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Article

Towards an Energy Future with Ubiquitous Electric Vehicles: Barriers and Opportunities

Mohammad Mohammadi [1,†], Jesse Thornburg [1,2,†] and Javad Mohammadi [3,*]

[1] Grid Fruit, LLC, Austin, TX 78758, USA; mmohamm2@andrew.cmu.edu (M.M.); jesse@gridfruit.com (J.T.)
[2] CMU Africa, Carnegie Mellon University Africa, Regional ICT Center of Excellence Building, Plot No A8, Kigali BP 6150, Rwanda
[3] Civil, Architectural and Environmental Engineering Department, University of Texas at Austin, Austin, TX 78712, USA
* Correspondence: javadm@utexas.edu
† These authors contributed equally to this work.

Abstract: The electrification of personal transportation holds great potential for lowering greenhouse gas emissions and reducing climate change. The promise of electric vehicles (EVs) to serve these goals has resulted in a broad range of supporting policies aimed at encouraging widespread EV adoption at both the state and federal levels in the United States and around the world. While the EV revolution and prospects of a world with ubiquitous EVs are impacting various industries and many aspects of daily life, strategic interactions between the power grid and EVs are crucial for a successful energy transition. However, managing the interplay between EVs and the power grid remains a challenge. Motivated by that tension, this paper surveys a variety of solutions, policies, and incentives that are focused on effectively managing EV charging behaviors. The paper's objective is to explore these tools to ensure that EV owners have ultimate control over their personal vehicles while simultaneously allowing the power grid to mitigate adverse network impacts. Furthermore, this paper examines the role of charging infrastructure technology and its strategic placement in facilitating the seamless integration of EVs into the grid. Additionally, the paper highlights financial mechanisms associated with EV integration and discusses the consequences of these mechanisms.

Keywords: electric vehicle; energy transition; smart grid; energy storage; smart charging; power grid

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1. Introduction

Electric vehicles (EVs) are proliferating quickly across the world's largest countries, from Germany to China to the United States (US). The rise of EVs is buoyed by government incentives (e.g., from the Inflation Reduction Act in the US) as well as a growing global focus on sustainability and the reduction of greenhouse gas (GHG) emissions. Increasingly, simple economics are driving the switch from fuel-burning vehicles to EVs. The World Bank found recently that even many developing countries would benefit economically from switching to electric mobility [1,2], and some, like Rwanda, are implementing their own EV incentives [3]. Savings to the EV owner continue through the life of the vehicle, coming not only from the lack of fuel costs (a saving of roughly $9000/vehicle across its life cycle) but also reduced maintenance costs (between $4600 and $5000 saved over the life of the vehicle) [1,4]. The economic benefits of EVs are not reserved for EV buyers and drivers, however. Electrical utilities stand to gain financially from this shift as well, especially if the utilities manage EV charging loads optimally. Electric grids are being affected by the uptick in EV sales and the ensuing power demand of EV chargers. This paper aims to survey options that electrical utilities can pursue to face the new burdens and opportunities created by increasing EV penetration.

While motivated to succeed financially, electrical utilities are obligated to deliver a high-quality service to rate-paying customers, i.e., providing them with frequencyregulated electricity that is reliable [5]. To ensure reliable service at all hours, some US utilities are deploying stationary energy storage, primarily using banks of lithium-ion batteries [6]. When charging and discharging are properly managed, these batteries provide the benefit of on-demand power without reliance on peaking plants burning fossil fuels [7]. The downsides are the high upfront capital cost for these battery banks and their tie to one location after installation. Other energy storage options, like pumped hydropower, also require high capital costs and are stationary. EVs, on the other hand, offer dynamic storage that moves geographically while requiring little capital upfront (at least to purchase physical assets) for the grid itself. Especially in urban areas, the times when many EVs are parked at charging stations roughly adhere to predictable daily patterns (e.g., following EV owners' commutes on weekdays).

Shifting loads in time to smooth (and ideally flatten) the aggregate demand helps utilities avoid blackouts or brownouts and to maintain a reliable service [8,9]. EVs can function as shiftable loads or energy storage for the power grid, but, until now, most utilities have treated EVs as simple loads. When uncoordinated, EVs typically begin charging as soon as they are plugged in. To grids, they constitute an on-demand load in these cases, adding to the demand curve and creating a burden at high-demand times. When their charging is controlled and coordinated according to grid needs, however, EVs can serve as both flexible loads and energy storage.

As small-scale solar photovoltaic (PV) and wind generation are proliferating, the energy supply is becoming increasingly sporadic and variable. As this trend continues, controllable assets are increasingly needed to supplement existing supply and storage [10]. The rapid rise in EV adoption offers such assets and a potential counterbalance to smooth the increasing variability. A growing fleet of networked EVs can be harnessed as controllable energy storage distributed across the power grid when EVs are plugged into chargers.

