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Zusammenfassung

Das Ziel des Forschungsprojektes «Enabling Flexible Electric Vehicle Grid Integration (ErVIn)» ist es, besser zu verstehen, wie der zunehmende Anteil von Elektrofahrzeugen (electric vehicles, EVs) netzdienlich in die Verteilnetze integriert werden kann. Konkret befasst sich dieses Projekt mit drei Forschungsfragen (research questions, RQs) und zielt darauf ab, (RQ1) vielversprechende Rahmenbedingungen sowie Herausforderungen (technisch, sozial und regulatorisch) für die bidirektionale Integration von EVs als Möglichkeit für die Bereitstellung von Flexibilität in Stromnetzen zu identifizieren und zu verstehen, (RQ2) wie das Zusammenspiel zwischen verschiedenen EV-Ladestrategien, Nutzertypen und Netzsituationen die Attraktivität von EVs als Flexibilitätsquelle in verschiedenen Verteilnetzen beeinflusst, und (RQ3) wie Anreize die Integration von EVs als Flexibilitätsquelle beeinflussen. Wir verwenden sowohl quantitative als auch qualitative Methoden mit einem quantitativen Schwerpunkt (Modellierung). RQ1 wurde mit Hilfe einer Datenbankanalyse und Experteninterviews beantwortet; für die Beantwortung von RQ2 und RQ3 wurde ein agentenbasiertes Modell entwickelt.

Bezüglich der Implementierung von bidirektionalem Laden (RQ1) zeigen unsere Analysen, dass sich die aktuellen Pilot- und Demonstrationsprojekte (globale Analyse) auf kommerzielle EVs konzentrieren, welche am Arbeitsplatz laden, sowie auf die Bereitstellung von Vehicle-to-Customer (V2C) (beinhaltet Vehicle-to-Home und Vehicle-to-Building) und Dienstleistungen auf Übertragungsnetzebene. Dies deutet darauf hin, dass insbesondere diese Bereiche vielversprechend für kommerzielle Anwendungen sein können. Allerdings werden kommerzielle Anwendungen derzeit durch verschiedene technologische, soziale und regulatorische Herausforderungen erschwert. Insbesondere die sozialen und regulatorischen Herausforderungen sind stark kontextabhängig und können sich zwischen den jeweiligen Ländern unterscheiden. Beispielsweise—und auch für die Schweiz relevant—bestehen Unsicherheiten hinsichtlich der zukünftigen Nachfrage und des zukünftigen Angebots an Flexibilität, der Beteiligung der Nutzer an bidirektionalem Laden und der Flexibilitätsbeschaffung auf Verteilnetzebene inklusive zukünftiger Markt- und Tarifstrukturen.

Hinsichtlich des Zusammenspiels zwischen verschiedenen EV-Ladestrategien, Nutzertypen und Netzsituationen (RQ2) stellen wir fest, dass sich verschiedene Ladestrategien in ihrer Wirksamkeit für die Bereitstellung von Flexibilität unterscheiden. Die Unterschiedlichkeit in der Wirksamkeit hängt vom Ziel der Flexibilität (z.B. Glättung von Lastkurven vs. Reduktion von Lastspitzen), der Technologieentwicklung und -verbreitung (insbesondere dem Ausbau von Ladeinfrastruktur) und dem Netzgebiet (z.B. Stadt, Land, Vorstadt) ab. Darüber hinaus können einige Ladeverhalten mehrere Flexibilitätsziele erfüllen, während andere nur für ein Flexibilitätsziel gut funktionieren und für andere Ziele mit starken Trade-offs einher gehen. Beispielsweise sind für Netzgebiete mit einem hohen Anteil an PV-Strom oder hohen Ambitionen den Anteil an PV-Strom zu erhöhen Ladeprozesse, welche die Ladelast zur Tagesmitte hin verschieben, vorteilhaft. Jedoch führen diese Ladeprozesse in unseren Simulationen nicht dazu, dass die Lastspitze reduziert oder die gesamte Lastkurve abgeflacht wird, was in manchen Netzgebieten eine Herausforderung darstellen kann. Wenn viele Flexibilitätsziele gleichzeitig erreicht werden sollen, können sich beispielsweise Ladeprozesse sehr gut eignen, welche mit geringerer Leistung laden. Dahingegen können andere Ladeprozesse wie beispielsweise ein abendliches netzdienliches Entladen des EVs und Wiederaufladen zur Mittagszeit oder am Ende der Standzeit die Verlagerung eines großen Teils der Last ermöglichen, aber die tägliche Spitzenlast sogar erhöhen. Wir unterscheiden zwischen zwei Komponenten des Ladens: dem Einsteckverhalten (plug-in behavior) und dem Ladevorgang (charging process). Während Ersteres vom Sozialverhalten des Nutzers abhängt und sich auf die zeitliche und räumliche Verteilung der Last bezieht, ist Letzteres typischerweise automatisiert - sobald es vom Nutzer akzeptiert wurde - und bezieht sich nur auf die zeitliche Verteilung der Last. Unsere Ergebnisse zeigen, dass gesteuerte Ladevorgänge einen größeren Einfluss auf die betrachteten Flexibilitätsmaße haben als Veränderungen im Einsteckverhalten. Die Auswirkungen des Einsteckverhaltens hängen vom Ziel der Flexibilität, der Technologieverbreitung und dem gesteuerten Ladevorgang ab, mit dem es kombiniert wird. Hinsichtlich der verschiedenen Nutzungsarten von EVs stellen wir fest, dass hohe Spitzenlasten typischerweise von bestimmten

Nutzertypen verursacht werden, wie z.B. von EV-Nutzern, welche ihr Auto sehr häufig benutzen oder solche, welche sehr weite Strecken fahren – obwohl diese einen relativ geringen Anteil an der Gesamtflotte ausmachen, z.B. ca. 20% im Kanton Zürich.

Hinsichtlich der Anreize (RQ3) zeigen unsere Analysen, dass unterschiedliche Ausgestaltungen von zeitvariablen (time-of-use, TOU) Tarifen unterschiedliche Auswirkungen auf die Last haben. Die Ausgestaltungen unterscheiden sich in der Höhe der Tarife zu unterschiedlichen Zeiten und an unterschiedlichen Ladestandorten (zu Hause, am Arbeitsplatz, öffentlich). Zudem berücksichtigen wir unterschiedliches Nutzerverhalten. So zeigen unsere Simulationen, dass beispielsweise typische abendliche Lastspitzen an Heimstandorten durch teure Preisniveaus erheblich reduziert werden können, jedoch eine darauffolgende Niedrigpreisperiode zu einem Überkoordinierungseffekt führen kann, welcher in einer (sogar höheren) Lastspitze resultieren kann.

Basierend auf diesen Erkenntnissen leiten wir Implikationen für Entscheidungsträger in Politik, Industrie und Wissenschaft ab, um die netzdienliche Integration des steigenden Anteils von EVs zu unterstützen. Der vorliegende Abschlussbericht fasst die wichtigsten Ergebnisse des Projekts zusammen.

