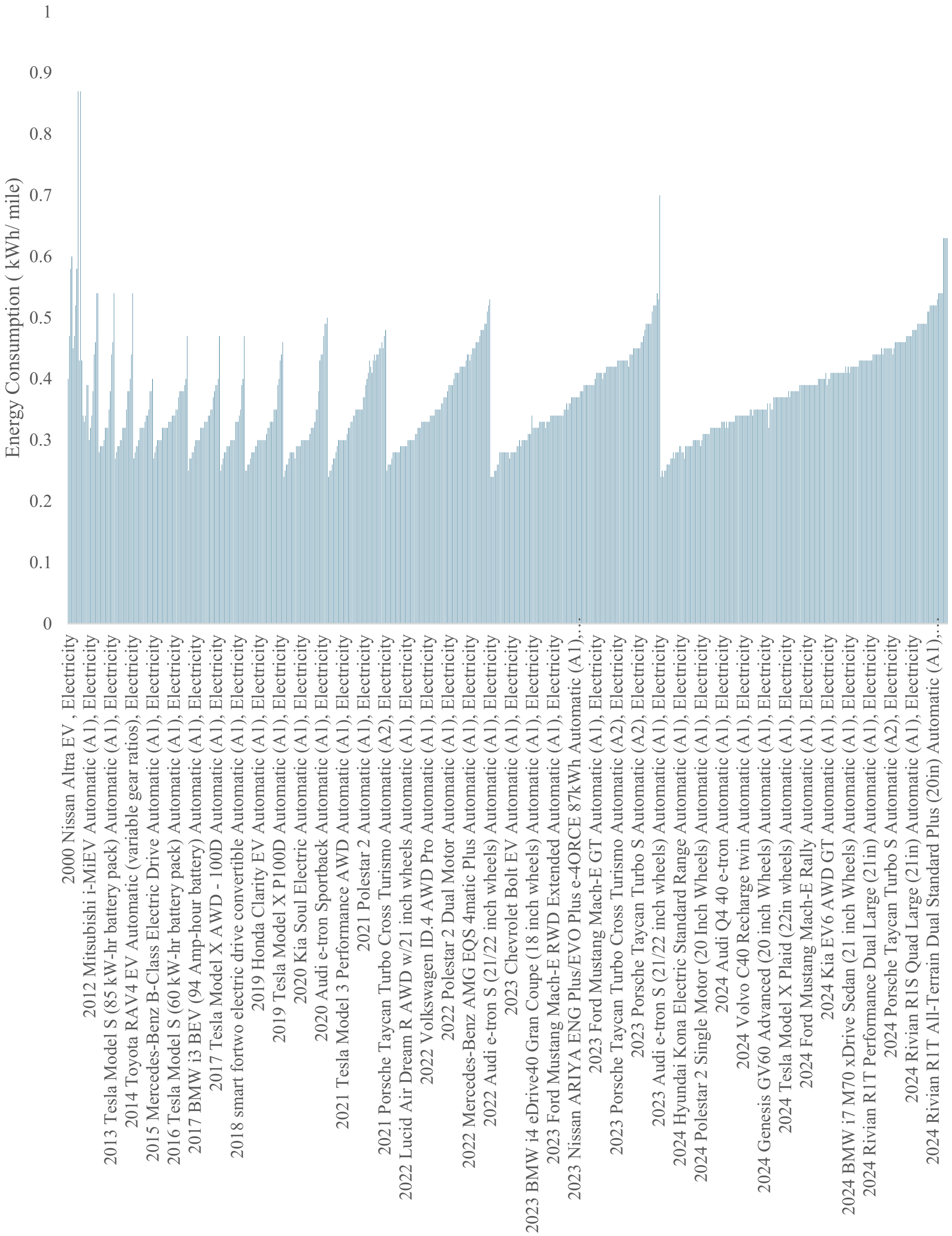

Fig. 18 Vehicle energy consumption (kWh/mile) profile 2000 to 2024 (Fuel Economy, 2024)