By contrast, if EVs are left uncoordinated in their charging, they stand to create supply challenges at scale for the electric power grid [11]. This is most likely when many EVs plug into chargers around the same time (e.g., as commuters arrive home after work) or when many EVs disconnect from chargers around the same time while charging. If left unmanaged by grid services, the former scenario would create a spike in power demand and the latter event a sharp drop in demand. These demand shifts can be smoothed with either centralized or decentralized approaches, especially demand response (DR) strategies, to reduce strain on the grid's existing supply and storage infrastructure [12]. Hence, EV and grid interactions are the cornerstone of successful energy transition. This paper aims to provide an overview of these interactions, and it is motivated by the growing presence (and rising impact) of EVs across power grids worldwide. In the following sections, this paper will look from multiple angles at the effect of EVs on transmission and distribution grids, including perspectives on energy resilience and grid operations. The paper will also discuss the resulting infrastructural needs and helpful financial mechanisms for addressing them.

2. Background

2.1. Electric Infrastructure in Transition

The future energy grid will look very different from the traditional multi-entity systems where each entity manages a geographical region. The ongoing movement toward energy democratization and decarbonization is resulting in higher penetration of controllable energy resources. This process, in turn, is increasing the number of grid entities. The paradigm shift is also fueled by increased adoption of intelligent sensors and actuators for advanced processing and computing. While collaboration among entities (agents of the multi-agent energy system) reduces costs and increases overall reliability, effective collaboration is challenging.

The main challenges stem from the computation (e.g., processing power) and communication heterogeneity of agents and the number of agents (i.e., problem scale) when multi-entity energy systems collaborate. Today's power grid relies on sporadic renewable generation, a mix of fossil-fueled and clean power plants, and growing loads, all spread across huge geographical distances. Loads arise at different times of day, as well as changing in many cases based on the season and real-time weather conditions. These loads have different priority levels, ranging from factories' industrial manufacturing equipment to hospitals' life-saving medical machinery [13]. EVs, like battery banks, act like loads at certain times (pulling energy from the grid), while, at other times, act as a supply (discharging to meet demand on the grid). A key challenge is scheduling time-shiftable loads and storage (like plugged-in EVs) to lower dependence on fossil-burning power plants [14]. This is one facet of the larger challenge to meet real-time demand (avoiding brownouts and blackouts) while minimizing emissions and generation costs.

2.2. The EV Variable

A valuable addition to the complex amalgam of renewable energy, stationary storage, and baseload power plants would be multi-agent EV coordination, with optimized charging of many EVs plugged in simultaneously. Charging an EV battery continuously from entirely depleted to fully charged requires a range of times depending on the charger and EV model. Teslas, for example, take 25 to 30 min to charge fully using the company's Supercharger [15–17]. With home chargers, Teslas and other EV models in the US (e.g., Rivians) take roughly six to eighteen hours to charge from depleted to full depending on the vehicle model [17,18]. The effective distance the vehicle can travel will differ based on various factors, including, but not limited to, the type of vehicle, choice of tires and wheels, manner of driving, traffic situation, initial battery charge, and external temperatures. As another example, the BMW home charger enables charging an all-electric BMW (at a rate of 9.6 kW) from 0% to 100% in as few as 12 h [19]. Charging can be treated as a time-shiftable load, however, and need not be continuous if the EV is plugged in for an extended period. Smart charging shifts EV charging in time so it serves to smooth the grid's aggregate demand and ensure that EVs in aggregate do not create their own demand spike, e.g., if they are all charged immediately upon being plugged in around the same time in the afternoon or evening.

Thus, EVs adopted at scale become a double-edged sword for the evolving power grid. Their impact on grid operations can either be beneficial or detrimental, depending on the integration strategy (or lack thereof). In the evolving landscape of today's multi-agent grid, it is crucial to consider EVs as intelligent agents and harness their autonomy to enhance grid resilience rather than turning a blind eye to their inevitable impact.

3. EV Impact on the Power Grid

3.1. Transmission (Upstream)

Over the past decade, there has been a significant increase in multilateral initiatives and commitments aimed at promoting electromobility. This surge in activity reflects the global support from governments to accelerate the transition to zero-emission transportation. It is a positive indication that international cooperation plays a crucial role in achieving decarbonization goals. Figure 1 clearly shows the upward trajectory of battery electric vehicles (BEV) adoption worldwide, but it also highlights that the growth in EV fleets in the US is not keeping pace with the global trend. This disparity in growth rates can be attributed to the impact of various supportive measures in place around the world. Depending on the rate of EV adoption, there may be limitations on the impact of EVs on urban electric grids and local infrastructure. However, as EV penetration increases, there could be observable effects on the upstream transmission grid. This makes it essential to consider the financial implications of various EV charging strategies on distribution grids, which has become a critical aspect of EV adoption. Veldman and Verzijlbergh's research [20] focuses on this topic and emphasizes the opportunities and challenges associated with large-scale implementation of smart charging strategies for EVs within the context of evolving smart grids. By comparing the perspectives of network operators and commercial entities, they assess the effectiveness of different charging approaches in minimizing peak demands and reducing network investment costs. Their findings suggest that encouraging EV owners to schedule their charging based on electricity prices, which are influenced by intermittent energy sources' production, can lead to a reduction in consumption peaks and a decreased need for grid reinforcements. Taking a broader perspective, [21] presents a comprehensive review of the current state of EVs, their charging infrastructure, and their impact on the electricity grid. The authors argue the need for standards to ensure safe and efficient charging with the rise of EV adoption. To support this argument, the authors highlight examples of international EV-charging and grid-interconnection standards. While the paper discusses the potential adverse impacts of EVs on the grid, it presents the concept of an "energy internet" as a potential solution for integrating EVs into the larger energy system.

