American Journal of Energy Research, 2023, Vol. 11, No. 1, 1-14
Available online at http://pubs.sciepub.com/ajer/11/1/1
Published by Science and Education Publishing
DOI:10.12691/ajer-11-1-1

The Impact of the Electric Vehicle Transition on U.S. Grid Infrastructure and Energy Policy

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Received December 14, 2022; Revised January 22, 2023; Accepted February 02, 2023

Abstract Vehicles have become a necessity to modern life, with ICEVs continuing to dominate the industry. The vast infrastructure surrounding ICEVs allows for reliable transportation. Recently, priorities have shifted to climate change becoming a top agenda. At the same time electric vehicle technology has advanced to emerging into the market at a reasonable price, with increased safety and reliability. Limitations surrounding the deployment of EV technology at market scale, is the capability of the current infrastructure, technology, cost, and the end user assuming technology accountability without incentive. In this study, the impact on electric vehicle technology, the advancement of Lithium-Ion (Li-ion) batteries, and its impact on the grid will be analyzed for use in the United States at a large scale for grid readiness. Three key areas will be examined to bridge the gap between the current state of Li-ion battery EV technology and grid infrastructure and where this technology needs to meet future demand. These areas include understanding the driving factors for the need to change to e-mobility. The second is to identify and examine the roadmap linking Li-ion technology to grid design and recommendation for resolving the negative impact on grid infrastructure. The third is to evaluate the pathway forward in emerging Li-ion battery storage and technology to meet consumer needs. Results of this study show the benefits of transitioning the transportation market from ICEV to EV is considered favorable.

Keywords: *energy, efficiency, sustainability, grid infrastructure, electric vehicles, policy, charging and discharging, internal combustion engine, lithium-ion batteries*

Cite This Article: Alec J. Ernst, Cooper R. Wade, David G. Dyer, Daniel K. Boakye Danquah, and Olusegun S. Tomomewo, "The Impact of the Electric Vehicle Transition on U.S. Grid Infrastructure and Energy Policy." *American Journal of Energy Research*, vol. 11, no. 1 (2023): 1-14. doi: 10.12691/ajer-11-1-1.

1. Introduction

The traditional transportation system that uses an ICEV is one of the contributors to air and environmental pollution. To decarbonize, reduce air pollution and reduce oil dependence in the transportation industry, there has been a dramatic increase in the market adoption of electric vehicles EVs in recent years. Electric vehicles run on battery technology, ultra-capacitors, and fuel cells as energy sources. This lowers the use of fossil fuel and causes no pollution as they operate [1]. To make EVs competitive in the market, several challenges need to be resolved, such as battery cost, efficient charging strategies, integration of the charging stations, and the impact of EV integration to the grid [2].

The future smart grid or the Internet of Energy (IoE) is expected to be more decentralized and disaggregated, which could fundamentally shift the way power has traditionally been generated, transmitted, or distributed. A significant amount of the future power demand will be generated from renewables, and some loads will be mobile, such as electric vehicles, electric boats, and electric ships and electric trains. The current development of electric vehicles' bi-directional energy transfer through vehicle-to-grid (V2G) technology, and their expected penetration in the IoE, brings a promising feasibility to exchange energy between vehicle and grid. The fourth quadrant of energy transfer could potentially bring a benefit in emission reduction and optimal renewable energy integration that present the potential to create some electrical penetration problems on the grid.

Moreover, successful growth of EVs over the last decade relies on the development of international standards and codes, universal infrastructures reforms, software and deep research is ongoing worldwide. Electric charging networks and charging infrastructure impact on the grid is worth a point of review. The objectives of this study are focused on four key areas. The first is to examine and analyze the technology difference between ICEVs and EVs. The second is to examine the cause of the shift from ICEVs to EV mobility. The third, is to examine the impact of electric vehicle penetration on the existing grid infrastructure. The fourth is to examine policies, limitations, and provide recommendations for the development of future electric vehicles EV against ICEVs.

2. Evaluation of Technologies – Internal Combustion Engine & Electric Vehicle

The internal combustion engine is the most common form of propulsion for motor vehicles [3]. Gasoline and diesel engines are the most common type of internal combustion engines. The principles of an internal combustion engine are mixing air and fuel and burning it to create power. Through the years, there have been many different changes in how that air and fuel are mixed and delivered. But the principles are all the same: control how much air enters the engine and mix the right amount of fuel with that air. Since the invention of the engine, until roughly the mid-1980s, almost every vehicle on the road used a carburetor. In order to transition fully, one must understand the current state and determine if the transition is feasible and a good investment of time, resources and capital. Table 1 presents key process indicators that should be considered.

Table 1. Key Metrics, Transition from Internal Combustion Engine to Battery Electric Vehicles [4-16]

Internal Combustion Engine Vehicles		Battery Electric Vehicles	
# of Active ICE Vehicles in the U.S.	284,000,000	# of Active Electric Vehicles in the U.S.	284,000,000
Average total gallons per Day Consumed	369,000,000	Average total kWh per Day Consumed	2,530,285,714
Average gallons per fill up	9.5	Average kWH per fill up (at 80%)	53.5
Average miles driven per day per vehicle	32	Average miles driven per day per vehicle	32
Average MPG per ICE vehicle	24	Average M/kWh per ELECTRIC vehicle	3.5
Average time to pump 1 gallon of gas on high setting(minutes)	0.10	Average time to charge per 6.8 kWh (1 gallon in MPG = 6.85 kWH in miles) (minutes)	12
Average price of gas 2022 per gallon	3.21	Average kWh price	0.10
Average range of ICE vehicle in miles	460	Average range of ELECTRIC vehicle in miles	234
Number of Service Stations in the U.S.	145,000	Number of Service Stations in the U.S.	145,000
Number of Filling nozzles total in the U.S.	1,500,000	Number of Charging nozzles total in the U.S.	1,500,000
Number of nozzles per station average	10.34	Number of nozzles per station average	10.34
Average gallons purchased per car per year	489	Average kWH purchased per vehicle per year	3,337
Average distance between gas stations city	3.5	Average distance between gas stations city	3.5
Number of fill ups per day	38,842,105	Number of charges per day	48,547,009
Average time to pump average gallons/day (minutes)	0.02	Average time to charge average kWH consumed/day (minutes)	16
Average price paid petro/ vehicle per day (100% efficiency)	$4.30	Average price paid kWh per vehicle per day (100% MPG efficiency)	$0.91
		Average cost in kWh vs gallon of gas based on 24 mpg	0.69
Gasoline electricity consumption / US gallon refined (kWh/gal)	33	Electricity consumption / US 6.85 kWh = 1 Gallon	6.8
Gasoline electricity consumption / US gallon (TWH year)	4,500	Electricity consumption / US gallon (TWH Year)	924

There are a number of key points from Table 1 that should be considered, when determining if transitioning to an all-electric transportation system makes sense for the United States. These three critical points include infrastructure readiness, stability of the system cost to the consumer. Table 2 examines the positives and negatives to each of these points.