Maryland. Since the power generation from solar varies throughout the year, the ability of bi-directional flow of power between homeowners and power grids becomes a viable solution. Teeing the utility interconnection point at the service entrance is the most economical, whereas smart integration of home battery energy storage systems

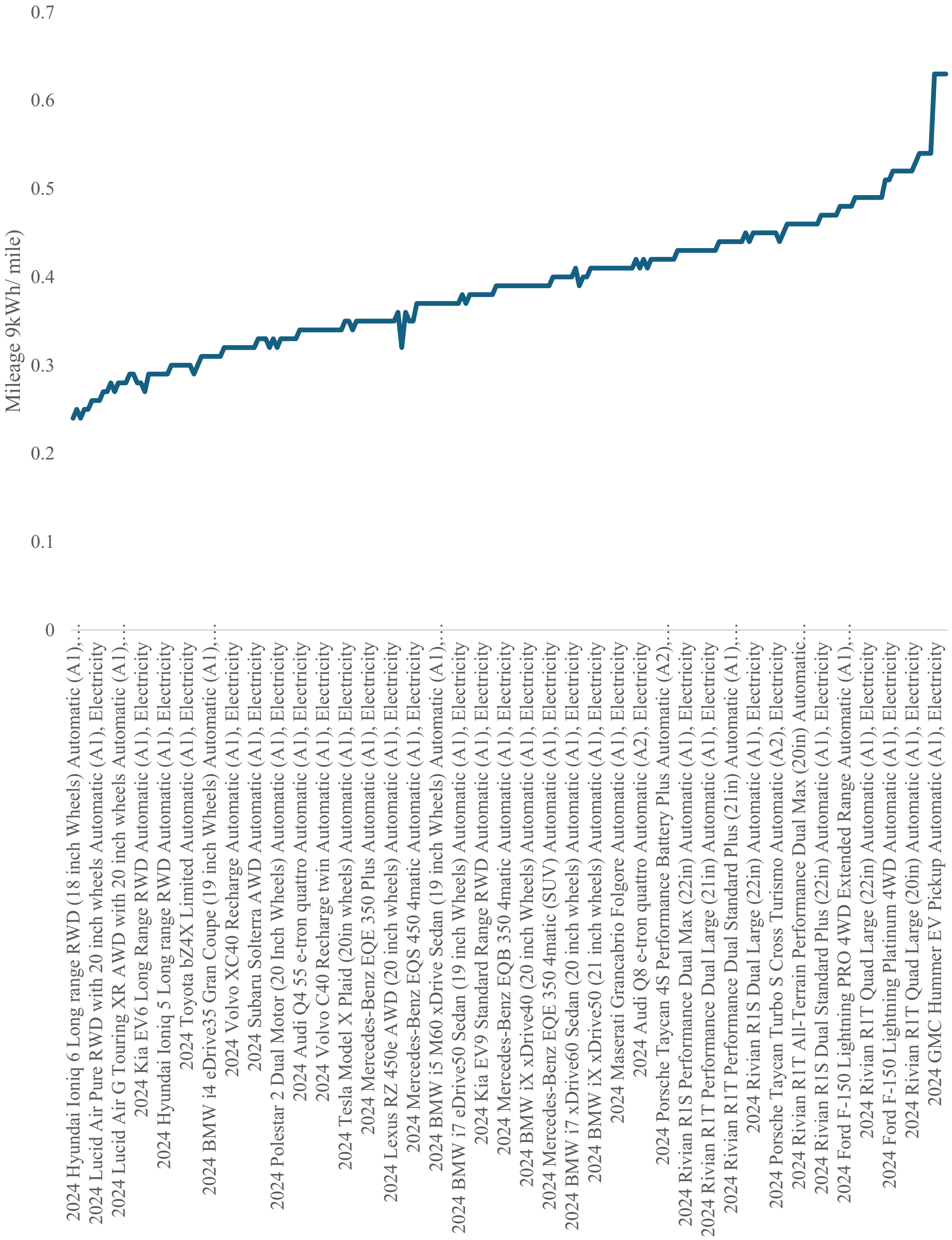

Fig. 19 Vehicle energy consumption (kWh/mile) profile 2024 (Fuel Economy, 2024)

requires energy management by HEMS. However, local codes and standards define the detailed electrical distribution system designs. The HEMS, with monitoring, controlling, managing, logging, and detection of faults capabilities, offers smart grid applications. Both these concepts of roof-top solar can materialize for residential