Résumé

Le but principal du projet de recherche Ervin est de comprendre comment une plus grande proportion de véhicules électriques peut être intégrée de manière flexible aux réseaux de distribution électrique. Ce projet vise à répondre à trois questions de recherche (QR) : (QR1) identifier les environnements prometteurs et les défis (techniques, sociaux et réglementaires) pour l'intégration bidirectionnelle des véhicules électriques (VE) en tant que source de flexibilité dans les réseaux électriques ; (QR2) comprendre comment l'interaction entre les différentes stratégies de décharge/charge des VE, les types d'utilisateurs et les paramètres du réseau affectent l'attrait des VE en tant qu'option de flexibilité dans différents réseaux de distribution ; et (QR3) analyser comment les différentes incitations affectent l'intégration des VE en tant qu'option de flexibilité. Nous combinons des méthodes quantitatives et qualitatives pour quantifier et modéliser. Plus précisément, nous avons effectué une analyse de base de données et mené des entretiens avec des spécialistes afin de répondre à QR1, et créé un modèle multi-agents pour répondre à QR2 et QR3.

Concernant la mise en œuvre de la charge bidirectionnelle (QR1), nous avons constaté que les études actuelles (analyses globales) se concentrent sur les véhicules électriques commerciaux qui sont rechargés au travail, ainsi que sur la fourniture de services vehicle-to-customer (V2C) (notamment vehicle-to-home et vehicle-to-building) et de transmission, ce qui les rend prometteurs pour une application commerciale. Toutefois, l'utilisation à des fins commerciales est entravée par plusieurs défis technologiques, sociaux et réglementaires. Les difficultés sociales et réglementaires, en particulier, dépendent fortement du contexte et peuvent varier considérablement d'un pays à l'autre. Par exemple, en Suisse, des incertitudes persistent quant à la demande et l'offre futures de flexibilité, la participation des utilisateurs et l'acquisition de flexibilité au niveau du réseau de distribution, notamment les futures structures tarifaires et de marché.

En ce qui concerne l'interaction entre les différentes stratégies de décharge/recharge des véhicules électriques, les types d'utilisateurs et les paramètres du réseau (QR2), nous avons constaté que l'efficacité des différentes stratégies de recharge dépend de l'objectif de la flexibilité (par exemple, aplatissement des courbes de charge par rapport à la réduction des pics), du développement et de la diffusion de la technologie (en particulier, déploiement de l'infrastructure) et de la zone du réseau (par exemple, urbain, rural, suburbain). En outre, bien que certaines pratiques de charge puissent répondre à plusieurs objectifs de flexibilité, d'autres fonctionnent bien uniquement pour un objectif de flexibilité et s'accompagnent de fortes contreparties pour les autres. Par exemple, dans les zones de réseau avec de fortes parts de puissance PV, les processus de charge qui déplacent les charges vers le milieu de journée peuvent être avantageux, mais ils ne réduisent pas le pic quotidien et n'aplatissent pas la courbe de charge globale. Pour atteindre plusieurs objectifs de flexibilité simultanément, des processus de

charge avec moins d'énergie peuvent être bénéfiques, mais d'autres processus de charge, tels que la décharge avantageuse du réseau pendant le pic du soir et la recharge en milieu ou à la fin de la journée, permettent de déplacer une grande partie de la charge. Cependant, ils peuvent même contribuer à accroître le pic global. Nous distinguons ici deux types de charge : le comportement de branchement et le processus de charge. Si le premier dépend du comportement social de l'utilisateur et concerne la répartition dans le temps et l'espace de la charge de travail, le second est généralement automatisé (une fois accepté par l'utilisateur) et traite de la répartition dans le temps de cette charge. Nous avons constaté que les processus de facturation contrôlés ont plus d'influence sur les adaptations faites que les fonctionnalités des plug-ins. L'efficacité du plug-in dépend de l'objectif de flexibilité, de la diffusion technologique et du scénario de charge qu'il est censé gérer. En ce qui concerne les véhicules électriques, nous constatons que les pics de consommation sont principalement dus à certains types d'utilisation, notamment ceux qui les utilisent fréquemment et ceux qui parcourent de longues distances. Bien que ces types d'utilisation représentent une part relativement faible de la flotte automobile, par exemple environ 20 % dans le Canton de Zurich, ils contribuent grandement à la consommation.

En ce qui concerne les incitations (QR3), nous avons constaté que différents modèles de tarifs horaires ont des conséquences variées sur les coûts de charge. Les prix varient selon le moment et le lieu de la recharge (chez soi, au travail ou en public), et nous tenons compte des réactions des utilisateurs. Nos simulations indiquent que, bien que les pics typiques du soir sur les sites domestiques puissent être considérablement réduits grâce à des tarifs élevés, le prix bas qui suit peut entraîner une coordination excessive, entraînant ainsi un pic encore plus élevé au début de la période de tarification basse.

Sur la base de ces résultats, nous pouvons déduire des implications pour les décideurs en matière de politique, d'industrie et d'enseignement afin de soutenir l'intégration des véhicules électriques dans le réseau électrique et de permettre une plus grande part de marché de cette technologie. Ce rapport final récapitule les conclusions les plus importantes du projet.

Summary

The overall purpose of the research project Enabling Flexible Electric Vehicle Grid Integration (ErVIn) is to understand how the increasing share of EVs can be beneficially integrated into distribution grids. More specifically, this project addresses three research questions (RQs) and aims to (RQ1) identify promising settings of and challenges (technical, social, and regulatory) for the bidirectional integration of EVs as a promising flexibility source in electricity grids, and understand (RQ2) how the interplay between different EV dis-/charging strategies, user types and grid settings affects the attractiveness for EVs as flexibility option in different distribution grids, and (RQ3) how different incentives affect the integration of EVs as a flexibility option. We use both quantitative and qualitative methods with a quantitative (modelling) focus. More specifically, we conducted a database analysis and expert interviews to address RQ1 and developed an agent-based model to address RQ2 and RQ3.

Regarding the implementation of bidirectional charging (RQ1), we find that current trials (global analysis) focus on commercial EVs that charge at work as well as the provision of vehicle-to-customer (V2C) (including vehicle-to-home and vehicle-to-building) and transmission services, indicating them as promising settings for commercial application. However, commercial application is hampered by several technological, social, and regulatory challenges. In particular, social, and regulatory challenges strongly depend on the context and can substantially differ between countries. For example—and also relevant for Switzerland—uncertainties exist regarding future demand and supply of flexibility, user participation and flexibility procurement at distribution-grid level including future market and tariff structures.

Regarding the interplay between different EV dis-/charging strategies, user types and grid settings (RQ2), we find that different charging strategies differ in their effectiveness for flexibility provision. These differences depend on the goal of the flexibility (e.g., flattening load curves vs. peak reduction), technology development and diffusion (in particular, infrastructure deployment) and the grid area (e.g., urban, rural, suburban). In addition, while some charging behaviors can address several flexibility goals,

others only work well for one flexibility goal and come with strong trade-offs for others. For example, and for grid areas with high shares of PV power or high ambitions to increase PV power, charging processes that shift charging loads towards midday can be advantageous. Yet, in our simulations, these charging processes do neither reduce the daily peak nor flatten the overall load curve, which could be challenging for certain grid settings. If several flexibility goals should be reached simultaneously, charging processes that charge with less power can be beneficial. However, other charging processes, for example that discharge in a grid beneficial way during the evening peak and recharge during midday or at the end of the dwell-time allow for shifting a large share of load but can even increase the overall peak. We distinguish between two components of charging, the plug-in behavior, and the charging process. While the former depends on the user`s social behavior and relates to the temporal and spatial distribution of charging load, the latter is typically automated—once it has been accepted by the user—and relates to the temporal distribution of charging load. We find that controlled charging processes show higher impact on the flexibility metrics considered than plug-in behaviors. The beneficial impact of plug-in behavior depends on the flexibility goal, technology diffusion, and the controlled charging scenario that it is combined with. Regarding different EV use types, we find that high peaks are typically caused by certain use types such as EV users using their car very often and EV users driving long distances—despite their relatively low share in the overall car fleet, e.g., about ~20% in the Canton of Zurich.

