Electric Vehicle Infrastructure

Public Policy Recommendations for Electric Transportation

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ABSTRACT

The most salient feature of today’s research in transportation infrastructure is the drive for viable fuel alternatives to fossil fuels. From a wide variety of possible fuels, petroleum still dominates the market for all terrestrial vehicles and its market fluctuations have had vast societal implications. The most viable alternative fuel vehicles that have been developed and put into production are the plug-in hybrid and fully electric vehicles. The scope of this document involves the prospective shift in transportation infrastructure from petroleum refining and distribution to electricity generation and transmission. While the multitude of electric vehicles being used for personal transportation still hold a very small share of the market, this may not always be the case. The consequences of a large scale shift from petroleum to electricity are closely examined in terms of technological barriers, public policy, and economic impact. The current trend of promoting electric vehicle sales and manufacturing without promoting electric vehicle infrastructure in equal measure will lead to underprepared communities and negative impacts that are shared amongst businesses and residences in the United States.

PREFACE

The debate over the need for alternative fuels precludes any useful analysis of a shift in transportation infrastructure. Current socio-economic and political issues notwithstanding, the electric vehicle has arrived on the streets of many industrialized nations. It is not the intended purpose of this document to offer any argument for or against the use of electric vehicles.

To limit the inclusion of dubious contention in the professional interests of transportation infrastructure, the following issues pertaining to plug-in hybrid and electric vehicles will not be offered for analysis:

- **Electric Motor Efficiency**: The motors used in production electric vehicles are vastly more energy efficient than internal combustion engines by any scientific measure or standard. Other considerations of efficiency will be examined later in the text.
- **Environmental Superiority**: Inquiries as to whether electric motors are better for the environment than internal combustion engines can be obviated by the fact that electric vehicles can be powered by a variety of fuels environmentally friendly or not; whereas today’s internal combustion engines can only run on petroleum or less than ubiquitous ethanol resources. Environmental issues in regards to electricity generating fuel sources will be discussed further, but as many studies have shown, electric vehicles reduce transportation greenhouse gasses.
- **Rare Earth Metal Supply**: While certainly relevant to DC electric motors, fully electric vehicles commonly use AC induction motors which require no rare earth material whatsoever, and should not be considered a necessity but a design choice.
- **Safety**: The safety of automobiles in general is beyond the scope of this document. Electric vehicles require safety measures universal among all motor vehicles, however, there are some specific issues that apply specifically towards electric vehicles that will be part of this analysis.

The aforementioned topics tend to distract from the intended subject matter, but the reader is encouraged to study them to gain a full understanding of mass electric vehicle production and use. Furthermore, the qualifying term “electric vehicle” or “EV” for this document is any vehicle that connects to the electric grid to recharge its battery. Hybrid vehicles that do not meet this criteria will be simply called hybrid vehicles.

INTRODUCTION

According to the U.S. Energy Information Administration (EIA), the overall energy consumption from the electric grid of the United States was approximately 38.1
Quadrillion Btu in 2011 [4]. Based on data provided by the EIA for the same year, the energy demand for the transportation sector was 26.7 Quadrillion Btu [4]. In another report by the Department of Energy for 2011, nearly half of that was consumed by light duty vehicles alone. For that year, if all light duty transportation vehicles switched their energy source to the nation’s electric grid, it would require a 35% increase in electricity production and capacity to maintain the same operating conditions for the nation’s grid. The comparison is valid only for appreciation of the scale in which energy demand for transportation use compares to the energy demand of every building, house and industrial facility in the U.S. The more realistic picture for the inclusion of electric vehicles into the U.S. transportation system would require an examination of the disparate transportation needs, as well as the disparate electric power capacities for different areas of the country. For many areas, a 15 to 35% increase in demand would be unsupportable, especially during major weather events. This initial assessment shows that any substantial increase in EV use would also entail an increase in electric energy demand on a scale that would be hard to ignore.

**Figure 1.** An illustration of energy use by source and sector [5].

**Figure 2.** A breakdown of the amount of energy consumed by each mode of transportation [4].

**BACKGROUND**

**HISTORY** - Since the dawn of the internal combustion automobile, the electric vehicle has stood as an alternative for transportation. The late 1800’s automobile was partially used as a novelty for wealthy households, but also as an alternative to another mode of transportation known for its pollution, unreliability, and economic strain: the horse. Before the automobile was used extensively in urban areas such as New York City, the horse was used as a means for both commercial and personal transportation. The city dwelling horses were the cause of what is called in retrospect, horse pollution. Not only was the bodily waste that accumulated in the streets a hive for disease, but when horses were injured and subsequently killed in the streets, the bodies were often left there if the cost of moving the carcass was prohibitive [1]. For those who purchased the first automobiles, the
wealthy owners carried a perception of not only being technologically advanced, but as cleaner than those who had to deal with horses.

For many years the status of the automobile remained mostly as a novelty and status icon for the wealthy, until some key developments occurred. The confluence of assembly line production, the development of infrastructure for cheap petroleum products due to anti-trust laws, and the driving forces of global warfare lead to the internal combustion engine automobile as a dominant mode of transportation.

HISTORY REPEATING - With today’s electric vehicle, another confluence of industrial developments is prospectively leading towards a new, more prevalent mode of transportation: the electric vehicle. As before with early internal combustion vehicles, electric vehicles sold today have a vastly larger market penetration with wealthier households then lower income households and have been widely accepted as environmentally friendlier, or cleaner. Battery technology driven by the computing and electronics industry, legislation and regulation for combating climate change, and the volatile oil market have led to the implementation of a viable mass market electric vehicle. It is likely that as infrastructure develops, electric vehicle use will grow more rapidly.

