Overview of flexibility potential in EV charging

Lappeenrannan-Lahden teknillinen yliopisto LUT

Sähkötekniikan kandidaatintyö

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Abstract

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Overview of flexibility potential in EV charging

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Examiner: Professor Samuli Honkapuro
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Fast adaptation of electric vehicles forces changes to electrical grid infrastructure. This bachelor's thesis examines how electric vehicle flexibility is utilized at the moment, future possibilities, and how grid upgrades should be approached. This thesis examines recent scientific articles and analyzes different flexibility methods and how feasible they are to implement.

As a result of the bachelor's thesis, flexibility methods were identified and analyzed for their effectiveness. Increasing flexibility through smart grid upgrades was found to be the most cost-effective way to upgrade the grid if the adaptation rate of EVs follows projected trends. Smart grid upgrades enable additional methods of controlling charging increasing flexibility further. Problems arising from the shift to renewable energy sources can be mitigated with smart grid technologies.

Tiivistelmä

Lappeenrannan–Lahden teknillinen yliopisto LUT
School of Energy Systems
Sähkötekniikka

Miska Jäppinen

Katsaus sähköautojen latauksen joustavuuspotentiaaliin

Sähkötekniikan kandidaatintyö
2024
20 sivua, 3 kuvaa ja 0 taulukkoa
Tarkastaja: Professori Samuli Honkapuro
Ohjaaja: TkT Nadezda Belonogova
Avainsanat: Sähköautojen joustavuuspotentiaali, kirjallisuusselvitys

Sähköautojen nopea lisääntyminen aiheuttaa muutoksia sähköverkkoinfrastruktuuriin. Tässä kandidaatintyössä selvitetään latauksen joustavuuden hyödyntämisen nykytilannetta ja tulevaisuuden mahdollisuuksia uuden verkkoteknologian käyttöönoton kautta. Työssä tarkastellaan ajankohtaisia tieteellisiä artikkeleita, analysoidaan eri joustavuusmenetelmien toimivuutta ja käyttöönoton kannattavuutta.

Kandidaatintyön tuloksena tunnistettiin ja analysoitiin eri joustavuusmenetelmiä niiden toimivuuden osalta. Joustavuuden kasvattaminen älykkäiden sähköverkkojen päivitysten kautta todettiin kustannustehoikkaimmaksi verkon päivitystavaksi, jos sähköautojen käyttöönotto seuraa ennustettuja trendejä. Älykkäiden sähköverkkojen päivitykset lisäävät ominaisuuksia, joilla saadaan lisättyä joustavuutta entisestään. Sähköautot ja älykkäät verkot yhdessä auttavat uusiutuviin energialähteisiin siirtymistä lieventämällä uusiutuvien energiantuotannosta syntyviä ongelmia.

Lyhenneluettelo

BEV	Battery electric vehicle
EV	Electric vehicle
PV	Photovoltaic
$V1G$	Unidirectionally controlled
$V2G$	Vehicle to grid
$V2H$	Vehicle to home
$V2L$	Vehicle to load
$V2X$	Vehicle to X

Contents

1 Introduction

Electric vehicle (EV) sales are rising rapidly. According to a report by BloombergNEF (2020), 58% of global passenger vehicle sales, and 32% of cars on the road will be electric by 2040. According to the same report, EVs will make up 5.2% of the global electricity demand. The percentages will be even higher in more developed countries. Projections made by U.S. electric power research institution show that 62% of the U.S. vehicle population will be electric by 2050. (Munshi and Mohamed, 2018). EV charging occurs in different places, such as residential homes, public chargers, and workplaces, enabling different approaches to extracting flexibility from charging.

While the increase in EV sales is unlikely to cause a significant increase in total power demand, it will likely reshape the load curve. The problem comes from higher peak power demands as more EVs are getting charged at the same time. Electric vehicles will have the most effect on the grid as higher evening peak loads when people plug in their cars after returning home for the day. Significant peak load increases would mean pushing local transformers beyond their capacity, causing possible blackouts and voltage drops. (McKinsey&Company, 2018).