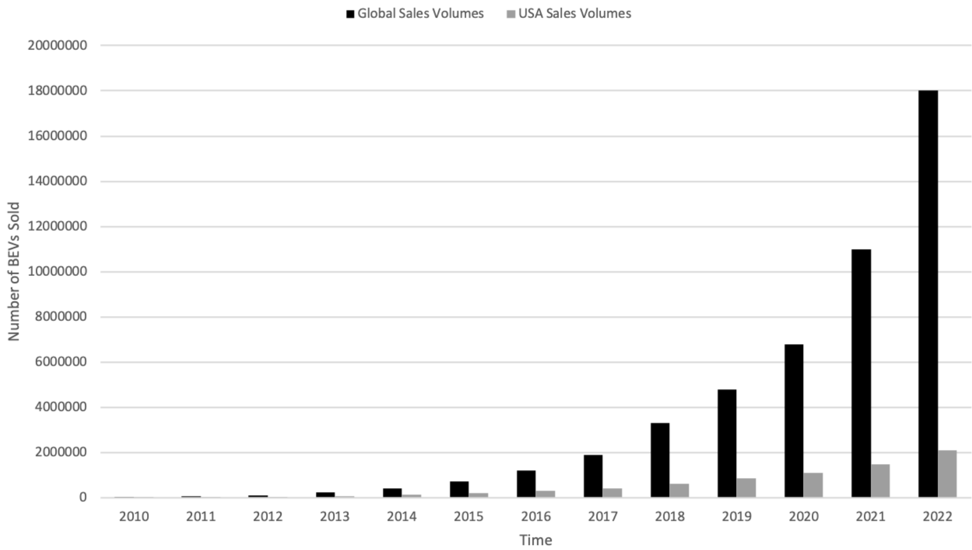

Figure 1. Total BEV sales, globally and in the USA (2010–2022) [22].

Many recent papers propose using vehicle-to-grid (V2G) technology as a solution to alleviate concerns about EV charging load and to turn EVs into assets for distribution and transmission grids. For example, ref. [23] discusses the benefits and methods of implementing smart charging strategies along with current research on V2G integration. It highlights remaining challenges, such as the lack of accurate models to assess V2G's effect on battery life, which may affect the promotion and application of V2G.

EVs equipped with bidirectional charging capacity have the ability to not only supply energy to residential buildings but also to contribute excess energy back to the power grid. Additionally, these EVs can serve as backup power sources during blackouts or emergencies. This technology includes various modes: V2G involves exporting EV energy to bolster the electricity grid, vehicle-to-home (V2H) enables the utilization of EV energy for residential or commercial power needs, and vehicle-to-vehicle (V2V) allows one EV to recharge another.

3.2. Distribution (Downstream)

An ongoing source of concern for grid managers, utilities, and third-party aggregators is uncertainty around EV use profiles originating from EV owners' dynamic, often unpredictable behavior. Researchers in [24] analyze the potential impacts of EVs on the residential distribution grid through considering uncertainties around EV arrival time, daily travel profile, and energy demand information. The proposed model is tested using the IEEE 123 Bus Test Feeder in the face of unbalanced voltage scenarios and EV penetration levels. The spatiotemporal impacts of EV charging and discharging (through V2G) are directly correlated with the location of EV charging stations. In [25], the authors discuss a methodology for the optimal placement of EV charging stations in an active distribution system, taking into account electrical and geographic constraints. The authors' strategy involves stochastic modeling and integration of EV charging needs and generation sources with power flow models.

In high-penetration scenarios, aggregate EV demands hold the potential to alter regional power generation profiles upstream. For example, ref. [26] discusses the potential impact of EVs on reducing demand peaks, reserve margins, and electricity prices. The authors rightfully note that EVs' impact on emissions is directly related to the regional power generation portfolio. Finally, many researchers advocate that EVs can play a positive role in future grids with high reliance on variable generation, such as wind power. For instance, ref. [27] models EVs to provide demand management through flexible charging requirements and energy balancing for the network, including both demand balancing and V2G discharging. The authors suggest that the behavior of EVs is driven by driver needs, electricity prices, and the availability of real-time market pricing information.