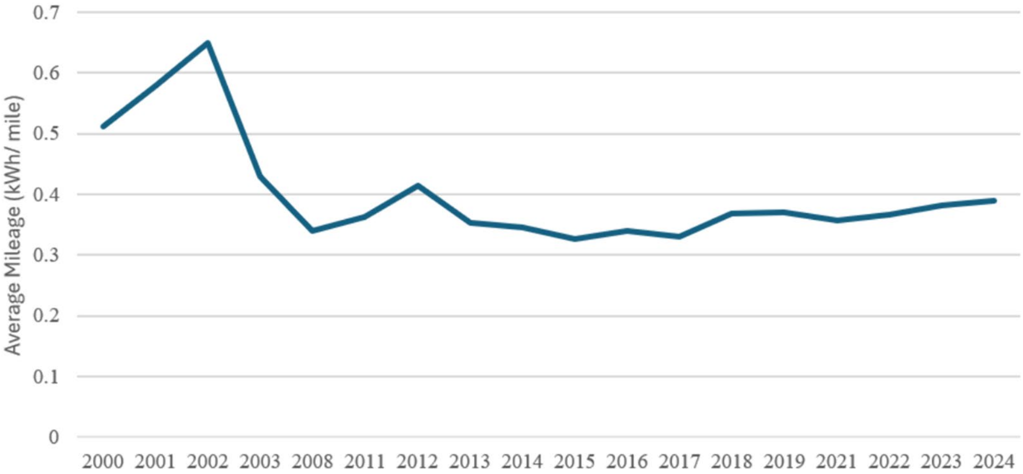

Fig. 20 Average energy consumption (kWh/mile) PROFILE 2000 to 2024

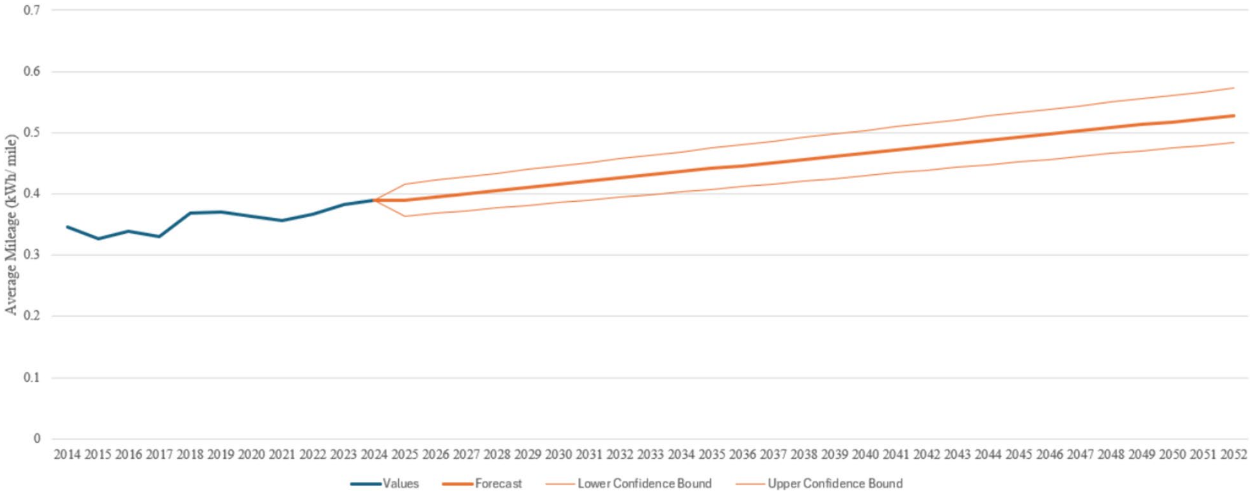

Fig. 21 Average energy consumption (kWh/mile) projection by 2052

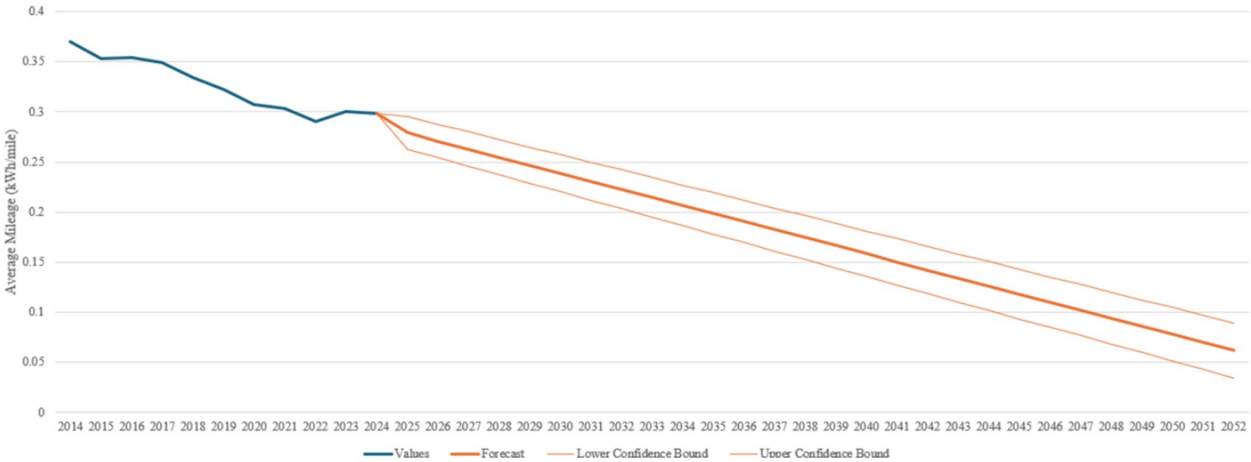