Regarding incentives (RQ3), we find that different designs of time-of-use tariffs result in different effects on charging loads. The designs differ in price levels for different time periods, but also for different charging locations (home, work, public). Moreover, we consider different user reactions. Our simulations show, for example, that while the typical evening peak at home locations can be substantially reduced due to expensive price levels, the following low-price period might result in an over-coordination effect, causing an even higher peak at the beginning of the low-price period.

Based on these findings, we derive implications for decision makers in policy, industry, and academia on how to support the integration of increasingly high shares of EVs in a grid-friendly way. This final report summarizes the main findings of the project.

Main findings

- To foster the implementation of bidirectional charging, decision-makers in policy and industry should support trials that test broad combinations of user types, charging stations and services. While current trials for bidirectional charging mostly focus on commercial EVs that charge at work and the provision of vehicle-to-customer (including vehicle-to-home and vehicle-to-building) and transmission grid services, broader combinations are expected to reduce risks such as market risks or the dependence on the behavior of specific EV user groups and allow for higher revenues.
- Moreover, technical, social, and regulatory challenges that hamper further V2X implementation have to be removed. Among the most critical barriers that we also consider relevant for Switzerland are uncertainties regarding the design of market structures or other mechanisms (e.g., tariffs, tenders, auctions) to acquire flexibility at distribution-grid level, future flexibility supply and demand, and the EV users' willingness to participate in V2G including the effect(s) of corresponding incentives.
- To design effective incentives for flexible EV charging, decision-makers in policy and industry need to consider automated and behavioral components of EV charging. EV charging consists of two different components: the (controlled) charging process and the plug-in behavior. While the former is typically automated—once it has been accepted by the user—and relates to the temporal distribution of charging load, the latter depends on the user`s social behavior and typically involves changing routines and relates to both the temporal and spatial distribution of charging load.
- The flexibility potential depends on the specific combination of charging processes and plug-in behaviors, the spatial structure (i.e., urban, rural, or suburban area and home, work, or public charging location) and technology developments and diffusion, in particular charging infrastructure. Controlled charging processes have, in general, a higher flexibility potential than plug-in behavior. However, the latter can have a relatively high effect in certain contexts, e.g., in cases of low technology diffusion and/or rural areas. The beneficial impact of plug-in behavior depends on the flexibility goal, technology diffusion, and the controlled charging scenario. Plug-in behaviors are more relevant in rural areas than in urban/suburban areas and their flexibility potential increases with high EV and charging infrastructure diffusion—yet, despite this increase, it is lower than that of charging processes at high technology diffusion. EV users using their car very often and driving long distances cause high load peak loads —and account for about 20% of the overall car fleet in the Canton of Zurich.
- Grid operators should evaluate the needs of a specific grid setting and design incentives accordingly. Different charging behaviors perform differently regarding different flexibility goals such as the integration of photovoltaic power or peak reduction. While some of the behaviors perform well in several flexibility goals, others are beneficial for one goal and come with trade-offs for others.
- Moreover, decision-makers in industry and policy should prepare to adapt incentives over time because the effect of combinations of plug-in behavior and charging processes changes with technology diffusion and the accompanied changes in user behavior. This requires monitoring technology diffusion and develop a good understanding of user behavior at different diffusion stages.
- Decision-makers in industry and policy designing time-of-use tariffs for flexible EV charging should be aware of a potential over-coordination effect that might occur during low-price periods. Moreover, they should ensure a high attractiveness of the tariff design to EV users and consider different charging locations and their specificities in their tariff design.

Contents

Abbreviations

BEV	Battery electric vehicle
DSO	Distribution system operator
EV	Electric vehicle
PHEV	Plug-in hybrid electric vehicle
PV	Photovoltaic
RQ	Research question
SOC	State of charge
TOU	Time-of-use
TSO	Transmission system operator
V2B	Vehicle-to-building
V2C	Vehicle-to-customer
V2G	Vehicle-to-grid
V2H	Vehicle-to-home
V2X	Vehicle-to-X

1 Introduction

1.1 Background information and current situation

In many countries, the number of electric vehicles (EVs) has started to expand[1]. In Switzerland, in particular, the original (set in 2018) target of reaching 15% EVs (Battery electric vehicles, BEVs, and plug-in hybrid electric vehicles, PHEVs) in new car sales in 2022 had already been fulfilled in 2021. The current plan is to reach a share of 50% in 2025, accompanied by the acceleration and improvement of related infrastructure systems (e.g. the availability of charging stations)[2]. In particular for passenger cars, the currently relatively low share of 2.3% of EVs on the total passenger car stock[3] is expected to increase substantially during the next years (e.g., to around 30% in 2030 and to up to 100% in 2040-2050 depending on the scenario considered[4]). Although the uptake of EVs can challenge existing grids in case of uncontrolled, instant charging[5], EVs can also provide flexibility and frequency services to distribution and transmission grids[6,7]. Hence, EVs can help to integrate high shares of intermittent renewable energy production, such as wind and photovoltaic (PV) power[8,9]. In doing so, they contribute to the decarbonization of both the electricity and the transportation sector. To this end, smart or controlled EV integration can support load balancing, reduce peak-loads, and reduce the uncertainty in electric load forecasting[10,11]. Yet, the extent of stress or flexibility that can be provided by EVs depends on grid settings, user types, and dis-/charging strategies. For example, a grid setting defined by high shares of solar PV fits a beneficial EV integration more than one defined by high shares of wind power because the daily pattern of solar PV generation can favor the storage capabilities of EVs[12]. Charging strategies of EV users range from instant charging (uncontrolled charging) to controlled charging (load and time) including bidirectional integration such as vehicle-to-grid (V2G)[11]. While the first charging strategy puts an additional burden on grid reliability by potentially increasing peak load, the second and third ones allow for a beneficial integration of EVs[9]. However, EVs rarely provide these services to the grid today; specifically bidirectional charging technology is still in its pilot phase[13]. The potential of EVs as flexibility source for the grid "has not yet been seriously explored"[14].

While previous research on the flexible integration of EVs into the electricity grid has mainly focused on developing technical solutions, less is known about socio-economic aspects[15], such as different EV dis-/charging strategies and/of different vehicle use types. Moreover, grid settings differ substantially between individual distribution grids[16]. Together with the currently sparse diffusion of grid-friendly EV integration solutions, specific incentives for smart dis-/charging might be necessary[17–19].