There is flexibility potential in the ways the EVs are charged. If EV charging is uncontrolled, it will increase the peaks already present in the grid. By utilizing more flexible charging methods it is possible to minimize the negative impacts on the grid. Flexibility in charging can also minimize expensive upgrades to the grid, that otherwise would be needed. This bachelor's thesis aims to investigate different ways to extract flexibility from electric vehicle charging.

2 Quantifying flexibility

The primary task in EV charging is achieving the desired battery percentage at the wanted time. The term 'flexibility' in the context of this thesis refers to the ability to change the charging variables and still reach the primary outcome. The basic variables are charging speed and time. Higher-tier concepts, presented in figure 1, increase flexibility by manipulating charging and discharging time more intricately.

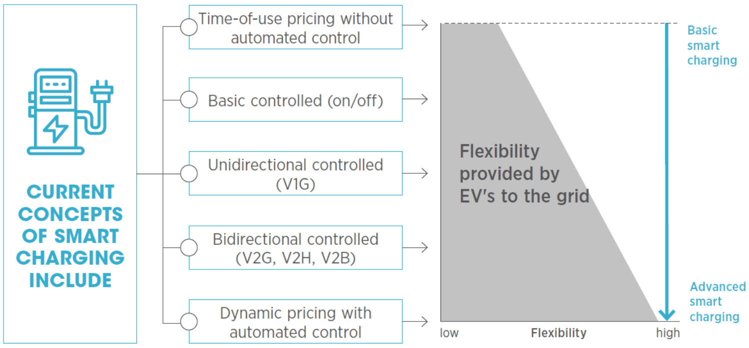

Figure 1: Flexibility potential with different flexibility methods. (IRENA, 2019)

When talking about personal electric vehicles, flexibility comes from the reality that the vehicle is used less often than it could be. This makes higher-concept technologies like vehicle-to-grid (V2G) operation possible. These technologies could use personal electric vehicles as an energy storage solution in combination with renewable energy sources to lessen societies' dependence on CO2-producing on-demand energy sources, which would be otherwise needed to ensure grid operation. (Einwächter and Sourkounis, 2014)

Flexibility potential comes from charge duration, charging power or when the car needs to be charged, which all differ between operating environments. For example, when people arrive home in the evening or late afternoon and need their car next time the following morning, there is a lot of flexibility in the ways of charging. Public charging poses larger challenges to grid management, as public charging is more demanding for its higher amperage, drawing more power from the grid. There is less flexibility in public high-amperage chargers, as they are used for the minimum amount of time because people do not want to spend their time waiting for their EVs to charge.

EVs have three unique characteristics that make them excellent assets for the grid: the charging power can be varied, batteries can be charged and discharged, and the charging power can be quickly altered (Mouli et al., 2017). Gaining access to these characteristics is the key to getting the most flexibility out of different environments. The term for getting flexibility from these characteristics is called smart charging.

2.1 Residential & urban environments

Most of the personal electric vehicle charging happens at home so it is one with the highest overall energy usage. The residential environment is also the place where the car will be parked the longest. Home is also the place where we have a lot of possibilities for flexibility, as the need for charging might not be immediate. One way to quantify flexibility is to collect data from a small EV fleet and observe demand response, and grid operators can make decisions based on that data. This gives operators opportunities to balance grid supply according to charging patterns. The charging pattern includes charging start time, end time, and power.

Charging in residential environments is done with AC EV chargers. The AC charger is an internal component of the car, and the cable you plug into the wall socket is basically an extension cord. EVs tend to gain more from being light, so there are weight restrictions set on internal components, so the internal AC charger could even be limited to around 20kW (Mouli et al., 2017).

To gain access to flexibility, an EV has to be plugged in. According to Barter (2013), a typical car stays parked 96% of the time. Most of the parking time is on residential parking spaces, so there has to be an incentive for residents to plug their cars in for the most amount of time to gain the most flexibility. Especially for more complex vehicle-to-grid integration, there has to be a motivation for consumers to plug in every time to extract available flexibility. Lithium-ion batteries cannot be charged as fast as you can fill your internal combustion engine car's fuel tank, so just owning and operating a personal electric vehicle will force a different kind of driver behavior. I.e., charging whenever the car is parked in the driveway.