Fig. 22 Average energy consumption (kWh/mile) projection by 2052

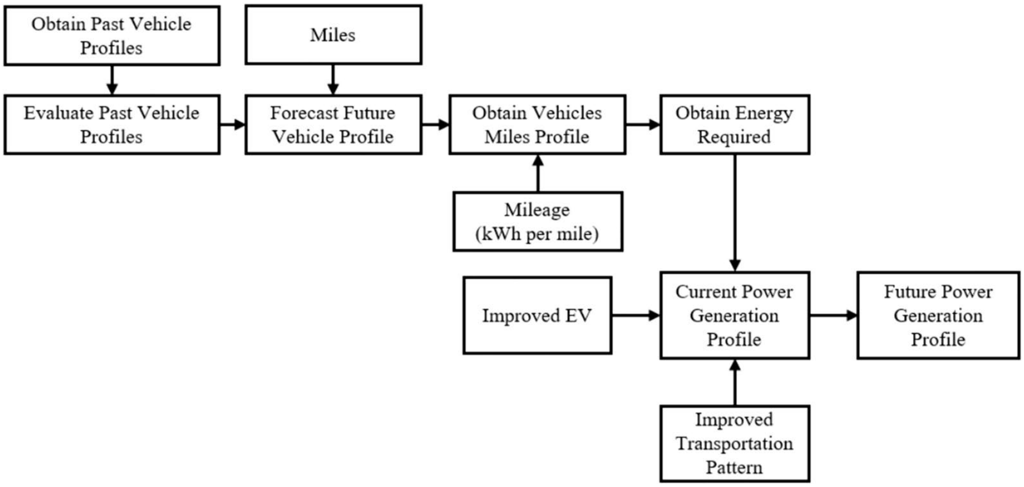

Fig. 23 Modified model

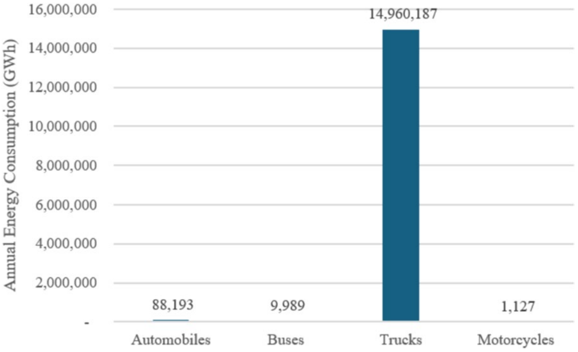

Fig. 24 Modified energy consumption

and commercial buildings, and their energy management system.