Infrastructure is not the only driver for establishing electric vehicle use. It can be argued that instability in the oil market has brought about the need for alternatives, starting with hybrid vehicles, which has now led to plug-in hybrids and commercially viable fully electric vehicles. While many are looking to electric vehicles to replace or supplant the internal combustion engine vehicles, the practical reality will likely lead towards a large scale hybrid transportation infrastructure. Given the arbitrary nature of energy and energy use, the demand for one can affect the price of the other (meaning a fluctuating economic advantage between electricity and petroleum based fuels). Similarly to petroleum products, the electricity provided for the nation’s power grid is used for a multitude of industries and personal uses. Once established, a competition between the internal combustion engine and the electric vehicle is likely to last a long time. The more electric vehicles are used for transportation over internal combustion vehicles, the less demand for gasoline and subsequently, crude oil. A lower demand in crude oil will likely lead to a lower, more competitive fuel price, as was seen in the 1990’s. However, investment in EVs may still maintain a competitive edge with consumers due to the stable, domestically and locally regulated pricing of electricity rather than entities such as OPEC. With EVs already on the market as a complete departure from the oil market, another severe oil crisis may drive consumers to purchase more EVs than is commonly projected. The figures below show a correlation with rising gas prices and EV sales, and a historical cost comparison between electricity and gasoline.

Figure 3. This figure highlights the trend of national hybrid and electric vehicle sales increases versus gasoline price increases [2].
THE ELECTRIC VEHICLE

While the number of electric vehicles on the road only number around 200,000, the number has doubled in the past year [21]. The demand for electric vehicles is being driven by a number of state and federal incentive programs to reimburse the buyer through tax credits. In 2011 State of the Union speech, President Obama set a goal for electric vehicle sales to hit the one million mark by 2015 [19]. However, the results have been far short of President Obama’s goal, and it has since been scaled back and revised to include more realistic pursuits to help promote EV sales. There are many reasons as to why the sales of EVs have not met the expectations of proponents, but the lack public infrastructure available to EV owners as compared to owners of vehicles that run on gasoline and diesel fuel seems to be a very limiting factor. Even with a new development in battery technology that increases the capacity in a significant way, the maximum travel distance of EVs will be limited by available public charging stations.

Vehicles that rely on electric drivetrain power have three different basic configurations:

- Hybrid Electric Vehicles – Currently the most popular and widespread in use, standard hybrid electric vehicles do not connect to the electric grid in anyway. Conventional hybrid vehicles use an array of designs which utilize both electric and internal combustion motors. These vehicles take advantage of both the energy storage of internal combustion engines and the efficiency of electric motors.
- Plug-In Hybrid Electric Vehicles – Plug-in hybrid electric vehicles use both conventional petroleum fuels and electricity supplied from the grid.
- Battery or All Electric Vehicles – Battery electric vehicles use only power supplied through the grid and only use electric motors for propulsion.

Despite the general improvements, electric vehicles offer over internal combustion engines, there are two key hindrances to towards widespread use of electric vehicles beyond a lack of infrastructure.

COST – Electric vehicles are still prohibitively expensive for many car buyers. This is largely due to the significant costs of the latest battery technologies and the current lack of demand to enable larger bulk purchases for manufacturers. The battery alone can account for a third of an electric vehicle’s cost [16]. In 2012, McKinsey & Company did a study on the parameters of electric vehicle competitiveness. Their conclusions suggest that a slower decline in battery prices and increases in gasoline prices will favor the development of plug-in hybrid vehicles, whereas a quick decline in battery prices and flat or rising gasoline prices favor the development of battery electric vehicles [17].

Figure 4. A comparison between gasoline prices and electricity prices in a vehicular context, adjusted for inflation [58].
According to research done by the Boston Consulting Group, the ideal competitive battery price of $250 per kWh will not be reached by 2020 [22]. However, their findings through working with battery manufacturers, national labs such as Argonne National Laboratory, and academia revealed that a steep decline, as high as 65%, is still to be expected by 2020. This will be mainly as a function of increased experience, streamlined production and a greater demand for the batteries. It is also important to note that their projected decrease in cost is a mixture of production-volume-dependent costs and production-volume-independent costs.

BATTERY TECHNOLOGY— One of the most limiting factors to the mass deployment of electric vehicles is the capacity of the batteries used to power them. This limiting factor causes an effect known as “Range Anxiety” amongst prospective consumers of electric vehicles. For electric vehicles to be competitive against internal combustion vehicles, EV batteries must have a greater charge capability and lower cost. The batteries used in electric vehicles are different from the simple lead acid batteries found in most vehicles. The main purpose of the lead acid battery is to turn the electric starter motor of the internal combustion engine. Ironically, the development of the electric starter motor led to the dominance of the internal combustion engine as it no longer required a hand crank [29]. In order for the EV batteries to compete with the energy storage of gasoline, which is 13,000 Wh/kg, conventional lead acid batteries simply cannot compete, with a specific energy of only 35Wh/kg [29]. Today, there are many materials being researched for potential improvement of battery capacity and cost. The figure below details the different weaknesses and strengths of...
different electrochemical materials being used in EV battery production.

![Diagram of different strengths and weaknesses of electrochemical materials](image)

**Figure 7. Diagrams of the different strengths and weaknesses of electrochemical materials. [22].**

**THE GRID**

Alongside the development of the automobile in the U.S., the battle between Thomas Edison’s direct current electric distribution and Nikola Tesla’s alternating current electric distribution was waged. Tesla and George Westinghouse’s hydroelectric facility at Niagara Falls, determined the alternating current infrastructure we use today. In the industry’s infancy, many power grids were maintained locally with no interconnection. Today, nearly all power grids in the United States are interconnected with few exceptions such as Hawaii. The operation and expansion of the nation’s power grid has undergone several paradigm shifts as it has expanded to become more interconnected, but the focus of the industry has consistently been towards reliability.