Oubelaid [28] introduced a multi-stage power management approach aimed at improving the security and performance of hybrid electric vehicles (HEVs), particularly safeguarding sensitive power sources like fuel cells (FCs) against sudden load changes. The strategy employs a model-based coordinated switching technique that uses customized transition functions based on power source dynamics. The management of power flow in HEVs is achieved through a fuzzy energy management method, allowing secure and predefined FC operation at different points. Additionally, the strategy integrates fault detection algorithms in its second stage to identify and rectify power source failures.

4. Financial Mechanisms to Increase EV Penetration

4.1. Incentivizing EV Adoption

Countries around the world have implemented diverse policies to increase EV adoption [29]. For example, the United Kingdom introduced legislation at the national level that starts EVs at the lowest excise duty rates [30]. In 2023, the United States introduced subsidies in the form of tax credits for commercial EVs, known as the Commercial Clean Vehicle Credit [31]. Policies in different countries take various forms, such as fuel economy standards, CO_2 emissions standards, deployment roadmaps, and sales or stock targets [29], resulting in varying EV sales trends over the past decade. To analyze and compare the EV sales trends in different countries, this research utilized the dynamic time warping (DTW) clustering model. Time-series data from the Energy Information Administration (EIA) were used to observe the sales of EVs in various countries [22]. Unlike conventional data, measuring similarity in time-series data is challenging since the order of elements in the sequences must be taken into account [32]. Traditional metrics, like the Euclidean distance, are not accurate for time-series data. Instead, the DTW metric has been proposed [33,34]. DTW is an algorithm that measures the similarity between two temporal sequences and identifies an optimal match between them given certain restrictions. It allows sequences to be "warped" nonlinearly in the time dimension to determine their similarity, independent of certain nonlinear variations in the time dimension [35]. Algorithm 1 below gives example pseudocode for the DTW algorithm used.

Using DTW clustering, the countries were grouped into five clusters based on the similarity in EV sales from 2012 to 2023. Figure 2 illustrates each cluster's countries and their respective trends in selling EVs. It was observed that the majority of countries fell into cluster 0, indicating a high level of similarity. Additionally, there were distinct clusters for Europe, China, and the world as a whole, while Germany and the USA were found in the same cluster.

A notable common feature across all clusters was that each country experienced an increasing trend in EV sales after 2016. This growth in sales was accompanied by fluctuations, such as the impact of COVID in 2020, as shown in Figure 3, which temporarily reduced the electricity demand for charging these EVs.

DTW clustering was chosen for its multiple benefits over other methods for calculating the similarity of time-series data. Traditional methods rely on the Euclidean distance, but this approach does not accurately reflect real-world scenarios. Time-series data includes both temporal and spatial dimensions. The Euclidean distance primarily suits spatial distance calculations, while dynamic time warping is better suited for capturing temporal differences. Assessing time series similarity involves evaluating the likeness between two sets of time-related data. Due to the unique nature of time-series data, a distance calculation approach is needed that leverages both temporal and spatial characteristics [36].

Algorithm 1 An example pseudo-code showcasing the dynamic time warping technique for comparing two sequences, denoted as strings s and t, consisting of discrete symbols. The method involves calculating the distance between two symbols, x and y, represented as $d(x, y)$, where the distance is defined as the absolute difference between the symbols, i.e., $d(x, y) = |x - y|$ [37].

```
Parameters Initialization: Initialize DTWDistance (s: array [1..n], t: array [1..m]) .
    DTW := array [0..n, 0..m]
for i := 0 to n do
    for j := 0 to m do
        DTW[i, j] := infinity
        DTW[0, 0] := 0
    end for
end for
for i := 1 to n do
    for j := 1 to m do
        cost := d(s[i], t[j])
        DTW[i, j] := cost + minimum(DTW[i-1, j ], // insertion
        DTW[i , j-1], // deletion
        DTW[i-1, j-1]) // match
    end for
end for
return DTW[n, m]
```

DTW is a prevalent technique for measuring distances in time-series clustering. It identifies the distance by finding the optimal continuous warping path between two time series. The primary drawback of DTW is time complexity. The computational complexity of the DTW distance grows quadratically with the length of the time series [38].

Various clustering models exist, with k-means being a prominent example that relies on averaging. Nonetheless, the advantage of the DTW model lies in its application to tracking EV sales across different countries using time-series data. DTW accommodates variations in time shifts and temporal distortions within these datasets, making it crucial for pattern detection in time-series data. Experimental results obtained indicate a high likelihood of failure when employing the k-means method for clustering in contrast to the DTW model [39].

4.2. EV Participation in Grid Services

Incentivizing EV-owner participation in grid services is critical for managing the relationship and interactions between those owners, power grid managers and third-party aggregators. In the latter category, private companies, like Grid Fruit, bring experience in building energy management for grid benefits [14,40]. They are poised to optimally add EV charging into the energy mix and to balance it with traditional loads. They optimally schedule time-shiftable demands (whether charging EVs or running commercial appliances) to capture rebates and payments from the grid (e.g., through DR programs) and pass those financial benefits on to the end user (e.g., the EV owner). The following studies show the benefits of applying such techniques at scale for EVs.