Table 2. Key Focus Points in the Transition from ICEV to EV

Critical Point	Benefits & Concerns
Infrastructure - 100% EV vehicle	Additional stations needed based on current state frequency of fill-ups.
Stability of the system	Increases in facility amount cause an increase in needed power. Utilities would have to be expanded and distributed appropriately. Renewables will help to power the commercial & residential sector. Bi-directional charging needs to be investigated more fully for maximum efficiency.
Cost to the consumer	Current average kWh costs for EV vs ICEV vehicles appear to be favorable by a savings of 75 %. Further research is needed to substantiate the investment costs, based on at-home charging and infrastructure upgrades.

Based on the proof of concept studies displayed in Table 1, the conversion to 100 % e-mobility appears to show favorable in each of the critical areas displayed in Table 2. The feasibility of this transition, however, is delicate and needs to be studied in full by creating a roadmap to the transition that is attainable. Understanding the current state of ICEV vehicles and how the infrastructure created around them will help to further the transition efficiently without critical error and risk to the end consumer.

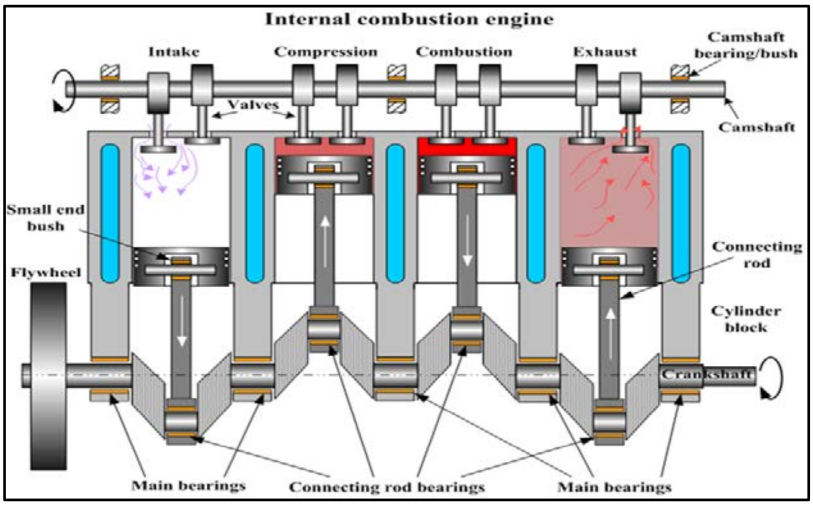

Figure 1. Schematic of internal combustion engine [17]

Table 3. Benefits and Concerns of ICEVs

Benefits	Concerns
ICEV are reliable through research and development advancements.	Continuous operation causes excessive air pollution.
Diesel fuel combustion engines produce less emissions than gasoline [6]	ICEV causes excessive noise, polluting the environment.
Efficient, available, high energy density.	Complex, heavy, requires maintenance, fluids such as oil cause damage to environment

Figure 1 shows the schematic of an internal combustion engine. In simple terms, the internal combustion engine utilizes four key components to operate. These include fuel injection, an ignition source, expansion of the piston, and exhaust. There are many benefits to the technology brought about by years of research and development, efficiency improvements and optimization. There are limitations, however, with concerns that have room for improvement as shown in Table 3.

A simple comparison of vehicle class sizes show that internal combustion engines in mid-sized vehicles create on average, 150.4 g CO_2 eq per kilometer. Comparing many SUV class internal combustion engine vehicles, they create, on average, 269.2 g CO_2 eq per kilometer [18]. This is important as vehicle class will play a key role in the transition and feasibility to alternative vehicles such as EV technology.

3. Cause of Shift from ICEV to EV Mobility

Below are several competing reasons why people are looking for change in mobility.

1. Climate Change: The move to sustain the climate against greenhouse effect as the internal combustion engine vehicles account for a higher percentage of greenhouse effect.
2. Possible End of Fossil Fuels: Petroleum supply is limited, and our demand for them is only increasing. OPEC countries are themselves realizing that their oil production will become unsustainable in a few decades, as little as 3 for some. We see countries like Saudi Arabia, UAE, and Kuwait revealing new roadmaps for creating new sources of income not dependent on oil alone.
3. National Security Issue: Governments are acutely aware that their economies are dependent on sources of petroleum that they do not control. Tensions have been building between countries to manage this overwhelming dependence on oil. The Suppliers of Petroleum productions know this and have tried to take advantage of the situation. The most significant case here would be when in the first few months of COVID, due to the lockdowns, the petroleum requirement went drastically down to the point that OPEC countries were asked by their customers to reduce oil production.
4. Renewable Energy Systems: Almost every country in the world is spending a significant amount of their GDP on developing power generation through renewable sources. Solar power cells have started to become more affordable and efficient. Additionally, as technology matures, we will see cheaper and more efficient systems becoming widely available.
5. Technology Advancements: As technology advances and artificial intelligence becomes more readily available, people try to move from ICEVs to EVs. Industry players are accelerating the speed of automotive technology innovation as they develop new concepts of electric, connected, autonomous, and shared mobility.
6. Regulation: Government and states have mandates, introduction of regulation and incentives to accelerate the shift to sustainable mobility, policy makers are finding more tougher ways to reduce emissions. Beyond such mandates, most governments are also offering EV subsidies, for example in European Cities are working to reduce private vehicle use and congestion by offering greater support for alternative mobility modes like bicycles. Paris announced it will invest more than $300 million to update its bicycle network and convert 50 kilometers of car lanes into bicycle lanes. Many urban areas are also implementing access regulations for cars.

4. Lithium-Ion Battery as Powertrain for Mobility

EVs are set to replace traditional ICEVs in coming decades as auto manufacturer's increase their production of EVs as a part of the global decarbonization, the key differences between ICEVs and the electric vehicles is the propulsion method. ICEVs use fossil fuel combustion to generate power, while the EV uses stored batteries energy. This difference alone affects the overall carbon emission production, with EVs producing far less than ICEVs, even when factoring manufacturing of components and a non-renewable power source. It is for this reason that the transport industry is rapidly shifting towards electrification.