Extant work has begun to evaluate how to better model EV user behavior[10]. However, they fall short in modelling the behavioral nuances that were evaluated empirically[20]. Extant work has also begun to evaluate how to best incentivize EV users to allow for smart charging[17] or participate in electricity markets[18,19]. Yet, studies that have started to consider some form of economic incentive typically focus, separately or in selected combinations, on specific grid settings[10,12,17,21,22], charging strategies and/of user types[10,12,21], and flexibility services[17], and hence fall short in combining all of them. Even recent work that has started to integrate several of these aspects into their modelling of EV integration[10,21] lacks a detailed understanding of the interplay of incentives and user behavior, and/or focuses on higher grid levels and thereby misses local congestions. Hence, extant studies neglect the combination of (i) an interplay between all of the aspects mentioned—particularly integrating social aspects[15] –, (ii) a comparison between a broader variety of arrangements of vehicle types, user profiles, and grid settings[11], and (iii) future technical developments such as technology improvements or the diffusion of other related technologies such as PV power, charging infrastructure or stationary storage[23]. Therefore, this project aims to develop a holistic picture by considering all these three dimensions, which are relevant for the successful integration of EVs into the electricity grid.

1.2 Purpose of the project

The overall purpose of the project is to understand how the increasing share of EVs can be beneficially integrated into distribution grid(s). More specifically, the project aims to understand how a combination of EVs and other and related technologies such as renewable power generation, infrastructure or stationary storage technologies can become an attractive solution for different distribution grid settings. We consider technical and socio-economic factors, such as EV user types, dis-/charging strategies, their interplay with complex and multiple grid settings, and different suitable incentives. Incentives such as flexibility remuneration or rate structures could help to steer EV dis-/charging and hence, leverage the potential benefits of EVs for the electricity grid, but need to be analyzed and understood in more detail. The project therefore aims to identify key levers and policy measures that allow for a smooth integration of EVs and/or can steer EV dis-/charging in a grid-friendly way to support increased shares of renewable power generation by taking the idiosyncrasies of both EV users and grid settings into account.

1.3 Objectives

This overall purpose is tackled by three research questions, each allocated to an individual work package.

Research questions

(1) What are promising settings and challenges (technical, social, and regulatory) for the bidirectional integration of EVs as flexibility source in electricity grids? (Work package 1)
(2) How does the interplay between different EV *dis-/charging strategies,* user types and grid settings affect the attractiveness for EVs as flexibility option in different distribution grids? (Work package 2)
(3) How do different incentives affect the integration of EVs as a flexibility option in different distribution grid settings? (Work package 3)

In this report, we summarize the findings of our studies in three policy briefs, each addressing one of the research questions. For more detailed information, we refer the reader to the related publications referenced in each of the policy briefs.

2 Promising settings of and challenges for V2X implementation

2.1 Executive summary

- Despite the high potential of V2X and an increasing number of trials, it is unclear which applications are most promising and how to master the step to commercial implementation
- Current V2X trials mostly focus on commercial EVs that charge at work and on the provision of vehicle-to-customer and transmission grid services.
- Technical, social, and regulatory challenges hamper further V2X implementation. Among the most critical barriers that we consider relevant also for Switzerland are uncertainties regarding the design of market structures or other mechanisms (e.g., tariffs, tenders, auctions) to acquire flexibility at distribution-grid level, future flexibility supply and demand, and the EV users' willingness to participate in V2G including the effect(s) of corresponding incentives.
- A broader combination of user types, charging stations and services should be tested in trials because pooling different use types, charging locations and services should result in the reduction of uncertainties and allow for more diversity in business models and higher revenues, industry should develop relevant technologies such as platforms, and policy makers should remove regulatory barriers such as flexibility procurement at distribution grid level as well as enable the cooperation between the different related actors.

2.2 The problem

A substantial increase in EVs is expected during the next years, globally and in Switzerland[1]. While EV charging can stress existing grids, e.g., in case of peaks in distribution grids and uncontrolled, instant charging[5], smart dis-/charging of EVs can also result in flexibility provision[6,7] and hence, help to increase high shares of intermittent renewable power production.

In addition to controlled charging processes that shift/reduce EV charging loads, bidirectional charging (Vehicle-to-X, V2X), i.e., the provision of electricity to the grid (V2G)[24] or the customer (V2C[1])[13], can result in additional benefits to transmission and distribution grids. Moreover, this serving of EVs as mobile batteries to the grid might also yield in additional revenues for the EV owners[25]. While the number of V2X trials has been increasing during the last years, commercial implementation is still rare[14] - despite its potential for electricity grids.

Hence, there is a need to improve the understanding of the future of V2X and to identify the existing challenges for V2X implementation. Which settings are most promising for V2X, and which challenges exist for the uptake of V2X and how do experts assess these challenges?

2.3 The findings

2.3.1 Commercial EVs that charge at work as well as the provision of V2C and transmission services are in focus of trials

Our findings base on an analysis of the database "V2G Hub"[26] and interviews with experts in the field. Our analysis of combinations of vehicle use types, charging locations and the provided services indicates promising settings for future V2X implementations. Figure 1 shows that commercial EVs that charge at work as well as the provision of V2C and transmission services are in focus of the trials.

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[1] V2C (vehicle-to-customer) includes V2B (vehicle-to-building) and V2H (vehicle-to-home).

According to the experts interviewed, the advantage of commercial vehicles is that fewer actors involved enable a centralized approach. Hence, for the same number of vehicles less contracts, training and infrastructure are needed. In addition, predefined usage plans, the state of charge and thus the potential for possible services can be predicted more accurately, which means that the EVs can participate in balancing energy with greater certainty. The currently less prominent domestic vehicles, however, also offer advantages, such as their low utilization for mobility (96% of the time unused) and thus high potential for grid services.

The focus on charging at work can result from the fact that the installation and maintenance of central charging—as opposed to decentral charging at home or public charging stations—is associated with less effort. In addition, grids at commercial locations often allow for higher charging capacities. Furthermore, charging domestic vehicles at the workplace can help to integrate PV power because the timing of the charging typically fits well to the timing of PV power production.

V2C is frequently implemented because it avoids the complex interface with the grid, simplifying implementation and the number of actors involved. In commercial applications, V2C can reduce peaks and thus reduce capacity prices. In domestic applications, V2C is mostly implemented for ideal reasons. Technology-affine households integrate their EV into their home energy system, e.g., increase the self-consumption of their produced PV power.

The preference for transmission over distribution grid services can be explained with the already existing control reserve markets at transmission level, allowing to estimate the economic value for the respective service. At the distribution grid level, this value is yet unclear. In particular, the lack of data on grid utilization hampers the estimation of required services and hence, possible sales.

Thus, experts recommend a mix of different use types, charging locations and services. In addition to higher revenues, pooling different use types, charging locations and services should result in a better spatial-temporal distribution of charging load as well as reduce the risks from uncertainties resulting from diverse driving and charging behavior and long-term market and flexibility developments.

This means that future trials should test broad combinations of user types, charging stations and services, combined with data collection e.g., on service provision or the users' plug-in behavior to support the developments of business models. Moreover, the interplay of V2X with future mobility concepts such as carsharing or autonomous driving should be investigated in more detail. While this requires efforts from all actors that participate in future trials, policy makers can support such trials with sufficient R&D funding and a suitable design of existing or new R&D funding programs.