In [41], the authors explore the potential of using EVs, building-to-vehicle (B2V), and vehicle-to-building (V2B) systems to provide energy flexibility in large commercial and public buildings with parking lots. To overcome regulation hindering financial transactions between the involved parties, the paper suggests discounting parking fees in return for

V2G services. This scheme is compatible with existing regulations and enables optimal renewable energy integration with large buildings.

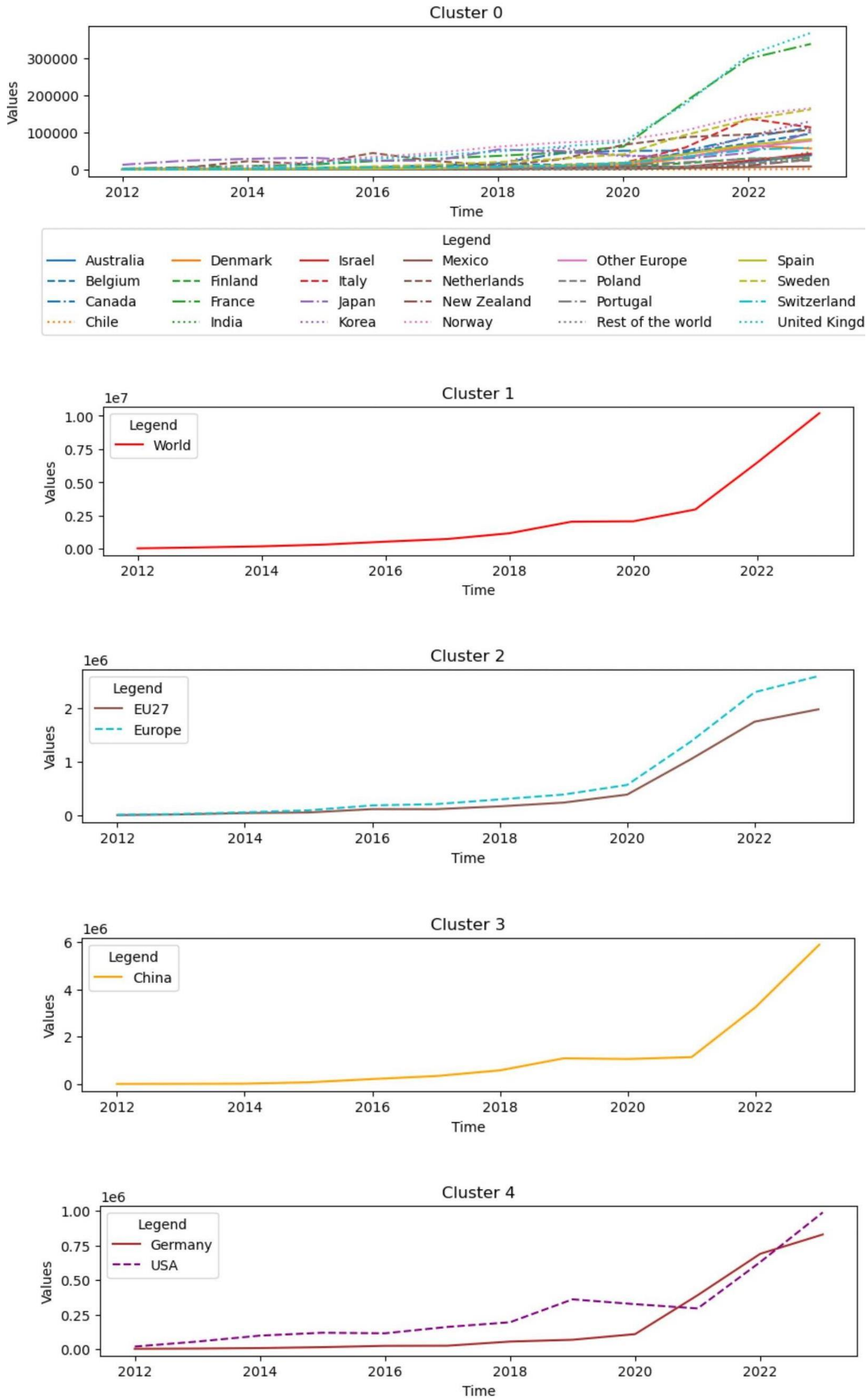

Figure 2. Dynamic time warping clustering results for EV sales in different countries (2012–2023). The data source for this analysis is presented in [22].