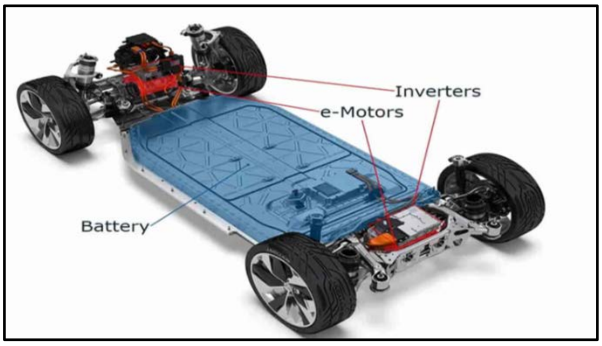

Figure 2. Electric Vehicle Powertrain [19]

The energy storage units within an EV, as shown in Figure 2, are the most important component of the vehicle, they dictate the car's abilities in terms of autonomy and range – two metrics that are based on the battery type and charge level. Lithium-ion batteries are the battery of choice for EVs, and while there are different types of lithium batteries on the electric mobility market, lithium is the critical component that unites them. The average lithium-ion battery system in an electric car has 8 kilos (17lbs) of lithium carbonate [20]. This makes lithium a core component and highlights just how much lithium will be needed to meet current EV demand. The lithium ion as technology of choice operates in a different way to burning hydrocarbons, A battery is made up of an anode, cathode, separator, electrolyte, and two current collectors (positive and negative). The anode and cathode store the lithium. The electrolyte carries positively charged lithium ions from the anode to the cathode and vice versa through the separator. The movement of the lithium ions creates free electrons in the anode which creates a charge at the positive current collector. The electrical current then flows from the current collector through a device to the negative current collector. The separator blocks the flow of electrons inside the battery, continues charging and discharging reduces the electrons strengths over a period of time, thereby reducing the cycle life.

5. Lithium-Ion Battery Technology as the Choice for Drivetrain

There are two main reasons for choosing this battery technology for vehicles.

1. They are the most efficient in their category - Lithium's chemical and physical properties mean that it can store large amounts of energy for its size.
2. They can recharge without losing capacity – these two desirable traits ensure that the alkali metal has a firm grip on the energy storage system market.

Table 4. Electric Vehicle Powertrain [21]

Electric Vehicle	Starting Price ($USD)	Battery (kWh)	EPA Range (Miles)	Weight (Lbs)	Core Efficiency Rating (kWh/Range/Weight)	Wh/mile
Tesla Model S LR	$79,990	100	370	4,850	5.57	270.3
Tesla Model X LR	$84,990	100	325	5,421	5.68	307.7
Tesla Model 3 SR+ RWD	$38,990	50	240	3,627	5.74	208.3
Tesla Model S Performance	$99,990	100	345	4,960	5.84	289.9
Tesla Model X Performance	$104,990	100	305	5,531	5.93	327.9
Tesla Model 3 LR AWD	$47,990	75	310	4,072	5.94	241.9
Tesla Model 3 Performance	$54,990	75	310	4,072	5.94	241.9
Tesla Model Y LR RWD	$48,000	75	300	4,185	5.97	250.0
Tesla Model Y LR Dual	$52,000	75	280	4,479	5.98	267.9
Hyundai Kona	$37,000	64	258	3,715	6.68	248.1
Mercedes EQC	$70,000	80	220	5,346	6.80	363.6
Kia Nero EV	$38,500	64	239	3,854	6.95	267.8
Volvo Polestar 2	$45,000	78	275	4,072	6.97	283.6
Chevy Bolt	$37,000	60	238	3,565	7.07	252.1
Honda Clarity BEV	Lease Only	25.5	89	4,024	7.12	286.5
Renault Zoe	$24,000	41	177	3,236	7.16	231.6
Nissan Leaf 5 plus	$36,500	62	226	3,780	7.26	274.3
Kia Soul EV	$33,950	30	111	3,715	7.28	270.3
Hyundai Ioniz	$30,000	28	124	3,000	7.53	225.8
Fiat 500e	$33,000	24	84	3,750	7.62	285.7
Nio ES8	$65,000	70	165	5,423	7.82	424.2
Porsche Taycan	$90,000	90	250	4,409	8.17	360.0
Rivian R1T	$69,000	105	230	5,586	8.17	456.5
Jaguar I-Pace	$70,000	90	234	4,702	8.18	384.6
Audi e-tron	$75,000	95	204	5,644	8.25	465.7
Xpeng G3	$33,000	47	155	3,494	8.68	303.2
VW e-Golf	$31,595	35.8	119	3,395	8.86	300.8
BMW I3	$44,500	42	153	2,972	9.24	274.5

Breakthroughs in lithium-ion batteries also mean that the capacity and range of EVs is continually increasing, as well as overall charge times – increasing their appeal for both manufacturers and consumers. Research into alternative battery types are still in their infancy, and with investment being poured into expanding current lithium infrastructure, supply chains, and recycling, lithium-ion batteries are certain to play a major role in global low-carbon goals. In Table 4, EVs are compared based on rated efficiency, starting price, weight and other key indicators.

6. Limitations of EV Technology

The global acceptance of EVs is highly dependent on their driving range, flexibility and refueling. Most of the factors are potentially related to the EV charging system. The following factors are the challenges for EV charging.

1. Batteries: The biggest limitation for electric cars right now is battery technology. Batteries are expensive, they have a limited range, and they take a long time to recharge. However, battery technology is improving rapidly, and these limitations are likely to lessen in the coming years.
2. Charging infrastructure: Another big limitation for electric cars is the lack of charging infrastructure. There are very few public charging stations, which makes it difficult to charge an electric car on the go. This is slowly changing, as more and more charging stations are being built, but it is still a significant limitation [22].
3. Cost: Electric cars are still more expensive than internal combustion engines, this is largely due to the cost of batteries, but also because electric cars are still a new technology. As production increases and economies of scale are reached, the cost of electric cars is expected to come down.
4. Range: Electric cars have a limited range compared to internal combustion engines. This is since batteries have a limited energy density. However, range is slowly increasing as battery technology improves.
5. Recharge time: Electric cars take a long time to recharge, which can be a major inconvenience. This is since batteries take a long time to charge. However, recharge times are slowly decreasing as battery technology improves.

7. Charging and Connectivity

According to the control and communication architecture of EV charging systems, EVGI management can be considered based on EV mobility, coordination, and control structure. In terms of coordination, uncoordinated charging means plug-in and charge when needed, which is not suitable for EVGI in the smart grid environment. In terms of mobility, static-based EVGI requires less information from EVs while dynamic-based EVGI needs more EV dynamic information and therefore is more efficient. Both have their advantages and disadvantages. In terms of Control Structure, EVGI management can be mainly classified into centralized and decentralized/distributed structures/algorithms, where static and dynamic mobility characteristics can fall under both centralized and decentralized/distributed structures.

8. Agency Roles in EV Integration

On the electricity infrastructure, there are various agencies that help in the generation and distribution of power to the final consumers. All these agencies play a vital role in the overall resilience of the grid as we migrate into Electric Mobility. These various agencies will be key in operating the EV integration, as displayed in Figure 3.