Energy demand calculation and EV charging infrastructure

With the forecasted vehicle profile in hand, both average miles driven and EV mileage or energy consumption per mile were accounted for in obtaining the total annual energy consumption. The annual energy consumption was 38,154,284 GWh and with the modified model, 15,059,496 GWh. The modified model factored in the improved mileage obtained from current trends. With the majority of power generation relying on fossil fuels there is a need to increase the usage of renewable energy. Large-scale solar PV systems for residential, commercial, and industrial use improve the power generation profile. Based on the energy demand for EVs by 2052 by each state, the capacity of EV charging infrastructure required is presented in Figs. 25 and 26 for both base and modified models.

Improvements

Improved transportation management with reduction of congestion and intelligently controlling the traffic movement ensures safety and reduction in travel times, thereby reducing the consumption of energy. Additionally, the increasing conversion efficiency of chemical energy to electricity from Li-ion batteries and improvements in vehicle dynamics in EVs result in reduced energy consumption. The modified model based on such efficiency improvements resulted in a 60% reduction to 15,059,496 GWh. The modified model was based on forecasted improved energy efficiency of the EV.

Issues

The forecasting was based on time series methodology, whereas some authors may prefer other statistical techniques such as moving square and linear regression. Additionally, some software in data analysis offers readily available tools and techniques to accurately predict future value based on past statistics. The selection of suitable tools and techniques is dependent on user preferences. However, this paper recorded the results based on the selected technique. Some assumptions on fuel economy or energy consumption per mile remaining constant during any trip, either city or highway, may be further modeled. The vehicle profile forecast was based on FHWA data. However, data available from other resources on the prediction of the future vehicle profile becomes another aspect of the study.

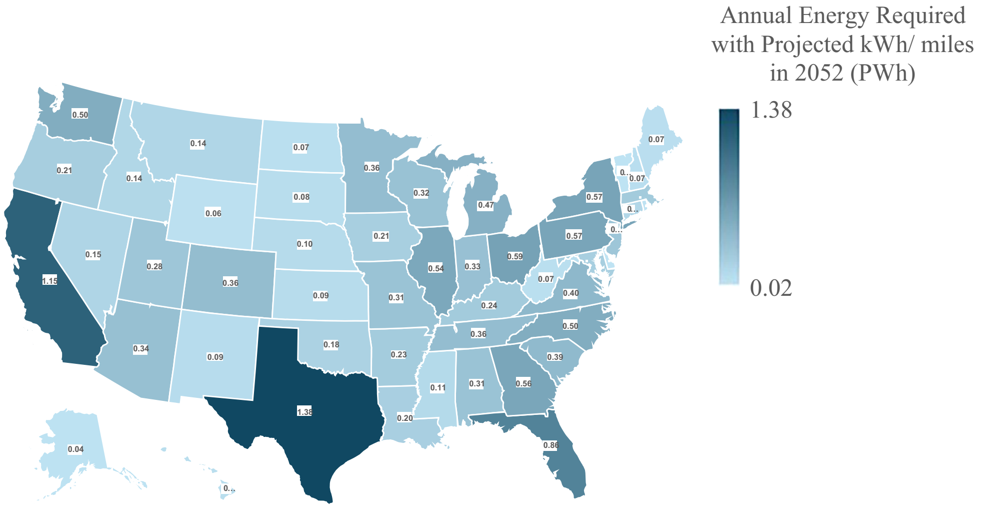

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Fig. 25 Modified annual energy consumption by state (PWh)