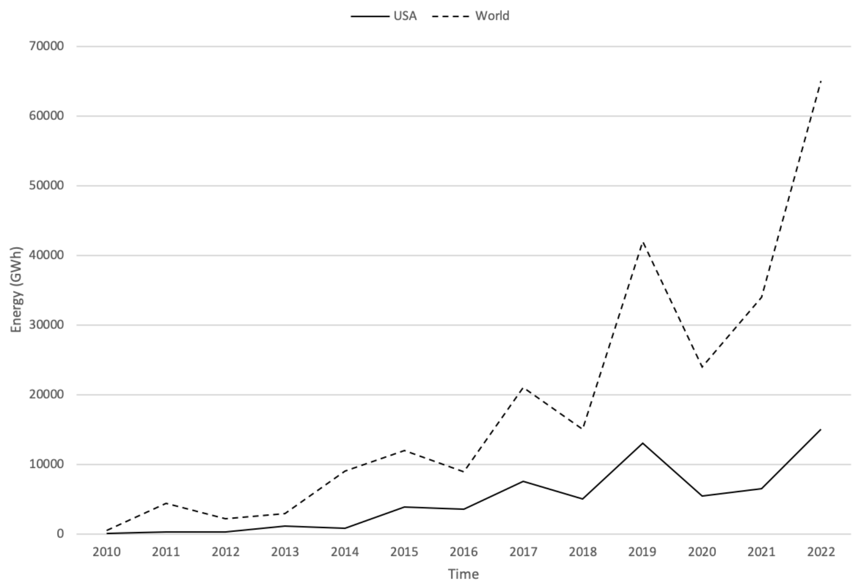

Figure 3. Total energy consumed by EVs globally and in the USA (2010–2022) [22].

Reference [42] introduces fair demand response for EVs through cloud-based energy management services. The solution aims to address the impact on power systems of fluctuating penetration of EV loads and increased deployment of distributed energy resources (DERs). The paper considers communities with a wide variety of customers (EV, DER, storage, multiple loads, and combinations of those categories). The authors argue that strong incentive design can promote fairness in energy trading, minimize operating costs for customers, and smooth the operation profile of EVs and DERs. Calculating the impact of incentives for behavior change is a key step in financial mechanism design. In this regard, ref. [43] focuses on the financial incentives necessary to encourage EV-owner participation in DR programs. The authors argue that existing DR programs, such as direct load control and time-of-use pricing, are insufficient to convince EV owners to sacrifice convenience for the marginal financial savings. Therefore, additional rebates and incentives are needed to ensure EV owner participation at scale. To address this issue, ref. [44] proposes a DR strategy for managing the load in a residential distribution circuit to accommodate EV charging while keeping peak demand unchanged. The strategy allows consumers to choose which household loads to control and when, while introducing consumer comfort indices to measure the impact of DR on their lifestyle. These indices can provide electric utilities with a better estimation of customer acceptance of a DR program and the capability of a distribution circuit to accommodate EV penetration.

Dynamic electricity pricing is a promising tool for encouraging certain EV charging and discharging behaviors. The authors of [45] proposed an energy scheduling model and optimization algorithms for residential electricity consumers in a dynamic pricing environment. The approach integrates various parameters, including electric, thermodynamic, economic, comfort, and environmental factors. The economic approach aims to minimize energy costs for consumers, while the comfort angle aims to maintain a comfortable indoor environment. The paper shows how advanced modeling of residential power consumers and an optimization algorithm provide benefits across these disparate dimensions.

Establishing financial incentives plays a key role in EV adoption and fighting climate change. This is highlighted by [46], which analyzed the factors that influenced EV adoption across 30 countries in 2012. The study found that financial incentives, charging infrastructure, and the local presence of production facilities were significant and positively correlated with a country's EV market share. Charging infrastructure was found to be the factor most strongly related to EV adoption. The research also highlighted how country-specific factors, such as government procurement plans or the target recipient of subsidies, could dramatically affect a nation's adoption rate. Unfortunately, incentivizing

EV owners is not "one size fits all". The authors of [47] studied behavior and engagement pathways for privately owned EVs, public transport EVs, and logistics EVs. Privately owned EVs are mainly used for personal transportation and have flexible charging and discharging schedules. Public transport EVs (e.g., buses and taxis) have fixed routes and schedules, which require a more precise charging plan to ensure their availability during peak hours. Logistics EVs are used for goods delivery and tend to have a higher demand for charging power due to typically larger battery capacity. Therefore, grid managers benefit significantly from implementing efficient charging strategies for logistics EVs to minimize their demand impact. In short, the paper proposes different financial incentive mechanisms to encourage EV owners of different usage classes to participate in grid support activities, such as peak shaving and valley filling (i.e., shed load and build load events), fluctuation mitigation, and frequency control.

Finally, the role of non-financial incentives should not be overlooked in EV adoption. The author in [48] reviewed the impact of reoccurring and non-financial incentives on EV adoption. The study found that these incentives could be effective in increasing consumer interest and adoption of EVs. Examples of such incentives include special lane access for EVs, free or discounted parking, and other non-financial benefits. Effective use of these incentives requires that policymakers understand which are feasible for their region and which are most likely to be effective in promoting EVs. Combining financial and non-financial incentives will create a more comprehensive approach to promoting EVs.