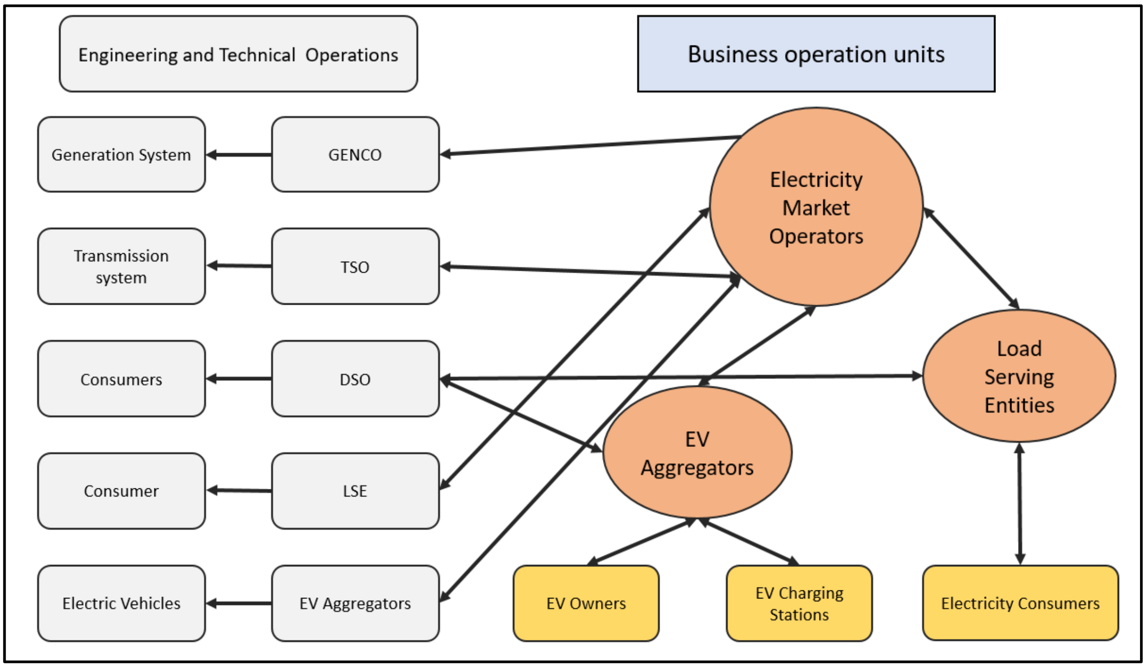

Figure 3. Technical illustration of Agencies for Grid infrastructure-Image produced by Daniel Kelly Danquah.-2023

- GENCO - Responsible for bidding electricity prices into the electricity market and ensures profitable power generation and selling to the energy market.
- LSE - Responsible for selling energy to the end users and supplier or retailer agent procures the electricity for end users and pays DSO the costs for deregulation and other service costs.
- TSO -Takes care of the operation security of the transmission system - Takes care of the system service procurements like operational reserve and frequency regulation.
- DSO - Takes care of the distribution grid. - Ensures a resilient and secured distribution network. - Provides support to the whole system stability and optimization. - Ensures fair and economic distribution network - Facilitates a competitive energy market.
- EV Owner - Represents each EV and provides load demand to charge the EV battery. - determine the ancillary services EVs can provide through V2G.
- EVSA/EV Aggregator - sells the electricity to EV owners - acts like other wholesale agents.
- CPM - Charging point manager acts as the final customer who buys and sells electricity for EV charging/discharging at a charging station.

9. Significance of the Electric Mobility Transition to the Grid

Storage is a key part of an EV as its material types, capacity, and charging durations are closely related to the impact on the grid. The higher the capacity and the quick-charging demand, the more severe its impact on the power grid as it draws more current. Table 5 displays the impact of EVs on the grid.

Table 5. Comparison of impact of electric vehicle on the grid integration

Negative	Positive
1. Stability issues	1. Renewable energy integration support
2. Power loss increase	2. Voltage and frequency regulation
3. Components overloading	3. Power quality improvement
4. Load demand increase	4. Power management
5. Phase and voltage unbalance	5. Black start support

10. Connecting EV Charging Infrastructure to the Grid

As EVs continue to grow in popularity, it becomes prudent to examine the integration of EV charging infrastructure into the electric grid. Analysis of the effects of increased demand and potentially uncontrolled driving/charging patterns must be completed, and the hurdles addressed. However, there also exist opportunities for schemes such as bi-directional charging, providing grid ancillary services, and various behind the meter applications. With careful assessments of electric systems and proper planning, the task of understanding and adding sufficient EV charging infrastructure becomes feasible.

11. Increased Demand

Shifting from conventional to electric transportation will correspond to a significant increase in electrical energy demand. The transportation sector currently accounts for about 28% of all energy use in the United States – 27,162 trillion BTU in 2021 [23]. Most of this transportation energy is in the form of fossil fuel combustion. Shifting this sector from direct fossil fuels to electric power, the grid must be able to handle the additional capacity requirements in all operational areas – generation, transmission, and distribution. Engineering analysis is essential to determine the expected loading of electrical lines and other equipment such as transformers, switches, breakers, etc. If the loading limits on individual components are likely to be violated by implementing EV charging infrastructure, they must be upgraded accordingly to handle the additional demand [23].

Another area of concern is the potential for power quality degradation from the increased EV charging infrastructure demand. Large loads on individual feeder phases can lead to an imbalanced electrical system as well as harmonic distortion [72]. Further, large loads concentrated within an electrical system can lower the voltage available at other points in the system [72]. As EV charging infrastructure is deployed throughout an electrical system, care must be taken to ensure power quality remains high and the system operating parameters, such as voltage and frequency, are always maintained within acceptable limits.

12. Driving/Charging Patterns

Understanding various driving and charging patterns is essential when analyzing the impact of EV charging infrastructure on the grid. Factors such as expected daily mileage, typical charging schedule, charging location, and the types of vehicles (commercial or private) must all be taken into consideration. Time of use varies greatly between commercial and private vehicles. Commercial vehicles are often used throughout the workday while private vehicles are often used during morning and evening commutes as well as during weekends. Commercial vehicle charging can be considered in terms of Return-to-Base or Public Charging models, while private vehicle charging models tend to focus on time and duration of use – both residential and while parked at a work location [24,25,26,27]. By analyzing the various vehicle usage patterns, predictions can be made regarding how much EV penetration the current electric grid can absorb and the upgrades that will be required to make the transition to electric vehicle mobility.

13. Opportunities with EV Connection to the Grid

The requirement to increase the integration of EV charging infrastructure and, by extension, the number of EVs connected to the grid has potential for multiple opportunities apart from cleaner transportation. Bi-directional charging and vehicle to grid (V2G) technologies allows EVs connected to the grid to be used in a variety of ancillary support services as well as behind the meter applications for individual customer energy resilience and management [28]. These opportunities should be considered when analyzing the costs of upgrading electric systems to accept EVs, as they have significant tangible benefits to both utilities and EV owners.

EV battery storage systems can provide required ancillary services for the electric grid. These services include operational and contingency reserves, voltage and frequency regulation, load shifting, and renewable energy support and balancing [29,30]. Not only are these services necessary to keep the electric system stable and reliable, but they also have economic value to utilities – providing a potential financial incentive for EV owners to participate in these services. As the ability to connect EVs to the grid increases, so does the opportunity for aggregate, grid scale energy storage.