As an alternative to the petroleum-based infrastructure most common in transportation today, the U.S. electric grid does not lend itself to simple metrics like the price of crude oil. As will be detailed later, the infrastructure and market wrapped around what is often considered a natural monopoly is much more complex and difficult to put in qualitative terms. However, unlike the OPEC-dominated global crude oil market, the price of electric energy in the U.S. is more isolated and determined by domestic policy rather than foreign policy. Electricity is vital to any industrialized nation, and its production and distribution must be reliable for nearly all other infrastructures such as water, communications, and even the petroleum industry to operate. Thus, much of the regulation and legislation pertaining to the electric grid has been towards maintaining reliability and an affordable cost of electricity for industrial, commercial, and residential consumers.

**PHYSICAL STRUCTURE** – One of the key differences between the largely petroleum based energy supply for transportation and the energy supplied by the AC electric grid utilized in the U.S. and abroad is the grid’s inability to store energy within the transmission and distribution network. With modern electric grids, power is generated in direct response with demand, with an emphasis on providing no more and no less than what is needed. When significant unanticipated loads on the grid occur, there is a risk of disruption of service. Conversely, when the demand for electricity is far less than what is generated, energy is lost and providing power becomes uneconomical. An overview of a typical power system in the U.S. is shown in figure 8.
The nation’s electric grid is conventionally composed of several structural levels in which electricity can be generated and transmitted. These levels are defined as the following:

- **Generation** – Electricity is commonly generated using turbines that spin synchronous generators that maintain a constant frequency. Generators are supplied mainly by steam engines which are heated by burning coal, natural gas or nuclear energy. Other sources include hydroelectric dams, wind, and solar panels. The process of operating generators to meet the demands of the grid is called “economic dispatch” or just “dispatch”. All power being supplied to the grid must oscillate at 60 Hz in three phases as shown below in figure 10. Most residential customers use one phase for their needs, but most industrial electric motors use all three phases as shown in figure 6.

- **Transmission Substations**: Using transformers, power can be converted into a high voltage, low current configuration. Transmitting a higher current level causes losses and heat that are undesirable for long distance transmission. Typically voltages are stepped up to greater than 138 kV.

- **Transmission Lines** – To achieve power transmission over long distances, the electricity generated is stepped up to a higher voltage to minimize loss through the long lengths of cable. Often this higher voltage ranges between 138 and 1,150 kilovolts and can handle 50 to 2000 megawatts of power [8]. Many of the long distance transmission lines in the U.S. are connected with different regions of the country in an interconnected mesh as shown in figure 11.
• Distribution Substations – Distribution Substations are the main hubs for power distribution. They are primarily used to step the high voltages used for long distance transmission down to voltages suitable for shorter distances. Substations not only contain transformers, but voltage regulators, reactors, capacitor banks, breakers and reclosers for control of their respective sub-systems. In addition to the largely electromechanical equipment, digital control systems known as SCADA (supervisory control and data acquisition) systems are incorporated to provide precise control from remote locations.

• Feeder Lines and Service Transformers – Unlike the interconnected transmission lines, feeder lines are distributed from the substations in a radial pattern to the end customers. Residential customers are mainly supplied with single phase 240 V lines and smaller commercial/industrial customers are supplied with 240 V three phase lines. Industrial applications are supplied with three phase 480 V lines, but can sometimes larger facilities are fed power directly from transmission lines. Figure 13 shows how residential customers receive one phase of power, whereas industrial customers receive all 3 phases. Because the three phases are split between residences, they are singularly regulated to maintain correct power supply.

Figure 11. The interconnected mesh of transmission lines in the contiguous United States [39].

Figure 12. Basic structures found in a distribution substation [38].

![Typical Distribution Substation](image)

Figure 13. Connections for residential versus industrial applications [40].
• Customer Loads – The end customer, residential or industrial, is provided power from the feeder lines, which is metered by the utility company. An entire power system has peak times of usage and off-peak times of usage, usually closely correlating with day and night times. Utility companies can charge different rates for peak and off-peak times to promote usage that maximizes demand during hours when more power is available. As can be seen in the image below, peak usage for customers varies with seasonal changes but still follows a predictable trend.

OPERATION AND STABILITY – The 60 Hz frequency of AC electricity found throughout the United States and the various voltage levels rated for each stage of transmission and distribution are monitored and maintained to a very precise degree of accuracy. The reason for this is because of the need to maintain a balance between generators supplying the grid and the load currently connected to the grid at any given time.

Generators and the electric grid as a whole operate under conditional stability, meaning the system can be forced towards instability when large changes in operating conditions occur. For the electric grid at all levels, unstable conditions can occur. This can come in the form of faults (sudden rise in demand), or breaker tripping (sudden loss of demand). The conditions for instability change at different levels of power demand, or peak and off-peak times (especially during peak). A consequence of instability can be brownouts (low voltage) or rolling blackouts. A basic analog of conditional stability is shown below:

Figure 14. Differing load profiles during winter and summer months for PJM [37].

Figure 15. This graphic depicts an analog for conditional stability. If the ball is rolled up towards the left to a certain height, it will roll back to a resting position. If it is rolled too far, it will roll back over the hill on the right and never recover. The same is true for power systems that experience faults and breaker trips, only the conditions for an unrecoverable state, or blackout, is determined by the balance of power supply and demand.

There are several devices and control methods used to prevent instability in grid operations at all levels. Load forecasting is essential to maintaining a stable grid system as generators do not turn on and off quickly to provide power to the grid. Based on load forecasting, power suppliers add generation capability in a manner
known as "load following". The process of taking generators on and off line is known as "economic dispatch", or just "dispatch" [25]. It is at this stage that electricity is traded in order to add power to a rising demand. Utilities often operate what are called "spinning reserves" as a contingency for future near term demand. These are generators that are kept running but add little or no power to the current grid demand. Should unstable conditions occur, power systems are designed to shed load and increase power until the system has settled into a stable condition [25].