5. Charging Infrastructure

The US has recognized the need for a strong network of charging stations to accommodate the increasing number of EVs in use. To achieve this, the country has introduced legislation at both national and state levels. The initiatives include offering incentives like 30% of project cost support for commercial EV charging projects and fixed grants for residential projects provided in the form of tax credits [49]. Additionally, there is a goal to reach 500,000 chargers by 2030 through USD 5 billion in formula funding for states and USD 2.5 billion for a competitive grant program [50]. States also have their own policies to enhance charging infrastructure, with California taking the lead, allocating 1 billion dollars in funding for a transportation electrification program, with 70% for medium/heavy-duty vehicle charging infrastructure and 30% for light-duty vehicle charging in Municipal Utility Districts, starting from 2022 [51].

To facilitate access to charging stations, there is an alternative fueling station locator available for users to find both public and private charging stations. Figure 4 illustrates the growth in public and private charging stations and assesses the current state of charging infrastructure in the US. Consumers and fleets considering EVs need access to charging stations, which typically begins with home or fleet facility charging. Installing charging stations at workplaces and public destinations can increase market acceptance by providing more convenient and flexible charging opportunities at frequently visited locations. The industry has adopted the open charge point interface (OCPI) protocol as a common standard for charging infrastructure [52].

Charging equipment comes in different levels. Alternating current (AC) level 1 equipment operates with a 120-volt AC plug, and most EVs come with a portable level 1 cordset, eliminating the need for additional charging equipment. AC level 1 charging is often used at home where only a 120 V outlet is available, providing sufficient charging for most drivers' needs. AC level 2 equipment offers charging through 240 V or 208 V electrical service. Level 2 equipment is commonly installed at public charging stations and homes for overnight charging as it can charge the EV battery fully during that time. Direct-current (DC) fast-charging equipment, typically with a three-phase AC input, enables rapid charging along busy traffic routes at installed stations. As of 2021, over 15% of public EVSE (electric vehicle supply equipment) ports in the US were DC fast chargers, and their numbers are expected to rise due to the adoption of medium- and heavy-duty EVs by fleets, as well as the installation of fast-charging hubs for transportation network companies like Uber and Lyft. Overall, most EV drivers rely on AC level 1 or AC level 2 charging equipment to charge their vehicles [49].

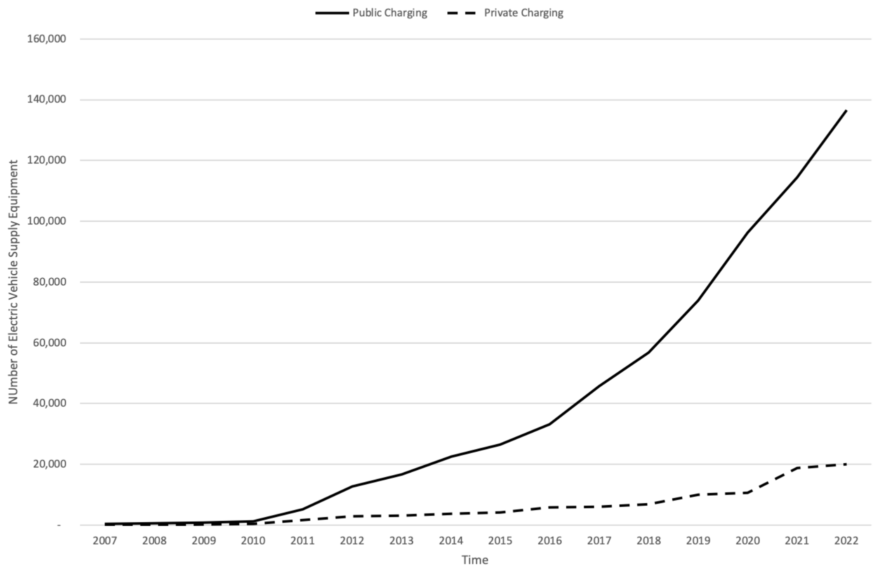

Figure 4. Growth in EV charging equipment in the USA (2007–2022) [22].

Range anxiety is still a leading concern for current and future EV owners, and many recent papers are establishing the link between charging infrastructure needs and EV adoption. Reference [53] analyzed EV charging behavior and infrastructure planning for standard and fast charging. The study highlighted that EV users prefer to charge at home during peak-demand evening hours, so incentives are necessary to encourage home charging at other times. The paper suggests that fast-charging infrastructure is likely to become commercially viable in the short to medium term, and priority should be given to strategic network location of fast chargers. Additionally, car parks are favored by EV users for public charge point locations.