2.2 Grid expansion

In urban residential environments, the future expansion demand of the grid depends on the penetration level of the area and the charging behavior of the EV operators. During peak times, simultaneous charging can cause overloading of components, congestion, and, in the worst case, blackouts. The more flexibility in charging, the less need for grid upgrades.

2.2.1 Cost assessment of upgrades

Smart charging concepts open up new ways to increase the capacity of the grid. The conventional response to increased network load is upgrades to the grid components, such as transmission lines and transformers. Smart grid upgrades aim to have the same effect of ensuring that the grid stays within a healthy operating range. Smart grid features are numerous; in this case, a charging management system is a good example. The goal of doing a cost assessment analysis is to determine which upgrade strategy is the most cost-effective while still maintaining a healthy grid.

2.3 V2X

Intermittent renewable energy sources bring challenges and opportunities. EVs could play a vital role in the integration and mitigation of the power system imbalances that come with these intermittent energy sources. When thinking about EVs, one cannot think of them as only cars; they are batteries on wheels. There are suggestions to use batteries as a storage solution for times when renewable production is high to store excess energy and as an energy source when needed. Electric vehicle sales have soared in the last few years, reaching 2.6 million battery electric vehicles (BEVs) sold in 2021. (Skidmore, 2021)

Vehicles can provide flexibility by discharging the battery. V2X is a term used to refer to where the battery is discharged. V2G is a vehicle to the grid, V2B is a vehicle to building, and V2H vehicle to home. V2G especially provides multiple use cases for increasing EV flexibility. Use as storage for renewable energy technologies is a great way to mitigate the downsides of PV and wind production (Mouli et al., 2017). Typical Finnish small-scale consumer with a non-electric heating detached house uses around 20-30 kWh of electricity every day (Motiva, 2023), so EVs with a large battery could supply a house for multiple days with V2H technology. CHAdeMO Association has proposed V2X usage in emergencies. Cars can be driven to areas suffering blackouts and power the disaster relief efforts from lithium-ion batteries using the V2X function. (Chademo, 2020)

2.4 Requirements for V2X

V2X requires a bidirectional connection between the car and the point where the battery is being discharged. There is some standardization happening already; NACS (North American charging standard) CHAdeMO and CCS (Combined Charging System) chargers support V2G operation. CHAdeMO, CCS, and NACS are leading standards for electric vehicle charging.

Most EVs tend to not support V2X communication at the moment of writing. For V2X to work on cars, the car must have the hardware and software necessary to enable bidirectional communication and power exchange. There are multiple stages of V2X deployment. Many cars only support basic V2L (Vehicle to Load) technology, used for 240V loads. For example, the Hyundai Ioniq 5 can do V2L at 3,6kW. At the moment of writing, the Nissan Leaf is the only V2X-compatible car that supports V2G. Multiple car manufacturers have shown interest in adding V2G to their cars, notably Volkswagen and Hyundai. Hyundai has also launched pilot projects to study large-scale V2G implementations in Europe. (Flaherty, 2022) (Hyundai, 2022)

2.4.1 V2X drawbacks and challenges

Challenges to large-scale V2G adoption include increased battery degradation and warranty concerns with more charge cycles. Bidirectional chargers are more technologically complex and expensive to implement, and the lack of revenue sources for V2G makes it costly for consumers. However, with the widespread use of smart charging, V2G is expected to play a vital role in the future. (Mouli et al., 2017)

There are also regulatory challenges with V2G implementation. Tesla Cybertruck can supply 11.5kW through the NACS connector, supporting V2L, but V2H only when using a proprietary Tesla Wall Connector and either a Tesla Gateway or Powerwall. (Tesla, 2023). According to Holzhausen et al. (2023), a Tesla engineer, Tesla opted to go with the proprietary implementation because of regulatory challenges. Different US states and countries differ in their regulatory demands for V2G operation, making large-scale implementation difficult. Regulatory bodies like the European Union could work with auto manufacturers to ease the implementation of V2G technology. This has proven to help with infrastructure adaptation, with minor downsides. The deployment of the CCS standard is a good example.