RELIABILITY EVALUATION - Many utilities use what are called reliability indices to gauge the frequency and duration of service interruptions. These indices are crucial to tracking where improvements in reliability are needed [8]. There are a wide array of indices used by utilities, but described below are the most commonly used forms.

The indices for frequency are as follows:

- **Customer Average Interruption Frequency Index (CAIFI)** – The average number of interruptions experienced by customers who experience one or more interruptions for a period of time.
- **System Average Interruption Frequency Index (SAIFI)** – The average number of interruptions per customer for a period of time.
- **Momentary Average Interruption Frequency Index (MAIFI)** – The average number of momentary interruption per customer for a period of time. The important distinction for this index is the separation of interruptions of smaller duration, usually less than three minutes [8].

The indices for duration are as follows:

- **System Average Interruption Duration Index (SAIDI)** – The average duration of all interruptions per customer for a period of time.
- **Customer Total Average Interruption Duration Index (CTAIDI)** – The average total duration of interruptions among customers who had one or more interruptions for a period of time.

The frequency and duration indices give different aspects of the utilities reliability. The frequency indexes give data on causes and the extent of service interruptions [8]. The duration indices give data on how well the utilities respond to service interruptions [8].

GOVERNMENTAL REGULATION – The nation’s electric grid is regulated at federal, state and local levels. Like the early railroad industry, the electric power industry was considered a natural monopoly in its development during the early twentieth century. This was reasoned because of the high cost of developing infrastructure and the prospective consequences of a competitive environment where households would require several competing power outlets installed. After years of exploitation by private holding companies that would own several public utilities and high power costs for consumers, the Public Utility Holding Company Act of 1935 reigned in holding companies who controlled large regional power monopolies [10]. Because of legislation such as this and the manner in which consumer needs and technical constraints are met, the result is a highly fragmented organizational structure for the grid. However, unlike other energy providing industries, these organizations have a physical interdependency through the grid that cannot be eliminated. As such, the regulatory agencies and nongovernmental organizations must conduct their business using the exact same medium for transmission and distribution, sometimes across state lines.

Federal Energy Regulatory Commission (FERC) - FERC is an independent federal agency and has controls on political party affiliations for its commissioners. All FERC decisions are reviewed through an internal judicial review. To maintain control over the wholesale electricity market and maintain reliability, the commission issues orders for compliance within the utility industries. The commission's regulations can be found under Title 18 Chapter I of the Code of Federal Regulations. The major legislation that details FERC regulation authority are the Federal Power Act, the Natural Gas Act, and the Interstate Commerce Act.

Independent System Operators (ISOs) and Regional Transmission Operators (RTOs) – ISOs and RTOs are independent system operators that regulate the trading markets for electricity and govern the fair use and planning of transmission lines. The two organizations fulfill similar roles to prevent development that creates a disproportionate advantage to utilities that sell electricity to other regions and states. Two-thirds of the nation’s economic activity occurs within the regional confines of ISOs and RTOs [60]. ISOs were developed from FERC order nos. 888 and 889 in 1997, and RTOS were developed from FERC order no. 2000 in 1999.

Independent System Operators:
- Alberta Electric System Operator (AESO)
- California ISO (CAISO)
- Electric Reliability Council of Texas (ERCOT) (also considered an RTO)
- Independent Electricity System Operator (IESO)
- New York ISO (NYISO)

Regional Transmission Operators:
- Midwest Independent Transmission System Operator (MISO)
- ISO New England (ISONE), an RTO despite the ISO in its name
- PJM Interconnection (PJM)
- Southwest Power Pool (SPP), also a Regional Reliability Council
Public Utility Commissions – A Public Utility Commission is a generic term for a number of entities that govern the end use of electric power. These commissions can regulate the use of power in their respective state, district, or city. They operate beyond the regulation of wholesale power exchanges and interstate grid reliability.

NON-GOVERNMENTAL REGULATION – As the fortunes of companies are intertwined with the need for a reliable and secure electric grid, non-governmental organizations fulfill roles suited to provide these needs. The organization that oversees the different regions and balancing authorities (described later) is the North American Reliability Corporation. It is important to note that NERC operates in the United States as well as Canada.

North American Reliability Council (NERC) – NERC was founded in 1968 by representatives of the electric utility industry. Its main purpose is to promote voluntary compliance with protocols developed with regard to transmission lines and bulk power exchange. As described before, this largely concerns reliability and security issues. NERC functions are the Electric Reliability Organization (ERO) for North America and is subject to oversight by FERC. For its purposes, NERC divides the grid for the U.S., Canada, and a small segment of Mexico into four separate interconnections in which eight different Regional Reliability Councils operate. These divisions are shown below in figure 17.

Regional Reliability Entities – The eight Regional Reliability Entities are responsible for mitigating reliability risks and representing statutory concerns specific to their region within NERC. The members to each organization include investor-owned utilities, federal power agencies, rural electric cooperatives, state, municipal, and provincial utilities, independent power producers, power marketers, and end-use customers.

The eight Regional Reliability Entities are as follows:

- Florida Reliability Coordinating Council (FRCC)
- Midwest Reliability Organization (MRO)
- Northeast Power Coordinating Council (NPCC)
- ReliabilityFirst Corporation (RFC)
- SERC Reliability Corporation (SERC)
- Southwest Power Pool, RE (SPP)
- Texas Reliability Entity (TRE)
- Western Electricity Coordinating Council (WECC)

National Association of Regulatory Utility Commissioners (NARUC) – NARUC is a non-profit organization.
composed of state public utility commissioners. The organization is tasked with representing the interests of public utility commissions at the federal level. This entails all three branches of government and can span legal and legislative representation as required.