Both commercial and residential EV owners can benefit from behind the meter applications, turning their EVs into valuable energy resilience and management assets. For example, the Ford F-150 Lightning is currently being marketed with bi-directional charging to act as a backup residential power source [31]. EVs can also be used for demand management, carrying individual homes and buildings during peak power use periods, and recharging during lower use periods. Commercial owners with EV fleets have an opportunity to use V2G technology to offset significant business costs depending on time of use rate structures [24]. These behind the meter applications allow EV owners to better manage their energy usage and provide for their own resilience while also adding the flexibility to lower electric grid connection

14. Electric Vehicle Effects on Existing Grid Infrastructure

The electric grid must undergo significant improvements to meet the needs of future energy use. This includes increased capacity for growing populations, bi-directional power flows, stability measures, and end-of-life replacement of thousands of aging electrical components and conductors. With the transition to electric mobility, a large portion of the energy sector must transition from direct fossil fuel power to electric power. This exacerbates both the need for capacity and the importance of ensuring the electric grid can handle the added demand. As such, we must examine the effect adding sufficient electric vehicle charging infrastructure has on the existing grid infrastructure.

15. Residential Sector

As the penetration of EVs continues to grow, the refueling paradigm will shift from almost exclusively shared infrastructure to include private charging stations as well. As such, utility planners must begin to include private EV charging stations in their demand projections. While commercial chargers are more likely to be in industrial areas with robust grid infrastructure, residential are**as** will likely require upgrades to accommodate typical EV charging patterns [23].

Residential utility planners currently consider factors such as square footage, electric appliances, and the presence of HVAC systems in their demand assessments. For example, San Diego Gas and Electric Company (SDGE) estimates between 1.5 kW and 8.0 kW for homes [32]. This covers a range from 0-3000 ft^2 and apartment units to detached, single family homes. Homes greater than 3000 ft^2 require more in-depth analysis to estimate the higher demand. Assuming homes are typically outfitted with Level 1 or 2 chargers, this means an added electrical demand of between 1.9 to 19.2 kW [33]. When aggregated, residential EV charging has the potential to more than double peak demand.

Many studies have been performed to simulate, model, and predict the effects of EV charging on residential grid infrastructure, and each author predicted a moderate increase in demand capacity [25]. However, most studies predict an increase in demand requiring significant upgrades to residential electric distribution systems [34-39,73]. The major element that appears to influence each of these studies is simultaneous vehicle charging and peak power demand, as shown in Figure 4. The studies agree that, to minimize the grid impact, charging times should be controlled so they occur during off-peak hours to minimize the electric system impact.

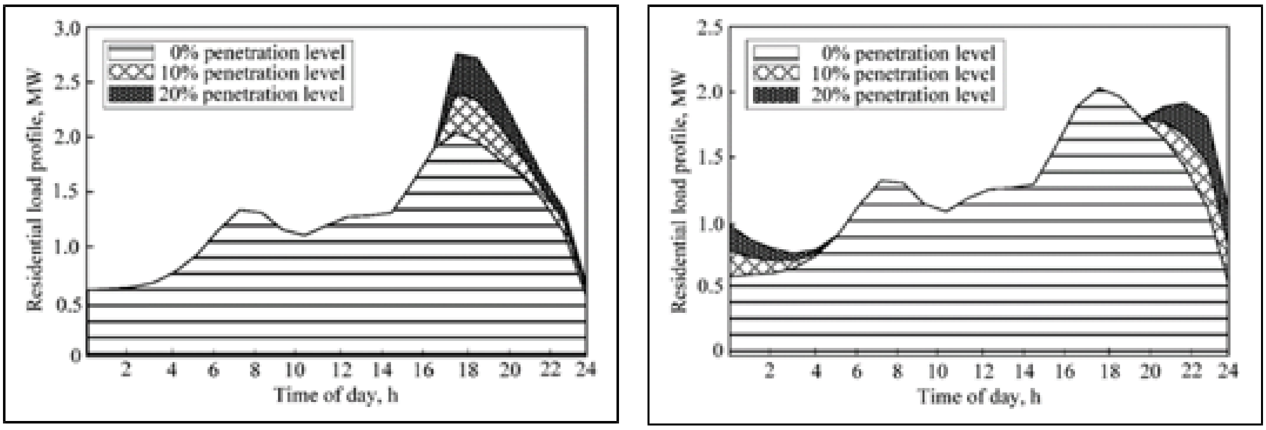

Figure 4. Difference between On-peak vs. Off-peak charging (Residential) [39]

According to U.S. Department of Transportation data, on average, each U.S. driver travels 13,476 miles annually – or 36.9 miles per day [40]. Assuming 0.35 kWh/mile, this equates to an energy usage of 12.9 kWh/day. If a Level 2 residential charging station rated at 7.2 kW (AFDC, 2022) is used, this requires approximately 1.8 hours/day of charging per driver [33,34]. Since most residential demand profiles peak between 5pm and 8pm, if EVs begin charging when drivers return home in the evening, the peak is exacerbated. However, if charging is set to occur between 9pm and 6am, the grid is much better prepared to meet this demand.

16. Commercial Sector

Commercial EV charging can be broken down into two categories based on their usage patterns – return-to-base models and models relying on public charging infrastructure [24]. Return-to-base models are those in which commercial EV fleets have dedicated private charging infrastructure at their facilities. Public charging models are those in which commercial EVs would need to have access to publicly available charging stations along their routes. These public charging scenarios could include lengthy local delivery routes as well as long-haul trucking. Each category of commercial EV charging has unique obstacles to overcome.

Return-to-base charging models face the following challenging issues:

1. Upgrading of electric power infrastructure
2. Peak demand electricity charges
3. Operational conditions of the business and facilities
4. Deterioration of battery health [24].

The relatively large size of commercial EV batteries and potential large number of vehicles in a commercial fleet would likely necessitate capacity upgrades to electrical infrastructure, potentially at multiple distribution levels, to deliver the required capacity to a single, private facility [41,42]. Since some utilities have peak demand charges for the highest demand for any given period during a billing cycle, uncontrolled charging of large loads could coincide with peak facility base load. This could result in significant excess costs via both utility bills and capacity upgrades for facilities using the same commercial rate for both the building and charging infrastructure [41].

As facilities control operational conditions, this could have impacts on the demand profile for vehicles as well as the infrastructure required to sufficiently charge all vehicles regularly [43,44]. To meet demanding driving schedules, vehicles could be required to charge at higher power, maintain a higher state of charge, and be subject to deep discharges – each of which could lead to the deterioration of battery health [45]. Addressing these challenges for the return-to-base model, commercial facilities should analyze proposed systems and work with utilities to ensure any EV additions have adequate electrical capacity. Operations management should also optimize the charging patterns of the on-site vehicle fleet.

Public charging models for commercial EVs face their own challenging issues – 1. Daily operational schedules; 2. Charging costs at public charging stations; 3. Utilization rates of public charging stations; and 4. Stability limits of the grid system [24]. Commercial EVs often must adhere to strict daily operational schedules. As such, public charging infrastructure should be accessible at times and locations conducive to keeping such a schedule – e.g., located at or around destinations, daily parking places, or fast chargers along major transportation corridors [41,46,47]. Time of use tariffs are often tools to incentivize EV drivers to charge at off-peak times. However, commercial EVs do not have the same operational flexibility, leading to paying much higher costs at public charging stations and potentially adding large electrical demand during peak hours [41,46].