2.5 Flexibility potential in different environments

2.5.1 Smart charging in residential environments

At the moment, the extent to which smart charging is utilized in residential environments doesn't include V2G or other concepts that would require communication between the grid and the vehicle. EV owners might get some smart features from the cars' internal chargers or wall connectors, which might have WiFi capabilities to communicate with the car with a smartphone. These smart charge features could include stopping and starting the charging remotely, at the desired percent, or delaying the start time of charging to gain access to cheaper electricity prices at night. These kinds of unidirectionally controlled systems are called V1G (IRENA, 2019). From the residents' perspective, having flexibility at the moment could save them money by taking advantage of time-based tariffs or purchasing electricity at times when market prices are lower and predictable.

In residential environments, higher-concept technologies like V2G could provide a new income source for the residents (Soares et al., 2022). When the revenue stream from customers to the grid is opened, it will ease the deployment of other renewable energy sources. If the car can be used as a revenue source, the idea that excess energy generated by solar panels could be sold back to the grid is more approachable.

2.5.2 Rural areas

Rural areas may face different challenges when it comes to electric vehicle (EV) charging flexibility compared to urban areas.

Rural areas have less charging infrastructure than urban areas, which can make it more difficult for EV owners to find a place to charge their vehicles, requiring more planning. This reduces chances for tapping into the flexibility potential of charging, as EV owners may have fewer options for charging their vehicles. Charging infrastructure is also more spread out with long distances between chargers, making it harder to plan to charge, reducing the flexibility potential.

Power grid capacity could also be less developed compared to more urban areas. High charging rates could end up being a bigger problem than in urban areas. This can make it more challenging to support high charging rates and large numbers of EVs charging simultaneously. There are a few initiatives underway in Europe to address the challenges of EV charging in rural areas, including the development of charging infrastructure and the integration of renewable energy into the grid. For example, the European Union's "Alternative Fuels Infrastructure Directive" aims to increase the availability of charging infrastructure for electric vehicles (EVs) in both urban and rural areas by mandating one charging point per ten EVs every 60 kilometers. (*EUR-Lex - 32014L0094 - EN - EUR-Lex* 2014)

2.5.3 Workplace

The car's longest parked time is in a residential environment, followed by work. Throughout the developed world, the leading way of commuting to work is by personal vehicle (Armstrong, 2022). By incorporating EV charging infrastructure into workplaces, employees could charge their vehicles during the day, unlocking around 8 hours of flexibility potential.

Businesses have many benefits to gain from incorporating high-concept V2X technologies.

Businesses can have EV fleets consisting of multiple cars, enabling more flexibility compared to residential environments. Establishing a symbiotic relationship with EV-owning employees is easier as there is already a relationship between employer and employee. Businesses could be a big player in increasing public understanding and acceptance of the benefits of V2X technologies, as investment costs for implementation are rather high for a single household.

Businesses have multiple ways of monetizing EV charging and higher-concept charging technologies. If the fleet is sufficient in size, it could be used as backup power in the case of a blackout. This could mitigate revenue losses and keep the business operating. Businesses could also use the fleet for cheaper electricity during grid peak load times. Compensation models for employees can make the idea of using their cars as reserve energy more appealing and increase participation rates.

3 Results

This section shows the findings of the literature review.

3.1 Public charging

A study examining the potential use of EV charging stations in Helsinki to provide flexibility for electrical grids. The study analyzes data from public chargers between 2015 and 2018 to calculate EV flexibility. The study found that a maximum of 16.84 kW of Frequency Containment Reserve for Normal operation (FCR-N) was available. FCR-N refers to the reserve power that grid operators deploy to maintain the electric power system's frequency within the prescribed limits. The study used Monte Carlo simulations to predict how EVs can contribute to FCR-N. The amount wasn't significant at the moment, but the study's findings anticipate that by 2028, the reserve power capability will increase to 380 kW. (Divshali and Evens, 2019)

An Australian study explored an optimal charging strategy for a smart electrical car park. The study was conducted as a simulation of real-world data collected from the park. The simulation compared normal charging practices to an optimal charging method that takes into consideration variable energy pricing. The optimization took into account the time of use tariffs, where the charging was scheduled for off-peak hours. This approach to charging could save 3 AU$ per day per user. (He, 2016)

3.2 Residential charging

Time-of-use rates are an effective way to reduce peak load demands. A study done by McKinsey&Company (2018), looked at simulated data of a feeder circuit feeding 150 homes with 2 EVs each. The study found that 25% EV penetration would increase peak demand by 30%. The study used a time-of-use rate after midnight to see how much the peak could be mitigated. As a result, the peak demand increase of 30% was mitigated to increase of 16%, a reduction of 47%, as seen in figure 2. 90% of EV users adopted the time-of-use rate, and the cars drove an average of 62km per day.