National Rural Electric Cooperative Association (NRECA) – NRECA is the national service organization for over 900 rural electric cooperatives. Their members provide electricity for 12% of the U.S. population [57]. The member utilities have various functions from power generation, transmission and distribution to data processing.

PUBLIC UTILITY COMPANIES – Public utility companies are businesses that facilitate the operation of critical public infrastructure including electricity among other infrastructures like gas, water, and waste management. Electric power utilities are generally split into three groups: investor-owned, publicly-owned and cooperative. The advantages and disadvantages of private versus public utilities is hotly debated. The figure shown below reveals the mixed results for the consumer in each state.

Publicly Owned Utilities – These utility services are either government owned and regulated. The structure of these utilities are the classic vertically integrated model in which the utility operates and controls all levels of generation, transmission, and distribution.

Investor Owned Utilities – These utility companies are privately owned by investors that compete with other companies for pricing and quality of service. They are still regulated for rate-of-return and can still be controlled by state and federal agencies.

Cooperative Utilities – Cooperative utilities are private, non-profit businesses that are regulated by their customers. They cover the largest area of land mass in the United States, up to 75% [56]. Federal requirements stipulate that cooperative utilities operate at cost and function democratically. The structure of cooperative utilities allows for local economic benefit rather than distant investor profit [56].

CURRENT DEVELOPMENTS – The electric utility industry is currently undergoing both structural and technological changes. Two major developments in the industry are the deregulation of monopolized public utilities, and the implementation of smart grid systems. These two progressions in the industry are not being done through mandatory federal legislation, but as an evolution to expand and improve the services provided by utilities.

Deregulation – Since the passing of the Energy Policy Act of 1992, multiple states have opted to deregulate their public utilities to promote a more competitive market and cheaper prices for consumers. The original intent of the deregulation process was to emulate the benefits seen in the deregulation of the airline industry in conjunction with the belief that monopolies are mandatory for electricity distribution, but not generation. The desired effect of deregulation is to allow customers to choose their own source of generation, but not necessarily transmission and distribution. The figures below show the differences between the conventionally regulated and deregulated power industry models.

Figure 14. A map of the United States showing the mixed results of private versus publicly owned utilities [49].
The results so far for this process have been mixed. The Western Energy Crisis of 2000-2001 is considered to be a failed result of the deregulation process. According to analysis done by FERC after the Western Energy Crisis and the bankruptcy of Enron:

“A number of factors contributed to the Western Energy Crisis of 2000 and 2001. These included: a low rate of generation having been built in California in the preceding years making California dependent on imports of electricity; northwestern drought conditions resulting in lower than expected water runoff for hydropower...
generation; a rupture and subsequent capacity constraints on a major pipeline supplier of natural gas to California markets (California was heavily dependent on gas-fired generation due to state air standards); strong economic growth and thus increased electricity demand throughout the west; and unusually high temperatures coupled with an increase in unplanned plant outages of older plants that were being run to meet increased demand in California. Further, transmission line constraints within California, both for imports and exports of electricity, exacerbated an already marginal situation during this time period. Finally, some energy companies attempted to manipulate wholesale electric and gas markets.”[34]

As a result reserves were diminished to 1.5 percent and required intervention by FERC and the Department of Energy. Due to the need for emergency action and the high prices experienced by consumers, the Western Energy Crisis has stood as the more prominent example of the impact of deregulation, and has had an inhibiting effect on further deregulation beyond the states shown below, despite relative successes in markets for regions such as PJM’s [10]. As the graphic implies, the market for electricity is far from homogenous, with a mix of tightly controlled monopolies to lightly regulated market competition according to each state. The current results as far as consumer price are shown below.

Seismic Shifts in Fuel Sources – The sources of fuel for power generation are being rapidly shifted from coal to natural gas fired plants. Additionally, renewable fuel sources such as solar and wind power are being steadily incorporated into electric grids as cost reductions and technology advancements make them more favorable. These new additions projected for future electricity generation will either contribute no carbon emissions, or substantially less than the emissions of coal fired plants [59].
Smart Grids – The Energy Independence and Security Act of 2007 stipulated multiple initiatives to modernize and improve the nation’s electric infrastructure. The term Smart Grid is a catchphrase for these developments, which largely entail forms of digital communications between loads, meters, and control systems connected throughout the grid. Many of the current control and analysis systems are by no means less intelligent or antiquated, as they do use sophisticated, state of the art programs for power systems.

The law provided that in addition to allocating research funding through the U.S. Department of Energy, the National Institute of Standards and Technology (NIST) is directed to coordinate with organizations such as the Institute of Electrical and Electronics Engineers (IEEE), NERC, and the National Electrical Manufacturers Association (NEMA) to establish interoperability standards for modernized power systems. The work in establishing this new interconnected system is still ongoing. Figure 22 shows an overview of the NIST concept for Smart Grids.

![Figure 22. Overview of the Smart Grid concept according to NIST [47].](image)

**ELECTRIC VEHICLE-GRID INTERFACE**

To any power distribution system, the electric vehicle, with its charger, is just another connected load. To the basic load profile for daily, monthly, or even yearly home use, a well-behaved charging electric vehicle would be distinguishable only in its regular charging time. For many utilities, the charging of electric vehicles at home would be convenient, as they would likely charge during nightly off-peak hours. However, the demand for more electricity can never be without consequence, be it additional strain on physical devices such as transformers or transmission lines, or more hazardous issues such as grid stability during exceptional and unforeseen events.

CHARGING - For EV charging, there are currently available three types of charging methods. Commonly, the different types are referred as Level 1, Level 2, and DC fast charge (sometimes referred to as Level 3). The specifications for each charging level are detailed below:

- **Level 1**: This level of charging requires only NEMA 5-15 120V outlets, commonly found throughout households and industry. Many electric vehicles include a capability for level 1 charging on-board. This level of charging usually demands a maximum of 1.9 kW and charges at a rate of 2 to 5 miles per hour of charging.