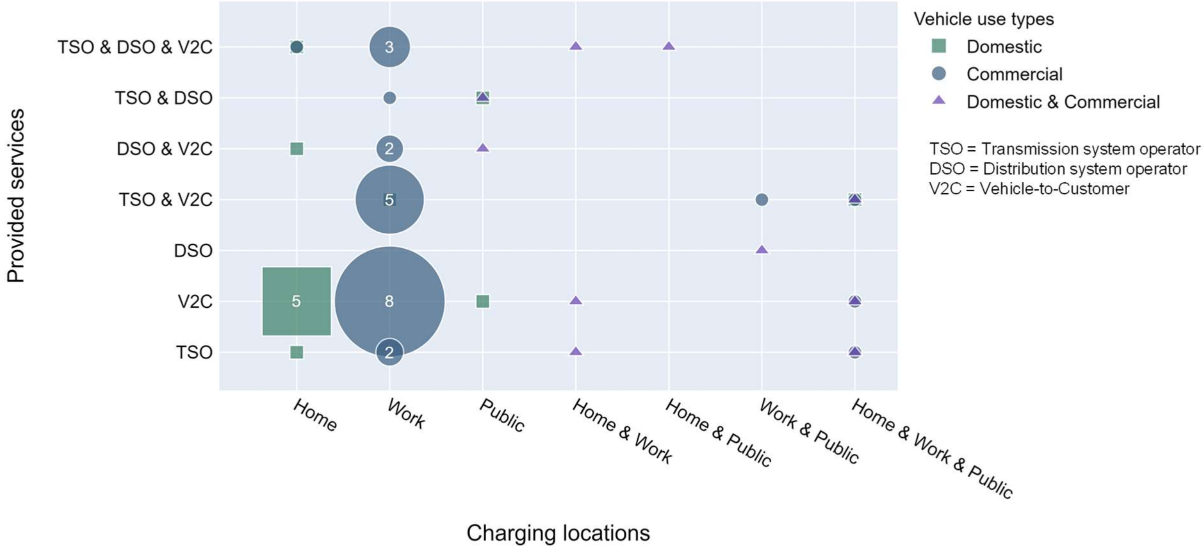

Figure 1 Configurations of analyzed trials. TSO = Transmission system operator, DSO = Distribution system operator, V2C = Vehicle-to-customer (including vehicle-to-building and vehicle-to-home). Source: Gschwendtner et al. (2021)[27]

2.3.2 Technical, social and regulatory challenges for further V2X implementation

According to the experts, challenges exist in the technical, social, and regulatory domains (Figure 2). While for some of the challenges, the experts interviewed share the evaluation, the experts' different evaluations for others as well as the identified knowledge gaps indicate the uncertainty around V2X.

In the technical domain, for example, the experts agree that battery degradation, which is often discussed as technical barrier, is not a technical but rather a social challenge. However, the experts' evaluation on the potential of V2X for distribution grid reinforcement deferral or even mitigation differs. While some experts see high potential and emphasize that smart solutions might even prevent distribution grid reinforcements, others are less optimistic. One of the most important knowledge gaps is the future flexibility supply and demand. While the demand is expected to increase in the future because of increasing intermittent renewable power production, the diffusion of technologies such as EVs and heat pumps might even result in an oversupply. In addition, this effect could be reinforced with increasing V2C adoption, which would also reduce flexibility demand.

In the social domain, for example, the general willingness to participate in V2X and the required incentives that increase its attractiveness are unclear. Both can hardly be estimated from trials. Particularly uncertain is whether people with less technological interest would participate. In addition, the intermediate stages with 10-30% participation challenge the system because there is high uncertainty due to less of a pooling effect of diverse driving profiles and less predictability. In addition, local clustering resulting from neighboring effects might even reinforce this problem. Moreover, experts' evaluations differ regarding the EV users' plug-in behavior as well as the compatibility of V2X with future mobility trends such as car sharing and autonomous driving.

In the regulatory domain, for example, the design of markets and mechanisms at distribution grid level is unclear. More specifically, it is unclear how flexibility supply and demand will be coordinated at the distribution grid level. This relates, for example, to the size / geographic area of the market and the mechanisms of financial compensation. One possibility is markets that cover specific geographic areas. However, the size of these areas is difficult to define. Although already at street level with 20 to 30 houses, there are different needs for a suitable load management, the high degree of flexibility needed in such small flexibility is difficult to achieve. This favors larger areas or cooperations with TSOs. Flexibility might be remunerated via different forms of time-of-use (TOU) tariffs, which have to be easily understandable for users, but experts also call for tenders or auctions, being more flexible. In addition, prequalification processes that impede participation for small providers due to minimum bid sizes, or the lack of incentives that support the implementation of smart solutions rather than grid reinforcement hamper V2X implementation.

This means that policy makers who want to support further V2X implementation should remove these regulatory barriers. Overall, this means that V2X should be (easily) implementable from a regulatory perspective—for different actors (small and big ones) and at different grid levels. One key aspect, which we also consider relevant for Switzerland, is how flexibility would be acquired and remunerated at distribution-grid level. The creation of markets would be one possibility, but also alternative mechanisms such as tariffs (e.g., time-of-use tariffs), auctions or tenders might be possible. Moreover, removing regulatory barriers involves the support of relevant technical standards, potentially the provision of financial incentives to DSOs to implement smart solutions rather than grid reinforcement, and the simplifying market participation for all, especially small, providers, e.g., by simplifying prequalification processes, shortening or sale cycles or reducing minimum bids. In addition, policy makers should be aware that existing policies supporting the installation of charging infrastructure might create a technological lock-in for unidirectional charging. Existing policies typically incentivize charging station providers to scale output rather than providing new and innovative solutions such as bidirectional charging. Moreover, the cooperation between the relevant fields such as the automotive and electricity industry should be strengthened. For example, the developments of standards and of cross-sectoral business models requires the actors to closely cooperate. Policy makers can support these cooperations e.g., via funding conferences or subsidizing joint projects.

In addition to participating in trials, industry players should develop agile platforms that allow for an economically viable service provision and monitoring systems that collect distribution grid data to allow for a better evaluation of business opportunities and the development of business models.

	Technical challenges	Social challenges	Regulatory challenges
Common evaluations	• **Battery degradation** is rather a social challenge	• Implementation of **decentralized charging**	• Market participation of **small providers**
Different evaluations	• Distribution **grid reinforcement deferral and mitigation**	• **Plug-in behavior** • **Future mobility**	• Hesitation of DSOs toward **smart solutions**
Knowledge gaps	• **Future flexibility** supply and demand	• Participation in V2X and **potential incentives**	• **Markets, tariffs, auctions or tenders** at the DSO level

Figure 2 Selection of most relevant technical, social, and regulatory challenges for V2X implementation. DSO = Distribution system operator. Source: simplified from Gschwendtner et al. (2021)[27]

2.4 The study

In our study[27], we combined a review of academic and practical literature with an analysis of V2X projects, i.e., trials, from the online database “V2G Hub”, and a series of interviews with experts from industry and academia. At the time of the analysis, the “V2G Hub” database comprised 80 projects (this number has increased to 107 at the beginning of 2023[26]), which predominantly occurred in Europe, Asia and North America. We focused on the 47 projects for which data regarding vehicle use types, charging locations and provided services had been available. To complement the data, understand the drivers behind the most promising V2X configurations, and identify the barriers for further implementation, we conducted 47 semi-structured interviews with experts. The interviewees had been sampled purposively and the final sample covers a variety of backgrounds and different stakeholder groups. We focused on experts from those countries with the highest V2X activities, i.e., Germany, the Netherlands, the UK, and the U.S., complemented by interviews with experts from other countries such as Canada, Denmark, France, Spain, and Switzerland.