Utilization rate, or the kWh per unit time, that public charging infrastructure achieves directly relates to the economic feasibility of such a charger existing. Therefore, in areas where utilization rates may be low, access to public charging infrastructure could be severely limited [47,49]. Like residential charging infrastructure, stability limits on the grid must be considered, and upgrades made, to support large commercial EV electrical loading at available charging stations [50]. Tackling these challenges for the public charging model, chargers should be located along commercial EV routes with sufficient capacity to handle planned stops from multiple commercial entities simultaneously. This will likely require significant electrical infrastructure upgrades, especially along high-traffic corridors where Level 3 chargers must be more prevalent to serve the larger commercial EV volume and operational schedule needs.

17. Electric Vehicle Policy

Decarbonization of any industry is a topic of growing concern and therefore interest. This effort has been largely influenced and driven through consumer interest, and soon followed by governmental entities around the world. This pressure from regulatory bodies and consumers has forced corporations around the globe to respond by adapting their supply chains, operating procedures, and overall consumer behavior. This effort has been largely motivated through industry research and government supported projects conducted to assist in realizing the public health and policy benefits that a cleaner atmosphere brings for both current and future generations. Therefore, the turn of the 20th Century has yielded vast amounts of policy proposals regarding environmentally friendly technologies across all sectors.

The United States has been among a small group of pioneering nations to recognize the need to decarbonize the transportation sector. During the past two decades, the globe has seen rapid deployment of wind and solar renewable resources to assist in the decarbonization of the electric grid. With these developments, energy storage in the form of electric energy batteries have seen equally as rapid developments with more progress anticipated to come, some experts estimating growth by 15 times from 2022 to 2030 [51]. These developments in energy storage for grid applications have yielded traversed benefits into the electric vehicle industry that have assisted in lowering EV production costs, increased battery efficiencies, and improved safety features on energy storage components [52]. All of these variables combined have contributed to the economic feasibility of purchasing EVs for the average vehicle purchaser.

Policy surrounding electric vehicles in the United States consists of largely three categories which are public policy, incentivized policy, and integration policy. Each policy category has their own unique set of goals that they seek to achieve based upon the jurisdictional authority and local goals. In the United States, the structure of energy policy consists of a complex structure of federal, regional, state and local entities that adapt policy based on their respective jurisdictions. Each policy category mentioned previously has a slightly different regulatory and policy structure revolving around EVs that changes based upon who is impacted. Each independent policy structure will be evaluated independently in the following sections. Bearing in mind, the policy issues explored surrounding EVs in the U.S. can also be seen ongoing similarly in countries around the globe as countries assess the growing need to adapt.

18. Public Policy

Public policy has long been the driver for renewable energy and has likewise transitioned the same motivation and interest towards EVs. Public policy is a set of regulations or laws that are designed to benefit public interest [53]. EVs have gained notoriety due to their acclaimed contribution towards public policy benefits. The U.S. Department of Transportation attributes EVs with the contribution of decarbonization via the mitigated burning of fossil fuels, which therefore do not contribute to climate change, global warming, and air pollution [54]. These mitigated effects of EVs as compared to traditional internal combustion engine vehicles directly contribute to improved public health benefits [54]. This alone is a large supporter of EVs from the perspective of lawmakers and representatives tasked with maintaining their constituents' best interests when making laws and regulations.

With public interest as the major contributor towards EV development and adoption, the U.S. among other nations have begun to set ambitious public policies surrounding the technology. As of 2021, the U.S. consumed 37% of all available energy (not including losses during conversion) for use by the transportation sector [56]. As shown in Figure 5, 94% of the transportation sector is fueled from petroleum based resources, 4% is fueled through renewable or alternative green fuels, and less than 1% is fueled by electric energy [56]. Realizing this, the federal government has decided to begin determining methods to decarbonize the transportation sector. The most likely contender for this presents an opportunity for EVs to position for rapid growth in coming years.

Through the recognition of the need to decarbonize the transportation sector, the U.S. has set some ambitious goals as a part of their public policy initiatives. Regarding policy structure, public policy consists of state and federal policies depending upon what the constituent bodies support for the respective jurisdictions. In 2022, the Biden Administration announced their aggressive transportation electrification plan, which targets achieving half of all new vehicle sales to be EVs by 2030 as well as implementing 500,000 EV chargers to support this goal [56]. Individual states have also begun setting goals for EV adoption such as California and New York leading the most ambitious efforts. In 2021, the state of New York set a goal for 20% of all vehicles to be EVs by 2030 subsequently vowing to support this through implementing over 10,000 EV chargers to support growth as well as setting the goal for all new vehicles to be zero-emission vehicles by 2035 [57]. Similarly in 2022, the state of California approved a policy led by the California Air Resources Board to set a goal of having all new car sales be 100% zero-emission vehicles by 2030, which is primarily supported through EV adoption [58]. From public benefit alone, it can be recognized that EVs are being relied on as a primary method to decarbonize the transportation sector, and now that goals are being set subsequent policy needs to be implemented that encourages the achievement of those goals.

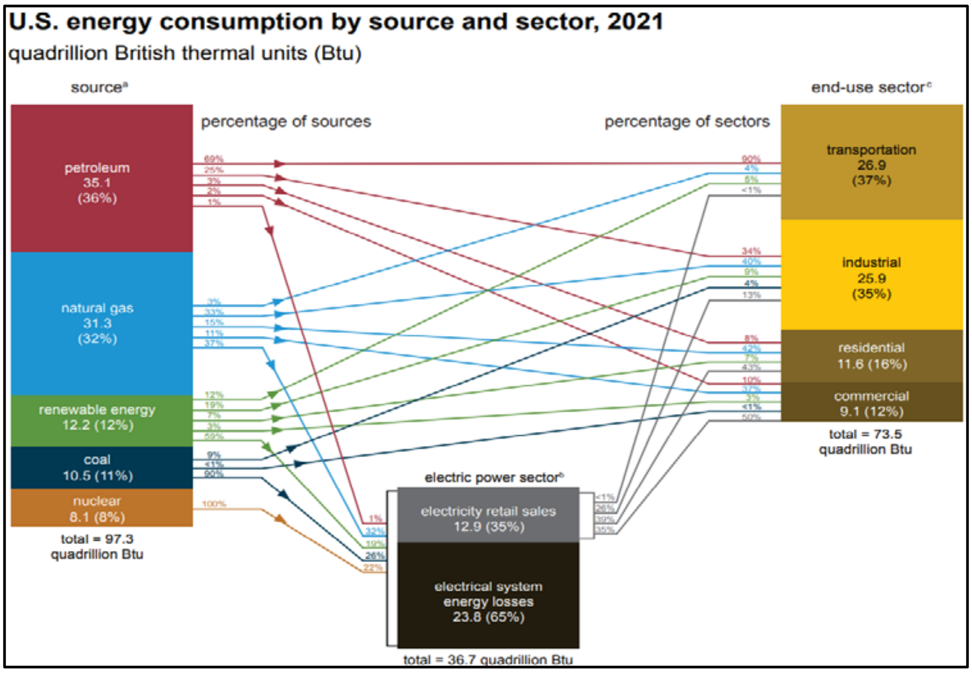

Figure 5. Consumption of energy in the U.S. by source and sector in 2021 [55]