- **Level 2**: This level of charging is more broadly defined as it can be used in both a residential and commercial/industrial setting. Level 2 chargers can utilize both single and three phase 220/240V power supplies. A charging station, commonly referred to as EVSE (Electric Vehicle Supply Equipment) is required for this type of charging. This level of charging demands a maximum of 19.2 kW and charges at a rate of 10 to 20 miles per hour of charging.

- **DC Fast Charge (Level 3)**: This type of charging is still being developed to decrease the amount of charging time to the lowest possible for an electric vehicle by supplying the most power possible. The type of connection required for this charger is not found in residential distribution and requires 480-600V industrial transformers to qualify. This level of charging can potentially demand hundreds of kW and typically charges at a rate of 60 to 80 miles per hour of charging but can charge faster with different technologies.

STANDARDS – Standards for EV production vehicles are still being developed from the charger connections to the communications to be used with utility companies. Today there are three different types of connectors used in the U.S. for charging electric vehicles, the SAE J1772, CHAdeMO, and the Tesla Mobile connector. None of the connectors are compatible to each other without the need
for an external adapter for the user to purchase. The currently used charge connectors are the following:

SAE J1772 – This is the international standard most widely accepted by automotive manufacturers and standards organizations in the United States. The maximum power rating for this charger is 240 kW. The SAE J1772 standard dictates more than just the type of connector used, but how entire charging stations are configured. The focus of the standard is to provide a charger that takes not only maximum power transfer efficiency into consideration, but also safety of the user, and proper integration with power grids. Figure 23 shows an image of the connector.

![SAE International](image)

Figure 23. This image shows the SAE 1772 connector and receptacle [52].

CHAdEMo - Abbreviated for “CHArge de Move”, this connector is used mainly by Japanese automotive manufacturers such as Mitsubishi and Nissan. The majority of EV fast charging infrastructure in Japan uses the CHAdEMo charging connector. Below is an image of this connector.

![CHAdEMo connector](image)

Figure 24. This image shows the CHAdEMo connector [52].

Tesla Mobile – Originally a proprietary design for Tesla Motors vehicles, the company has recently announced a transition towards open source licensing of their products. These connectors are found at Tesla Supercharging stations and are rated to transmit power up to 120 kW. Recently, Tesla has offered its charging station technology to open source licensing. Below is an image of this connector.

![Tesla Mobile connector](image)

Figure 25. This figure shows the Tesla Mobile connector [53].

Unlike the competitive market for connectors facilitating audio, video, and general data transfer, the need for a coherent standard in electric vehicle charging is essential to its market viability. An analog to the current situation would be if Ford motor vehicles required a round gas nozzle, and GM vehicles required a hexagon shaped gas nozzle. The common goals of enabling fast, safe and consistent charging can be defeated by requiring adapters in a needless competition that benefits no one in a market that is still trying to establish itself.

WELL-TO-WHEELS EFFICIENCY – While the electric motors used in hybrid and electric vehicles feature a much higher efficiency rate known as tank-to-wheels (TTW) efficiency, the larger picture is not as advantageous. The measure of efficiency known as well-to-wheels (WTW) efficiency takes into account the distribution system of a vehicles energy supply. Figure 26 shows the amounts of energy lost in the U.S. electric grid in quadrillion Btu.
As can be seen in the image, there are substantial energy losses, around 63%, from the conversion of coal, natural gas and nuclear powered heat to electric energy. Because of this inefficiency, which is from the most widely used sources for electric power, fully electric vehicle’s WTW efficiency suffers the most. The manner in which electric vehicles receive power causes some ambiguity towards analysis of energy efficiency as once electricity is produced on the grid, it is indistinguishable amongst
generation sources. However, due to the combination of petroleum production efficiency and electric motor efficiency, the plug-in hybrid shows a clear advantage in this area when charged by power sources with high conversion losses [28]. Electric vehicles powered by clean, renewable sources however, may render energy analysis irrelevant due to the superior environmental impacts.

GRID STABILITY – There are several ways in which unpredictable charging behaviors can affect a power grid. Under ideal conditions, a power grid features a stable frequency, adequate reserve margins for generation, and predictable load behavior. Whether an unexpected large scale level 1 or 2 charging event, or a confluence of mismanaged high power DC charging station events, electric vehicles can pose a serious enough threat towards local grid stability to warrant a closer look at potential stability disruption.

According to a study done by the International Energy Agency, grid stability can become an issue when massive amounts of vehicles charge at levels above 6 kW with no control signaling for load management [54]. For level one charging, there is no control signal often used as this type of charging operates from a normal household power outlet, and charges at a lower power level at approximately 1.9 kW max. Level 2 and DC fast charging (Level 3) pose a different challenge as level 2 chargers and above can exceed 6 kW in power demand. However, they can be manufactured to incorporate communications such as the SAE J2847/1 vehicle to grid communications protocol, which is currently under development. An illustrative detail of this protocol is shown below.

![Diagram of the SAE J2847/1 communications protocol](image)

Figure 28. An illustration of the SAE J2847/1 communications protocol [24].

CHARGE TIMING – Electric vehicles can be helpful or harmful to grid operation depending on the timing of the charging. During peak operation, when utilities increase generation to high levels of power for the increasing customer load, massive amounts of charging vehicles could have a pernicious effect on the grid’s ability to supply power to customers. A study done by Idaho National Laboratory in 2013 as part of the EVProject
revealed the highly variable load profiles for charging stations of different cities in the United States. Of particular note is the profile of DC Fast charging stations versus regular level 2 chargers. Public level 2 charging stations show a pattern of use that occurs during common peak hours for utilities. The different load profiles are shown below.