3 The effect of EV charging strategies on the flexibility of EV charging load in different grid settings

3.1 Executive summary

- EV charging consists of two different components: plug-in behavior and the (controlled) charging process. While the former depends on the user`s social behavior and relates to the temporal and spatial distribution of charging load, the latter is typically automated—once it has been accepted by the user—and relates to the temporal distribution of charging load.
- Controlled charging processes perform differently with respect to different flexibility goals. While some of the controlled charging processes perform well in all flexibility metrics considered, for other controlled charging processes trade-offs are quite large.
- Controlled charging processes have, in general, a higher flexibility potential than plug-in behavior. However, the latter can have a substantial effect in certain contexts, e.g., in cases of low technology diffusion and/or rural areas.
- The beneficial impact of plug-in behavior depends on the flexibility goal, technology diffusion, and the controlled charging scenario. Plug-in behaviors are more relevant in rural areas than in urban/suburban areas and their flexibility potential increases with high EV and charging infrastructure diffusion—yet, in the latter case, it is lower than that of charging processes.
- EV users using their car very often and driving long distances cause high load peak loads —and account for about 20% of the overall car fleet in the Canton of Zurich.
- To incentivize the most suitable charging behaviors for specific grid settings, decision-makers in industry and policy should be aware of the flexibility goals of the specific grid areas and consider trade-offs between flexibility goals. While charging processes generally have a higher impact on flexibility provision than plug-in behaviors, the plug-in behavior has a more pronounced effect in rural than in (sub-)urban areas. In particular, motivating users to plug-in their car and charge once the SOC has fallen below a certain threshold could substantially reduce load peaks in rural areas.
- Moreover, decision-makers in industry and policy should prepare to adapt incentives over time because the effect of combinations of plug-in behaviors and charging processes changes with technology diffusion and the accompanied changes in user behavior. This requires monitoring technology diffusion and develop a good understanding of user behavior at different diffusion stages.

3.2 The problem

To cope with climate change mitigation requirements, high shares of EVs are required, together with high shares of renewable power production[28]. While the increasing share of EVs can challenge existing grids, EVs can also provide flexibility—and hence support the integration of intermittent renewable power production[29,30]. For example, controlled EV charging can shift loads to times with high PV power supply[6,31] or spread the charging across time and locations. Controlling EV charging is not only a technical issue but also a behavioral one because the heterogeneity of EV load profiles depends on both driving and charging behavior[32,33]. This is especially relevant for distribution grids and different spatial structures (i.e., urban, suburban, rural areas or home, work, and public charging locations) because patterns might aggregate at small geographical areas and, hence, cause high and local load peaks.

However, extant approaches modelling EV charging loads have mostly overlooked the heterogeneity in charging behavior[34]. In addition, extant studies have typically focused on the automated charging process during individual dwell times (e.g., Arias et al.[35] and Xiang et al.[36]) and hence neglect the flexibility potential resulting from plug-in behavior, i.e., when and where the car is plugged in to charge. Plug-in behavior is relevant for spreading charging loads not only over time but also over locations and hence relates to the flexibility potential due to the distribution charging loads between dwell times

Which kind of flexibility is required depends on the specific distribution grid's setting such as the amount of PV production or the existing load profiles (and their flexibility). Hence, not all controlled charging strategies might perform equally well for different flexibility goals resulting in trade-offs. A good understanding of the impact of controlled charging on the flexibility potential in different grid settings and charging locations is essential for decision makers in policy and industry to design incentives to leverage this potential.

3.3 The findings

3.3.1 Different controlled charging strategies result in trade-offs between different flexibility goals

Our findings base on simulations of EV load profiles using an agent-based model. We develop different frame-scenarios covering different technology diffusion stages and developments such as battery capacities and charging station developments and EV deployment ranging from the status quo in Switzerland (scenario *Current State*) to a 100% share of BEVs in the passenger car fleet (scenario *Full BEV*) (see Table 2 in the Appendix for a more detailed description of the scenarios). We consider different charging locations (home, work, public) and (grid) areas (urban, rural, suburban) and use simulated mobility data for passenger cars of a synthetic population of Switzerland[37]. These data cover an average weekday for different time steps from today until 2050 and different EV user types, i.e., driving behaviors. We focus on three geographical areas in Switzerland, an urban agglomeration (Zurich), a rural multicentric (Freiburg) and a rural monocentric (Graubunden) case.

We measure different flexibility goals with four metrics: total load shift, increase in midday load, peak reduction, and the reduction of standard deviation of daily load. While total load shift measures the general flexibility of in- and decreasing loads, the other three metrics relate to more specific goals. Increasing midday load measures how well EV charging load would relate to PV power production during midday, peak reduction measures the height of the daily peak, and the reduction of standard deviation measures the overall flattening of the EV charging load curve.

We consider that EV charging consists of two different components: plug-in behavior and the (controlled) charging process. While the former depends on the user`s social behavior and relates to the temporal and spatial distribution of charging load, and the latter is typically automated—once it has been accepted by the user—and only related to the temporal distribution of charging load. We focus on five plug-in behaviors and six charging processes, which are described in Figure 3. In our simulations, changes in plug-in behavior and/or charging processes do not affect the driving behavior or the duration of dwell times.

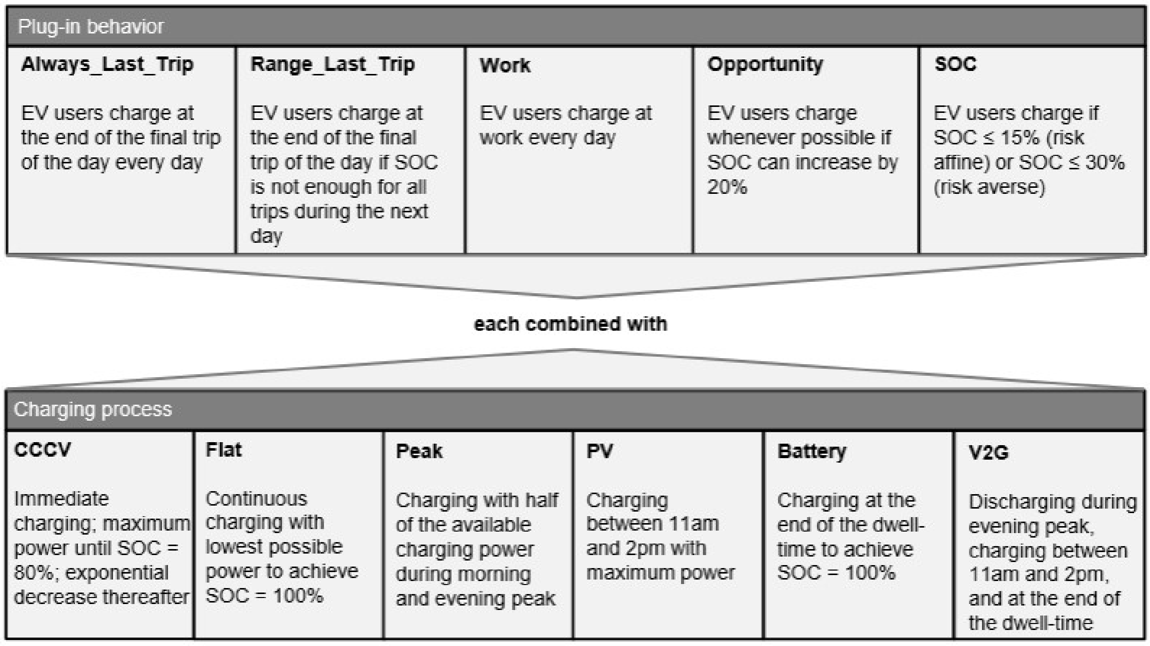

Figure 3 Different plug-in behaviors and charging processes. SOC = state of charge, CCCV = Constant current constant voltage, PV = photovoltaic, V2G = vehicle-to-grid. Source: Gschwendtner et al. (2023)[38]