19. Incentivized Policy

Private industry has utilized incentives to manipulate consumer behavior since the 1920's and the U.S. government, whether it be state or federal levels, have begun providing incentives to drive consumer behavior [59]. Some legal researchers have traced energy subsidies from the U.S. government back to the earliest accounts in 1789 shortly after the country's Independence in 1776 [60]. Nevertheless, this strategy has long been prevalent in the energy industry and can be popularly recognized since the beginning of the 21st Century through renewable energy incentives. In 2017, an evaluation was performed that found that the U.S. has provided energy incentives of over $1 trillion from 1950-2016, thus indicating the level of importance of the industry with regards to national security and public prosperity [61]. These revolutionary incentive models began as Investment Tax Credits, Production Tax Credits, Bonus Depreciation, Rebates, etc. and have evolved rapidly to begin influencing the EV market. These forms of incentives are intended to financially motivate early adopters to purchase these new technologies such as EVs. In early cases, EVs weren't cost competitive when compared to traditional combustion engine vehicles, and therefore the government stepped in to assist new vehicle owners through easing the costs of purchasing an EV.

Currently, EV incentive policy consists of state and federal programs that provide benefits for manufacturing, purchasing, and EV chargers. In 2022, the largest infrastructure funding plan in the U.S. was enacted through approval of the Inflation Reduction Act [62]. This federal law package provided mutual manufacturing and consumer incentives for zero-emission vehicles. This act established the Clean Vehicle Credit, which modifies the previous IRC 30D: Qualified Plug-in Electric Drive Motor Vehicle Credit, to provide consumers with a tax credit of up to $7,500 per zero-emission vehicle purchased in 2023 and after [63,64]. Subsequently, to qualify for this credit the vehicle must have final assembly performed in the U.S., which also supports the U.S. economy through manufacturing [65].

From a state level perspective, every state currently has incentives for either incentives applied towards purchasing a zero-emission vehicle or funding for installing chargers at homes, businesses, and public places. Colorado currently has the most valuable incentives for purchasing a new zero-emission vehicle by providing up to $10,000 in the form of rebates [66]. Regarding EV chargers, in 2021 the state of New York passed the Infrastructure Investment and Jobs Act which provided $175 million in funding for long distance EV charging infrastructure [67]. It is evident from these examples that when combining state and federal incentives for EV charging as well as EV purchasing, the endeavor could be potentially more rewarding than driving an internal combustion engine vehicle when it comes to the decision to purchase.

20. Integration Policy

The United States' energy industry is managed through a complex hierarchy led by the Department of Energy and then flowing down the local distribution electric utilities as shown in Figure 6 [68]. The Department of Energy utilizes the Federal Energy Regulatory Commission alongside the North American Electric Reliability Corporation to develop standards that the industry must follow.

The hierarchy displayed in Figure 6 flows down to the regional authority consisting of regional transmission operators and independent system operators that are more tuned to the needs of their regional transmission and distribution utilities. At the local level, 35 states have public utility commissions that regulate distribution utilities and the method for integrating resources into the grid. This structure is what develops, adapts, and enforces technology integration that operates in tandem with the grid.

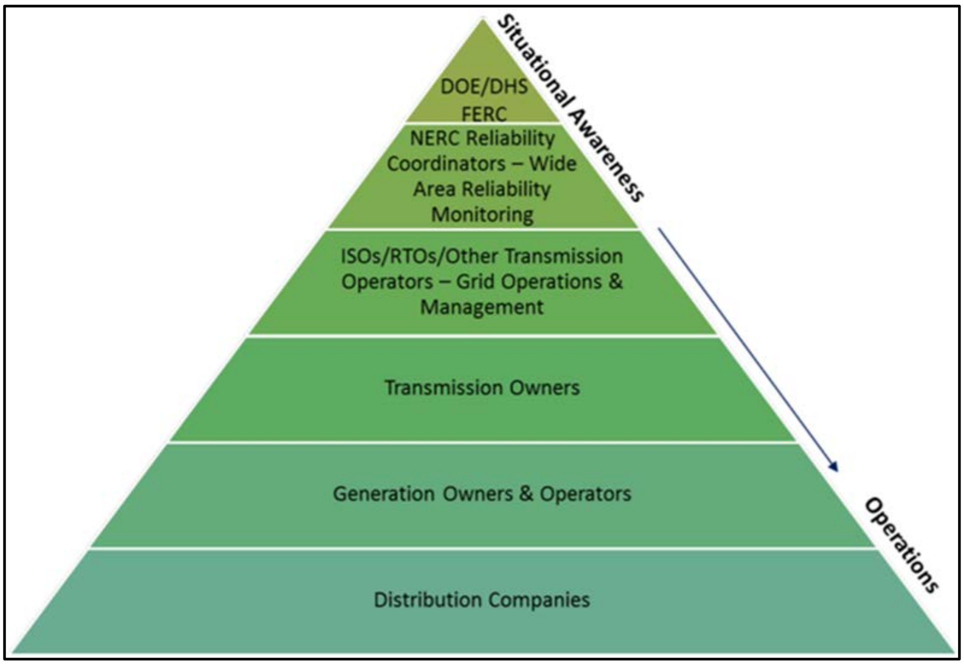

Figure 6. The hierarchy of Jurisdictional Authority of the U.S. energy industry [68]

At this point, electric vehicles are primarily viewed as consumers of energy, however, there are discussions ongoing that are exploring grid interactive functionality. Electric vehicles have a significant amount of energy storage currently available within them, and automakers as well as utilities are evaluating the feasibility of utilizing these mobile batteries to relieve the grid in times of need. On average, an EV contains an energy storage capacity of about 60 kWh which is enough to power the average American home for two days [69]. During the past 10 years annual car sales have been between 14.4 million and 17.4 million vehicles, if the Biden Administration's goals of having half of all new car sales by 2030 being EVs then that results in an additional amount of energy storage ranging from 432,000,000 kWh – 522,000,000 kWh each year [70].

This thought exercise helps everyone to realize the resources being deployed around the country that could be utilized to benefit the American electric grid. The challenge here is figuring out a standard for providing the electric utilities access to stored energy within EVs at the time of need, ensuring grid reliability and user safety, providing vehicle owner's compensation, and ensuring that vehicles still maintain a state of charge for their owners. These resources as they grow in saturation are currently being looked at as to how to implement the technology needed for EVs to back feed to the grid when needed. Changes needed to accommodate this operational ability are potential changes to National Electric Code regarding EVs since they currently do not fall under this code. This could also result in UL listings developed specifically for EVs designed to back feed to the grid. From a strictly policy perspective rather than standards, the federal government will be the first to set a standard defining this process and the necessary tolerances. As discussed previously and shown in Figure 3, the process will continue downward to the local jurisdictional levels to adapt the solution to the localized need.