![Load profile for all DC Fast Charging stations in areas studied by Idaho National Laboratory [30].](image1)

![Load profile for all Public Level 2 chargers in areas studied by Idaho National Laboratory [30].](image2)

While DC fast-charging stations made up a small percentage of the energy consumption in the study, their load profile is independent of peak hours and has considerably sharp spikes in power consumption. As mentioned previously, these sharp differences can have a negative impact on grid stability, but can be mitigated by grid communications and control. As electric vehicles become more prevalent in personal transportation and the demand for faster charging times increase, DC fast chargers may pose more of an operational risk.

**PUBLIC POLICY ISSUES**

The manner in which major legislation on the utility industry gets passed is largely in reaction to a recent disaster, such as the blackouts of 1965, 1977, and 2003. As such, many of the regulatory statutes that give FERC and other agencies authority over the electric utilities are drawn up to prevent past failures. Legislation such as the Energy Independence and Security Act of 2007 can sometimes passed not as a reaction to a past failure, but rather a concern for cybersecurity and energy efficiency.

**GRID RELIABILITY** – There are several studies that indicate that the overall grid of the United States could generate and distribute power for a large portion of light duty vehicles should electrification become rapidly accelerated. An estimate by the Department of Energy estimates that today’s electric grid could power as high 70% of vehicles on the road today without the need to add capacity [11]. However, the status of the overall picture of the electric grid in the United States is not an indication of electric vehicle readiness, nor a lack of any potential threats to grid reliability. This is especially true in states like Texas with considerably lower capacity margins due to changes in infrastructure and vulnerability to extreme weather conditions [12]. In regions such as the New York metropolitan area, reliability becomes an issue with a much higher potential for electric vehicle expansion than more rural areas.
It is important to note that the ERCOT decline in reserve margins is because of their structure of paying for generation only as it appears on the grid. These shortfalls are by their design. While it is important to have an adequate reserve margin, power systems with a high reserve margin can still be overcome by extreme weather events. ERCOT experienced involuntary rotating loadshed events due to extreme weather in 2006 and 2011 when it had 16.4 and 17.5 percent margins respectively [33]. In 1989, the Houston Power and Light Company had to initiate rolling blackouts due to winter weather events affecting production and distribution [33]. While the energy capacity for the overall grid of the United States is relevant to the qualification of the idea of powering electric vehicles, it is not particularly indicative of regional realities. A study done by ConEdison on New York City, which has a unique and sufficiently complex distribution grid, on the impacts of EV adoption for transportation showed a need for Smart Grid charging infrastructure to prevent overloading the city’s distribution grid [13]. As can be seen in the graphic below, different boroughs become overloaded sooner than others, but the entire city has demand that exceeds capacity in both smart charging and non-smart charging scenarios.
Another example is provided by Detroit Edison Energy, which evaluated their distribution grid for the possible impacts of electric vehicle adoption up to 30%. Their analysis showed again, a substantial decrease in overloaded transformers with controlled charging, but not a complete elimination [36].

For both governmental agencies such as FERC and non-governmental organizations such as NERC, a regular status report of grid reliability is mandatory. Along with current conditions, projections are made for future demand and generation margins. As of today there are no regulations requiring data on the impacts electric vehicles are having on the nation’s electric grid. As electric vehicles and electric vehicle infrastructure develops, a new scenario of unpredictable traveling loads will appear on the nation’s electric grid. In areas where electric vehicles travel across state lines, competitive actions between states and utilities may require federal intervention.

CHARGING STATION STATUS AS UTILITY— In several states the status of companies operating electric vehicle charging stations as public utilities is in question. In some states the charging station operator is considered a utility customer and not subject to state utility regulation. In others the operators themselves are considered utility companies and can be directly regulated by the Public Utility Commissions. This developments has wide ranging implications from the establishment of varied compliance standards to economic competitiveness. There are currently only nine states with legislative exemptions for electric vehicle charging stations: California, Colorado, Florida, Hawaii, Illinois, Maryland, Minnesota, Oregon, and Virginia [35].

AGING INFRASTRUCTURE – As demand for power increases year after year, so too does the wear and strain on the nation’s power infrastructure. As of 2013:

- More than 70% of transmission lines and transformers are 25 years or older [24].
- More than 65% of circuit breakers are 25 years or older [24].
- 25-35% of generation and transmission equipment is nearing end of useful life and 8% are already beyond useful life [24].
- As of 2010 51% of generating capacity is aged 30 years or older [14].
Much of the nation’s distribution grids for residents and businesses were planned without consideration towards electric vehicle charging. For infrastructure that is already aging, load increases from electric vehicles will enhance the degradation of aging infrastructure components [27].

PUBLIC POLICY ALTERNATIVES

Many of the public policy initiatives related to electric vehicles being undertaken have a specific focus on promoting the sale of electric vehicles and replacing internal combustion engine vehicles.

There are several federal and state initiatives to promote electric vehicle sales with little consideration towards the health of the nation’s electric grid. Here are some commonly used federal initiatives and their current status:

- **Tax Credits for Consumers**: The Department of Energy offers $7500 for a qualifying electric vehicle purchased after 2010. Only after a manufacturer has reached 200,000 vehicles sold does the tax credit phase out, six quarters after reaching that number. The provision includes no yearly time limit for the future and no limit on cost reduction. For the ten major automotive manufacturers producing electric vehicles in the United States, this tax credit is currently limited by 2,000,000 vehicles which will increase as more manufacturers produce electric vehicles.

- **Tax Credits for Utilities** – None. As more legislation and EPA directives saddle utilities with more costs for investment in emissions reduction, there are no federal benefits offered to utilities that promote and reduce any negative impacts of electric vehicle infrastructure development.