We find that different charging processes perform differently regarding different flexibility metrics and that there are trade-offs between flexibility metrics of the different charging processes considered in this study (Figure 4, the average is taken across all plug-in behaviors). While all the charging processes considered result in a shift of load during the day and increase the share of load during midday—compared to the base case of *CCCV—,* only the charging process *Flat* substantially reduces the daily peak and flattens the overall load curve. Hence, the metrics reaching peak reduction and flattening the load curve are harder to be achieved than to shift load and increase the load during midday, which can be achieved by all or at least several of the considered controlled charging processes. Moreover, some of the charging processes such as *Flat* or *PV* perform well in all metrics, i.e., show relatively small tradeoffs, whereas for others such as *Battery* or *V2G* trade-offs are quite large. The charging process *V2G*, for example, can help to shift substantial loads during the day and move them to midday while it results in an overall increase of the daily peak. This increase of the daily peak typically occurs in the morning or during midday and might be challenging for specific grids and should.

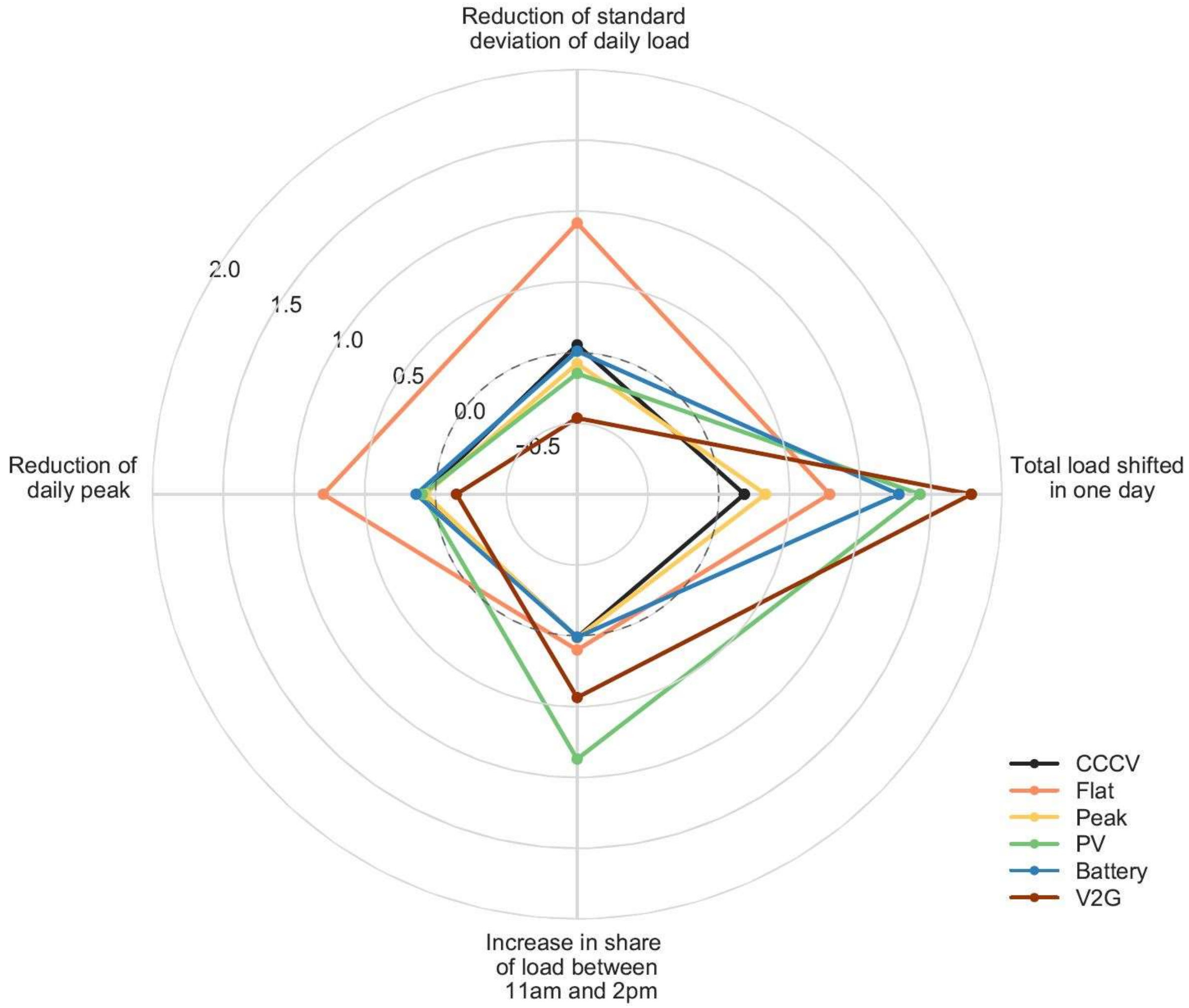

Figure 4 Overview of the considered flexibility metrics and the average performance of the six considered charging processes in the *Ful BEV* scenario for the urban agglomeration case (Zurich). The average is taken across all plug-in behaviors. The flexibility metrics have been calculated as differences from the baseline of the plug-in behavior *Always Last Trip* combined with the charging process *CCCV* (see Figure 3 for details). The metric *Total shifted load in one day* measures the general flexibility and, hence, adds load increase and reduction, which explains why the numbers of this metric are higher than for the other metrics. Source: Gschwendtner et al. (2023)[39]

Hence, decision-makers in industry such as grid or charging station operators should be aware of the required flexibility goals in the respective grid areas. For example, in areas with high shares of PV power or high ambitions for the integration of PV power, charging processes that shift loads towards midday perform best (e.g., the charging processes *PV* or *Flat*) whereas they do not help much in reducing the daily peak or flattening the overall load curve. If a broad variety of flexibility goals should be achieved, charging processes with the least trade-offs such as processes that focus on flattening the load curve or on increasing peak demand during midday should be prioritized. Moreover, industry players should also think about a combination of controlled charging processes if several flexibility goals should be achieved. For example, assuming that the charging processes can be fully controlled by industry actors once the EV user has agreed, actors could offer different charging processes for the EV users. Alternatively, assuming less control over the respective charging process, industry players could offer different incentives that correspond to different charging processes and attract different user groups. Moreover, charging processes could combine aspects that we have analyzed individually, e.g., reduce charging power at critical peak times, while otherwise optimizing for PV integration.

Moreover, decision-makers in policy and industry should think about how to incentivize the desired charging behavior. Different incentive schemes might prove useful to one charging process but less so for another. For example, TOU tariffs with high price periods during the evening peak and low-price periods during the day seem promising to result in less evening charging and can, hence, incentivize processes such as the charging process *Peak*. However, these price differentials cannot be used to incentivize a flattening of the overall curve, which might rather be incentivized by offering discounts on electricity prices.