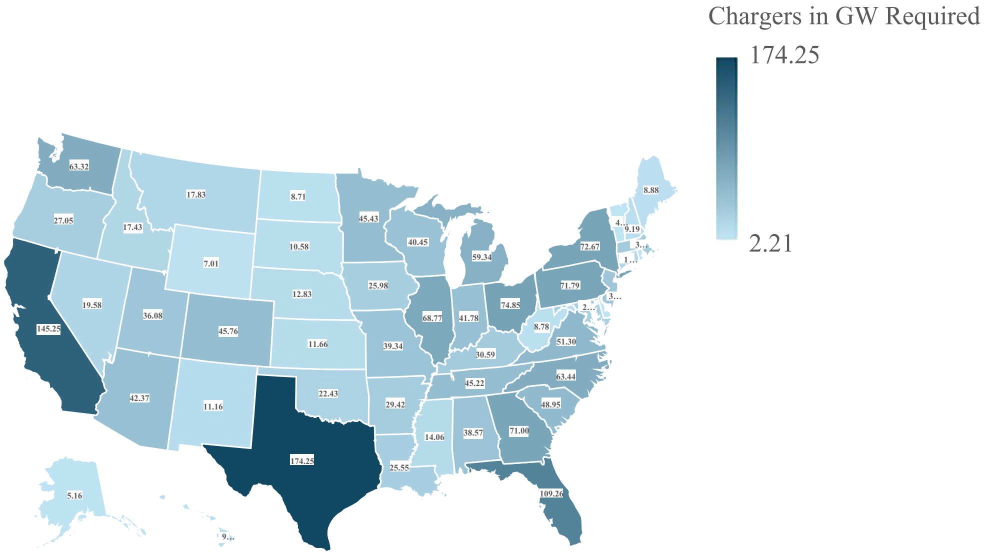

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Fig. 26 Modified charging infrastructure required by state (GW)

Practical implication

The presented study allows homeowners and developers to plan the addition of roof-top solar PV systems with or without battery energy storage systems. Utility companies must be prepared for the rising electrification in the automobile industry by adding power generation by renewable energy or encouraging captive power generation at residential or commercial properties from renewables such as solar or wind power systems. The results obtained from the forecasted EV profile by 2052 not only prepare the car manufacturers for planning the manufacturing facilities to meet the demand, but also the local government agencies who prepare policies in providing incentives and funding for promoting a positive change towards a sustainable future. Several authorities may utilize the presented vehicle profile in projecting the purchasing needs for the EV before the 100% transition in 2052. For researchers and graduate students, the methodology laid becomes a foundation for future studies in electrification. Although the EV transition depends on the government and other stakeholders' interests, a simple evaluation of higher fuel economy and reduced carbon emissions from EVs against their ICE counterparts makes EV transition, a positive move. Three pillars of sustainability try to maintain a best fit within social, economic, and environmental impacts; thus, returns on investment for such a large-scale electrification need a fit with social and environmental returns. For example, reduced emission from EVs contributes towards safer and healthier premises.

Discussion and future scope

The losses due to transmission and distribution of power were ignored. However, a typical industry-wide transmission and distribution loss of 5 to 7% may increase similar burden on the generation companies when supplying the increased energy demand from EVs. The concept of charging while in motion on the roadways is a futuristic concept, and the widespread use of ultra-fast chargers may improve the user experience and comfort levels. City dwellers living in multi-family residential buildings may have a restricted availability of roof-top space, so a community-shared roof-top solar becomes a viable option. However, the community may rely on shared resources for EV charging within the community. Many residential and commercial building complexes possess an untapped spare capacity in their main electrical service electrical switch gears. For example, a 1200 Amps, (120/208) Volts electrical service at a residential building when initially designed included 25% spare capacity for future use, but due to many reductions in loads from switching to energy-efficient heating and ventilation systems, or light-emitting diode (LED) lighting, there is the likelihood of the presence of some spare capacity to supply electric charging loads. So, there are excellent opportunities available for city dwellers not only from the spare capacities, but also from the parking spaces available in their community that become an ideal site for EV charging infrastructure addition.

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Author contributions
Pravin Sankhwar wrote the article and performed independent research.

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Availability of data and materials
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Declarations

Ethics approval and consent to participate
Not applicable. This is the author's original work.

Consent for publication
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Competing interests
The authors declare no competing interests.

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Publisher's Note

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