There is no question that EVs present the potential to be a vital resource to support grid reliability as needed, but they also present challenges due to the increase in demand that they introduce to the electric grid. This transition is not to be taken lightly, because an entire transportation industry becoming electrified to any substantial degree is going to present a significant burden on the electric grid that needs to be mitigated. This is a significant amount of load that wasn't present on the grid before that is now rapidly increasing its presence. The challenges this presents is the need for improved transmission and distribution infrastructure to handle this amount of load that based on behavioral patterns is likely to occur during two short timeframes during each day.

In an effort to address the ongoing transmission capacity challenges anticipated, the Inflation Reduction Act of 2022 included approximately $2.9 billion in funding for transmission improvements to support EVs and renewable energy implementation [71]. From a distribution standpoint, this responsibility largely is delegated to electric utilities and state Public Utility Commissions to determine. Typically, distribution improvements such as upsizing conductors, breakers, transformers, or adding additional circuits and the associated costs therein are borne by the rate payers of the respective utilities.

To mitigate the amount of improvements and subsequent costs imposed, state regulators and utilities are proposing alternatives to help ease the financial burden of the infrastructure improvements. The most progressive methods currently considered throughout the U.S. involve time-of-use rates that financially motivate consumers to charge and potentially discharge during certain periods in order to maintain lower costs. Other methods include load controls that allow the utility to adjust consumer demand in order to benefit the network. In either manner, integration standards are still being developed and considered as we are still in the early stages, but nevertheless this is how regulators and utilities should be thinking as this develops further.

Energy policy is complex and requires constant adjustment as technology changes and the need to adapt over time. The U.S. is currently pursuing ambitious public policy and incentive policy regarding zero-emission vehicles. The areas that need further development are the integration policies surrounding the potential to back feed the grid or buildings such as a home or business. The three categories that need to be coordinated for this to occur are:

1) Grid-EV interconnection via chargers
2) Charge-discharge compensation
3) Vehicle safety & operational standards
4) Controls allowing utilities to access stored energy.

If solutions can be found that coordinate between different makes and models of vehicles to safely allow grid integration, then the demand response capability of EVs could be significant and help ease grid stress due to charging and discharging.

21. Recommendations

Based upon current trends in technology, policy, and pricing, EVs are anticipated to increase in saturation in the coming years around the globe. Some issues that are expected to occur due to the rapid saturation of EVs are the increased loading during specific time frames, power quality fluctuations, and capacity constraints. Policy and regulation will have to address these operational issues and in turn recognize these EVs as grid assets rather than as end users. In this manner, utilities and consumers can benefit each other through fair and equitable policy set in place for mutual benefit. Recommendations based upon the review of current technology, integration methods, and policies are listed as the following:

- Utilities should include EV charging demand into capacity planning for both residential and commercial areas of the grid.
- Utilities should account for increased charging capacity needs along high traffic corridors.
- Utilities should investigate the opportunities arising from EVs as energy storage assets in the larger electric grid.
- Local and regional policy makers should create mutually beneficial rate schedules or compensation methods between EVs owners and utilities
- Regional grid operators should develop transmission expansion plans to stay ahead of capacity from consumer demand anticipated

- Regional grid operators develop operational standards for EV charging and back-feeding methods

From the list of recommendations above, it is evident that the areas needing the most development are the integration and operational aspects of EVs. This requires attention and collaboration from policy makers, grid operators, utilities, and EV manufacturers to develop operational standards to better benefit all stakeholders. At this point goals have been set and funding has been allocated for the development of the EV industry, but the integration standards need further development. Progress in this area needs to occur in a timely fashion, because it takes a significant amount of time to expand grid capacities and EVs are increasing in adoption at an increasing rate.

22. Conclusion

In this paper, we have examined the technology transition from ICEVs to electric EVs and the effects of this transition on both the U.S. electric grid and energy policy in key areas. First, we have constructed the framework through which to view the transition – establishing key metrics for evaluating and comparing fossil fuel powered vehicles to those powered by lithium-ion batteries, today's dominant EV power technology. We then examined the technical impact of a private and commercial EV transition to the electric grid. Next, we have analyzed the effects of the transition on the development of public and incentivized energy policy as well as discussing the path in developing crucial EV integration policy. Finally, we have made recommendations based on the impacts of the EV transition to the grid.

The EV transition will have serious implications on electric grid infrastructure. Shifting the vast demand currently served by the fossil fuel transportation industry to the electric grid will require careful planning in both residential and commercial areas of the grid. Most residential areas will probably require component capacity upgrades to accommodate a shift in the vehicle refueling paradigm from external fuel stations to home charging – which will increase the average home's energy demand considerably. While commercial areas may also require capacity upgrades to accommodate large EV fleets, these customers are typically located in areas designed for larger power consumption profiles. Both residential and commercial users will likely require a shift in charging operations to intervals of lower demand (e.g., overnight charging) to mitigate exacerbation of peak load. However, both types of users could also potentially benefit from demand response and resiliency aspects of EVs as energy storage assets. The greatest changes to accommodate the shift to EV mobility will likely be an increase in distribution component capacity in residential areas as well as high traffic corridors to adapt to the high demand of simultaneous EV charging.

The single largest energy transition that has been seen on Earth is occurring through the implementation of electric vehicles. The electric industry contains complex regulatory, policies, and standards that are intended to ensure safety, reliability, efficiency, and affordability for all Americans. Policies govern the rate at which EVs are adopted as a technology in America, and the federal government has established environmental goals, manufacturing incentives, infrastructure incentives, and consumer incentives to support this transition. The next step is to work with grid operators, utilities, and manufacturers to develop policies and compensation structures that fairly compensate EV owners while providing grid benefits to all involved. In this scenario, it will take a collaborative effort from all stakeholders to develop necessary technology, rate schedules, and safety standards to effectively usher in the new EV infrastructure. This is the current bottleneck for the industry to mitigate as the grid load is expected to increase at a significant rate during the next 3 decades. Policy will govern the adoption rate of EVs and it is critical for the Federal Energy Regulatory Commission to provide integration guidance soon, so that state level regulators and utilities have time to enact procedures that benefit the local networks.

The transition to EVs and away from fossil fuel powered transportation is a necessary step in decarbonization and mitigating the impacts of climate change. However, this will have a major impact on electric grid infrastructure. By taking EV infrastructure requirements into engineering and policy decisions, we can ensure the transition is not hindered by our inability to adapt our existing systems.

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Competing Interests

The Authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study, conception and design, material preparation, data collection and analysis. Together, the authors constructed the first draft of the manuscript and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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