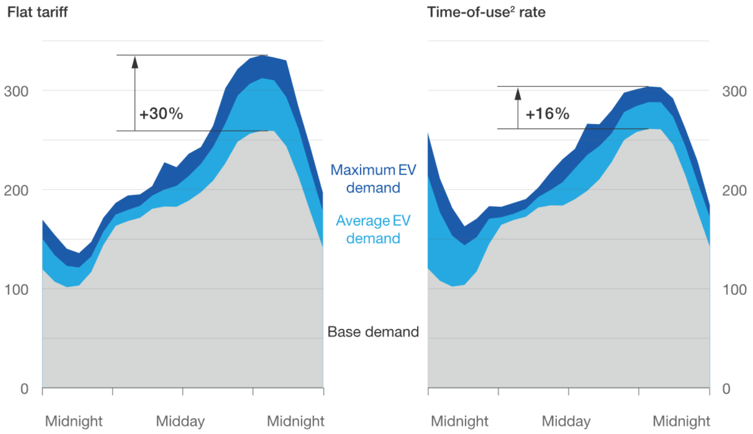

Figure 2: Effect of utilizing a basic time-of-use rate to reduce peak loads. (McKinsey&Company, 2018)

Another study examined time-of-use rates. Simulation of the load profile was done in GridLAB-D, and the simulation was a size of 1000 houses. The strategies used by the study were simple time-shift strategies to avoid the highest peak demands during set times. With non-restricted charging, the peak load demand could be over 27% higher than without EVs. Setting strict time limits on charging and shifting all charging to the lowest load demand time, which is after midnight, the system peak load didn't increase even at 50% EV penetration. Even a two-step approach, where some cars start charging at 7 PM and rest at 8 p.m., could mitigate the increased load demand to less than one percent. (Doğan, 2015)

A Norwegian study on real-world charging data from a large housing cooperative, examined EV charging at 3.6 kW and 7.2 kW charging speeds. Flexibility estimates were made by analyzing charging session times. Private charging points were found to increase flexibility compared to shared charging points, as private charging points have longer plug-in times for the same energy charged. The study suggests that flexibility potential increases with higher power and that there is significant potential for residential EV charging flexibility when parking spaces are provided with EV charge points. (Sørensen, 2021)

A Finnish study on around 400 apartments and parking spots with the same amount of cars with 11 apartment houses. The charging power is constant at 3.6 kW, so this is a good example of residential slow charging. As seen in figure 3, higher EV penetration levels increase charging power almost linearly. With 100% penetration, transfer power can be as high as double without controlled charging. Higher load power peaks lead to the need for large-scale improvements to the grid. The study also explored smart grid solutions to the increased demand. If you assume that EV charging load can be delayed by a few hours, the charging can be shifted to off-peak hours. Optimizing the charging to night hours can reduce the need for grid upgrades. With 25% penetration and smart charging, there is no significant increase in power during peak demand hours. Smart charging can mitigate the increases in distribution fees that might otherwise be needed. The study found that smart charging can significantly decrease the value of transferred energy, with 25% penetration levels the value of transferred energy can be even lower than without EVs due to leveling the load curve. Analysis results by Monte-Carlo analysis. (Tikka, 2011)