V2H, V2V, and V2G technologies are key to more sustainable and efficient charging. These three technologies can be used to enable the integration of renewable energy sources, reduce peak demand on the power grid, and provide backup power during emergencies, as described in [54]. These technologies can help balance the supply and demand of electricity on the grid, reduce greenhouse gas emissions, and improve energy efficiency. Additionally, they can provide economic benefits to vehicle owners by allowing them to sell excess energy back to the grid. Overall, these technologies have the potential to strengthen the utility grid as EV charging continues to scale. The paper also highlights challenges that need to be addressed in order to fully implement V2H, V2V, and V2G technologies. These challenges include developing appropriate standards and regulations, ensuring cybersecurity and privacy, managing the increased demand from charging, addressing technical issues related to charging and discharging, and addressing social and economic issues around ownership and usage.

Belkhier [55] also talked about the application of battery storage systems (BSS) in HEVs to improve effectiveness and optimize performance. Although FCs by themselves might not adequately fulfill power requirements, BSSs are utilized to attain quick initiation, high power density, and enhanced dynamic responsiveness. The efficiency of power allocation plays a crucial role in the triumph of this setup. The primary focus revolves around sustaining torque stability within the permanent magnet synchronous motor, which acts as the vehicle's traction motor, all while ensuring prompt reactions.

Additionally, difficulties arise around the cost-effectiveness of these technologies and their integration with renewable energy sources. Cost is a key driver of consumer preferences, which are described in [56]. That paper highlights the importance of infrastructure at home, work, and public locations, consumers' access to charging infrastructure, the cost to charge an EV, how many charge points are needed to support further EV scaling, maintenance of the charging infrastructure, and charging's impact on power grids.

Public charging infrastructure is being installed with many local and federal subsidies. In [57], the authors explored the potential impact of these installations on increasing EV sales, electrified mileage, and lowering GHG emissions. The study examined the trade-offs between the number of national stations and the electricity surcharge, as well as regional station deployment scenarios. They projected that, by 2050, a national initiative to build 50,000 DC fast-charging stations could increase the fleet-wide electrified mileage by 8%. The researchers also found that public DC fast chargers were more effective at increasing EV sales and lowering GHG emissions than public level 2 chargers.

Figure 5 summarizes the barriers and opportunities to EV integration described above.

	Aspect	Benefits	Challenges
Electric Grid Interactions	Smart Charging	Minimizing peak demand & reducing network investment cost	EV owner's participation and unpredictable behavior
	V2G, V2H, V2V	Improve efficiency and stability of distribution and transmission grids	Inadequate models for V2G's impact on battery life
	Grid Resiliency	Demand management & energy balancing for network	Uncontrolled charging behavior make demand spike
Financial and Non-financial Mechanisms	Dynamic Electricity Pricing	Reduce customer operating costs and optimize the operation profile of EVs	Insufficient incentives for EV owners to sacrifice convenience for marginal financial gain.
	Peak Shaving and Valley Filling	Effective implementation for privately-owned EVs and logistics EVs	Challenging implementation for public transport EVs due to their fixed routes and schedules
	Beyond Monetary Rewards	Advancing EV adoption	Difficulty in designing customized rewards
Charging Equipment Technology	AC Level 1	Used for home charging with a 120V outlet and eliminating the need for additional charging equipment	Charge slowly and require a longer time for a full charge
	AC Level 2	Public charging and allowing EVs to fully charge over night at home	Installation and labor cost
	DC Fast Charging	Facilitates timely charging on heavily trafficked routes	Limited availability of fast charging stations and cost

Figure 5. The summary of EV integration barriers and opportunities that are presented in this paper.

6. Conclusions and Future Work

Recent advancements in EV technology, together with government incentives to purchase EVs, have led to rising adoption of EVs that continues each year. However, unregulated charging of EVs may result in increased load at peak-demand hours, which puts unnecessary strain on the power grid. Effective strategies for controlling EV charging is crucial to reduce peak demands and network investment costs. This paper provides a review of the impacts and challenges associated with the increased penetration of EVs. It considers current charging technologies and incentives while offering solutions to mitigate concerns about aggregate EV charging load. These solutions include V2G technology, optimal placement of EV charging infrastructure, and demand management techniques. Financial mechanisms and policies play a vital role in incentivizing and organizing the rollout of these solutions. These tools build enthusiasm for EVs while enabling EV owners to maintain ultimate control over their charging behavior and still provide aggregate benefits across the utility.

Optimally managing EV charging and offering corresponding incentives are increasingly important to ensure power grid reliability, resilience, and affordability. The choice of charging technology and the location of chargers are important factors to consider when planning and rolling out new charging infrastructure. Additionally, EV batteries can be used for energy storage even after their life cycle within EVs is finished, i.e., if they are recycled after removal from EVs. At least five companies across Europe, North America, and Africa are pursuing this "second life" for EV batteries to continue being usable for energy storage after being retired from EVs [58,59]. Finally, many non-financial incentives for EV adoption (such as special lane access, free parking, or discounted parking for EVs) are being explored but are not yet mainstream. Future work should explore these non-financial measures for policymakers and business people to leverage for continued acceleration in EV adoption.

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