- **Guaranteed Loans** – The Department of Energy provides guaranteed loans through sections 1705 and 1703 of Title XVII of the Energy Policy Act of 2005, as well as through their Advanced Technology Vehicles Manufacturing loan program. None of these programs are specific to electric vehicle infrastructure.

- **Clean Cities Projects** – Since 1993 this program for the U.S. Department of Energy has worked with cities across the United States to reduce the emissions generated for both their power demands and transportation needs. The departments focus is to provide information, build state and local partnerships, and fund projects that promote the use of alternative fuels and electric drive vehicles. Since 1993 they have provided over $366 million dollars in funding towards projects that have leveraged an additional $740 million in matching funds and in-kind contributions from other sources. On Sept. 8, 2011, Energy Secretary Steven Chu announced awards for 16 electric vehicle projects in 24 states and the District of Columbia totaling $8.5 million.

- **Smart Grid Investment Grant (SGIG)** – Authorized by the Energy Independence and Security Act of 2007 and amended in the American Recovery and Reinvestment Act of 2009 to award 4.5 billion dollars to modernize the electric grid. SGIG currently funds 3.4 billion dollars for 99 projects dedicated towards smart grid implementation. A part of the programs focus was towards EV charging controls.

- **California Air Resources Board (CARB) Zero Emissions Vehicle (ZEV) Requirements** – A major public policy consideration for automotive manufacturers is the mandated requirements for automotive manufacturers to produce and deliver a certain percentage of zero-emissions vehicles (i.e. a vehicle that produces zero emissions while being driven). Recently, the ZEV initiative has potential to expand as governors from 7 additional states have signed a memorandum of understanding pledging to take similar action [32]. Below is a detail of the vehicle percentages required:

<table>
<thead>
<tr>
<th>Model Year (MY)</th>
<th>ZEV Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-2011</td>
<td>11%</td>
</tr>
<tr>
<td>2012-2014</td>
<td>12%</td>
</tr>
<tr>
<td>2015-2017</td>
<td>14%</td>
</tr>
</tbody>
</table>

CONCLUSION AND RECOMMENDED ACTIONS

The overall picture of the nation’s infrastructure for electric vehicles is a mix of abundant generation and transmission capacity and distribution networks that are inadequate without revision and modernization. Should the localized and mostly urban distribution grids take no action as electric vehicle use increases, reliability due to electric
vehicle use becomes an issue. However, should state and local governments adopt standards developed to preclude any reliability issues, the expansion of electric vehicle use could potentially have a benign impact on the U.S. electric grid. With federal support for utilities equal to the amount provided to consumers and automotive manufacturers, the United States could achieve a more coherent and balanced adoption of electric vehicles for transportation.

Because of the intensive capital costs for electric infrastructure, the effects of a mismanaged investment in electric vehicle infrastructure can last for a long time. Electricity is the lifeblood of the U.S. economy and adequate consideration should be taken when any dramatic shift in energy use is about to take place. The following public policy options are recommended for the promotion of electric vehicle readiness in the United States. Their respective level of government is indicated in parenthesis.

LOCAL RELIABILITY ASSESSMENT (State and Municipal) – As electric vehicle use becomes more widespread and distribution grids become more loaded with electric vehicle charging, reliability assessments will have to include data on charging behaviors and their impacts on reliability and power quality. The availability of DC fast-charging stations and the predictability of their use should become more well-understood and incorporated in these assessments. The use of vehicle communications data should be mandatory in these assessments. EV adoption in distribution grids and reliability index data such as SAIFI and CAIFI should be reported so as to determine the impacts of EV charging as it becomes more prevalent.

UTILITY INCENTIVE (Federal) – In addition to the federal tax credits given to consumers and guaranteed loans for automotive manufacturers, it is recommended that a similar form of federal aid be established for utilities to develop EV infrastructure. Such a program could alleviate the burden of cost for both utility and consumer. The form of revenue for these initiatives can come in the form of trading any EPA noncompliance penalties for EV infrastructure projects. This allows utilities to invest in a technology that potentially returns on investment rather than a complete loss in revenue due to prospective carbon emissions penalties. In conjunction with smart grid programs, the increase in efficiency could reduce greenhouse gas emissions by increasing efficiency and help take internal combustion vehicles off the road.

INCORPORATE EV INFRASTRUCTURE INTO CURRENT PROGRAMS (State and Federal) – Federal programs such as Clean Cities and any future Smart Grid funding can incorporate projects that make local distribution grids more robust ahead of their EV adoption programs. In order to expand electric vehicle infrastructure, more than charging stations will need to be deployed in areas where demand can exceed capacity faster than other areas. Identifying and focusing on these locations would make for an EV-ready community and a more reliable power supply in general. For future power installations, EV infrastructure should be considered, as the cost of upgrading after the fact exceeds the cost to build [8].

EV RATES (State) – With the use of sub metering on EV chargers, a utility can promote more electric vehicle use by offering lower rates for electric vehicles. The effect would be two fold, in that residents could enjoy lower rates directly, and commercial adopters can increase profit from patrons using their chargers. The second effect would be valid for Public Utility Commissions that don’t deem public EV charging station operators as utilities.

REFERENCES

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ACRONYMS AND ABBREVIATIONS
AC Alternating Current
BTU British Thermal Unit
CHAdEMo CHArge de Move
DC Direct Current
ERCOT Electric Reliability Council of Texas
ESCI Enhanced Serial Communication Interface
EUMD End Use Measurement Device
EV Electric Vehicle
EVSE Electric Vehicle Supply Equipment
FERC Federal Energy Regulatory Commission
kWh kilowatt-hour
NERC North American Electric Reliability Corporation
OPEC Organization of the Petroleum Exporting Countries
PEV Plug-in Electric Vehicle
PJM Pennsylvania-New Jersey-Maryland
TRE Texas Reliability Entity
Wh/kg Watt-hour per kilogram