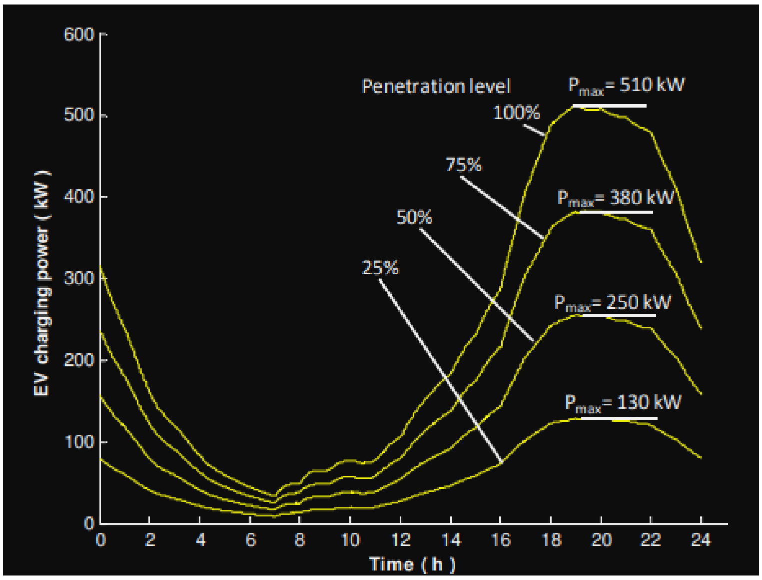

Figure 3: EV charging load curves with different penetration levels. (Tikka, 2011)

3.3 Grid upgrades

Cost calculations show that when comparing a severely affected grid equipped with a charging management system to conventional upgrading, expansion cost-saving potential could be over 30% when the area has more than 30% EV penetration. When examining the average of grids, the charging management system-equipped grid is more expensive at lower penetrations due to smart component costs being higher than conventional expansion components. When EV penetration gets to around 30% charging management system grids have about 10% cost-saving potential. (Uhlig et al., 2017)

High renewable energy usage can have increased positive effects on the grid when EVs follow price-based charging. Veldman and Verzijlbergh (2015) found that when the grid is experiencing high wind power input, the net present value of investment and energy losses are higher. Price-based charging ended up increasing the grid's net present value by 25% when experiencing high wind power production compared to the situation where the EV charging peak was minimized. The large difference between network-based strategy and price-based strategy disappeared when there wasn't high wind penetration.

4 Conclusions

There is flexibility to be extracted in almost every situation, and grid upgrades should be directed toward smart grid implementations. Smart grid and V2G implementations are more expensive upfront compared to traditional upgrades but will end up being cheaper, depending on the level of implementation. Higher-tier smart grid implementations are more expensive if the level of EV penetration stays the same. However, if the EV penetration levels increase as forecast, even the high-tier smart grid implementations will be the more affordable option.

As the BEV landscape is still relatively new, the literature is still lacking in some places.

1. V2G implementations have only seen small-scale usage in the real world, so most of the papers focus on simulations.
2. When simulations are used, they focus on a small part of the smart grid system as a whole, making it hard to draw definite conclusions on what level of smart grid implementation will be the best option for that part of the world.
3. As there's a lack of real-world data, the human element is largely simplified in these simulations. Utilizing time-of-use rates could have wildly different participant rates depending on how and where it is implemented. Understanding the acceptance levels of different methods, like dynamic pricing and demand response programs, is important. User willingness is important, as most flexibility methods available are dependent on the end users' participation.
4. As the literature is still largely in the proof-of-concept phase, there is little consideration of how regulations and policies affect the deployment of flexibility technologies. There has been proof that V2G implementation suffers from a lack of standardization on the regulation side, making V2G-compliant vehicles difficult.

Electric vehicles can be a great asset for future grid operation. The trend of increasing renewable energy sources makes the energy supplied to the grid more unpredictable, and EVs can be used to stabilize the demand response and make the grid more profitable, even when utilizing simple price-based methods (Veldman and Verzijlbergh, 2015). Implementing higher-level flexibility methods makes the response to renewable energy production even better, and V2G would enable the use of EVs as a massive battery storage system.

EVs don't become a problem for grid health until EV penetration levels exceed 20%, and even after that, the problems are localized in certain parts of towns during peak load times. Even simple time-based tariffs or price-based systems will mitigate the problem.

Most of the EV load issues are fixed when the charging is spread out over time. There is research that shows that even with 100% EV penetration, stricter time limits on charging time are enough not to cause network problems (Doğan, 2015). Strict time limits aren't ideal from the end user's perspective, so smart grid upgrades could be implemented to maximize flexibility.

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