3.3.2 Different plug-in scenarios have different flexibility potentials

While Figure 4 shows the average effect of different charging processes across different plug-in behaviors on different flexibility metrics, we also investigate the effect of different plug-in behaviors. Note that changes in plug-in behavior can be less automated than charging processes because they require a change in the EV users' routines (e.g., where to park and plug-in the car), which might be harder to achieved and, hence, might need to be incentivized.

Like the controlled charging processes, the flexibility potential of changes in plug-in behavior varies with the metric considered, i.e., peak reduction and load shifting in Figure 5. For example, charging the vehicle whenever it has a low state of charge (SOC) and without any preferences for locations (plug-in behavior *SOC*) can shift substantial loads and reduce the daily peak (compared to always charging after the last trip), whereas for others such as preferring to charge at work shifting substantial loads can be accompanied by even an increase of the daily peak.

Moreover, the potential of plug-in behavior for flexibility provision often increases with higher technology diffusion. While this trend relates to both metrics for some of the plug-in behaviors, i.e., *SOC* or *Range_Last_Trip*) for others such as *Work* or *Opportunity* higher technology diffusion results only in an increase of the total shifted load in one day—the potential for peak reduction even decreases. We find that a combination of plug-in behaviors that allows for changing the charging location such as *SOC* with a high number of home and work charging stations allows for a spatial, and hence temporal, diversification of charging load.

Regarding grid settings (not depicted in Figure 5), we find that the load profiles differ between different spatial structures. The aggregated load is highest for urban areas in the canton of Zurich (urban agglomeration) and declines for more rural areas. Hence, urban areas in urban agglomeration cases provide the highest potential for peak shifting with spatially diverse charging infrastructure. However, the average peak load is highest in rural areas in the canton of Zurich indicating high peaks while the aggregated load remains relatively low. No major differences between the average peaks in the different areas of the other cases considered have been found. Hence, these local peak loads could be reduced with changes in plug-in behavior.

For policy makers and industry players, this means that incentivizing plug-in behaviors that focus on charging at a low SOC of the EV battery can help to shift loads and reduce peaks—especially in cases of high charging infrastructure diffusion. Incentives hence can include price differentials not only between times but also between spaces, and result in more spatially diverse charging. This should be accompanied by supporting spatially diversified charging infrastructure diffusion as well as increasing trust in the technology so that the user is willing to drive at relatively low SOCs, e.g., with information campaigns.

However, we also find that differences between different areas are rather caused by different driving behaviors than plug-in behavior. The highest peaks are caused by two driving profiles, high car use and long distances and EV users with these driving behaviors are especially prevalent in rural areas. Hence, grid operators have to be aware of the area type of their grid(s) and the driving behaviors in these areas. Especially in rural cases with high shares of these driving behaviors, incentivizing changes in plug-in behavior might be complemented with suitable controlled charging processes.

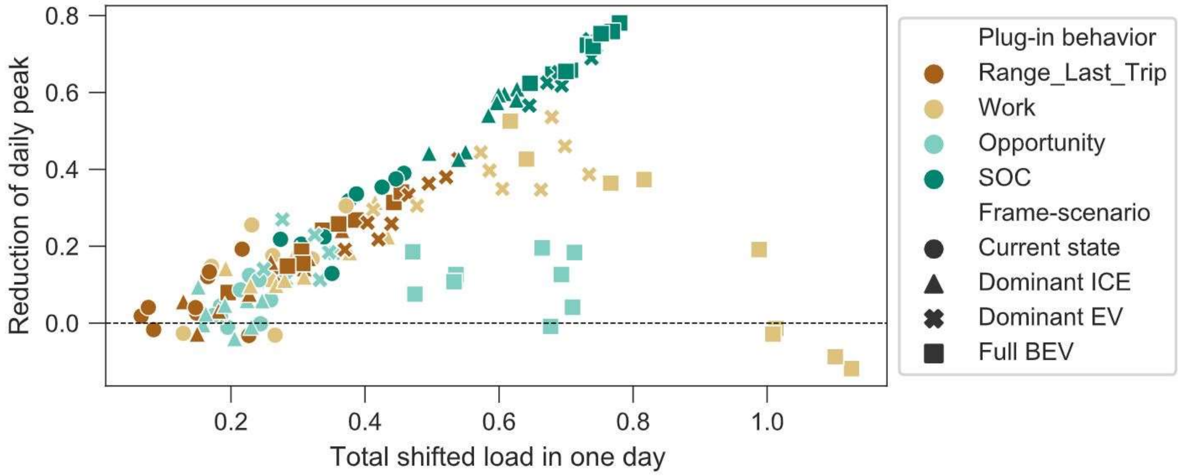

Figure 5 Overview of the average performance of different plug-in behaviors in different flexibility metrics for the for the urban agglomeration case (Zurich), the rural multicentric case (Freiburg), and rural monocentric case (Graubunden) and four frame-scenarios. The flexibility metrics have been calculated as differences from the baseline of the plug-in behavior *Always_Last_Trip* combined with the charging process *CCCV*. Source: Gschwendtner et al. (2023)[38]

3.3.3 The interplay of plug-in behavior and charging processes

But how do the different components of EV charging interact? Which of the two components is more effective and which combination most beneficial? Figure 6 shows that the beneficial effect of plug-in behavior discussed above depends on technology diffusion, the objective of the flexibility provision, and the controlled charging scenario.

While both plug-in behavior and controlled charging processes have substantial effects on most of the metrics in cases of relatively low technology diffusion (left column of Figure 6), controlled charging processes show a substantially higher impact on the flexibility metrics than plug-in behaviors under high technology diffusion, which is shown in the clustering according to colors rather than to forms in Figure 6. However, this effect is less prevalent in rural areas (see Figure 9 in the Appendix). Moreover, some of the metrics such as the increase of load during midday are hardly affected by plug-in behavior even in cases of low technology diffusion. In addition, we find that the effect of the plug-in behavior also depends on the controlled charging process. For example, the charging process *V2G* relatively strongly depends on the plug-in behavior. This might render *V2G* a riskier option—assuming that plug-in behavior can harder be controlled than charging behavior.

Moreover, and regarding charging locations (not depicted in Figure 6), we find that most of the peaks during midday occur at home or public locations whereas peaks at workplaces occur in the morning. Especially peaks at work and public charging stations depend on the plug-in behavior whereas peaks at home charging stations are rather independent from plug-in behaviors.

Hence, policy makers and industry players such as grid operators should know the flexibility needs of specific grid settings and design incentives accordingly. They need to be aware of the interplay of the two components of charging behavior and how this can vary at different technology diffusion stages. While, in general, plug-in behavior is less effective than controlled charging processes, plug-in behavior can have a substantial effect in certain contexts. For example, in cases of low technology diffusion and/or rural areas and. In these areas in particular, decision-makers should consider incentivizing the desired plug-in behavior. In cases with high technology diffusion and especially in non-rural areas, incentives should rather focus on charging processes than plug-in behavior. Moreover, incentives probably have to be adapted over time with increasing technology diffusion and the accompanied changes in user behavior. This requires to closely monitor technology diffusion and a good understanding of user behavior at different diffusion stages.

Moreover, decision-makers should monitor technology diffusion and develop a good understanding of user behavior at different diffusion stages because incentives might have to be adapted over time. All of the measures require close collaboration between the different stakeholders included as well as a regulatory environment that allows for controlled charging (e.g., the recently started process to design paragraph 14a of the German Energy Industry Act[40,41]).

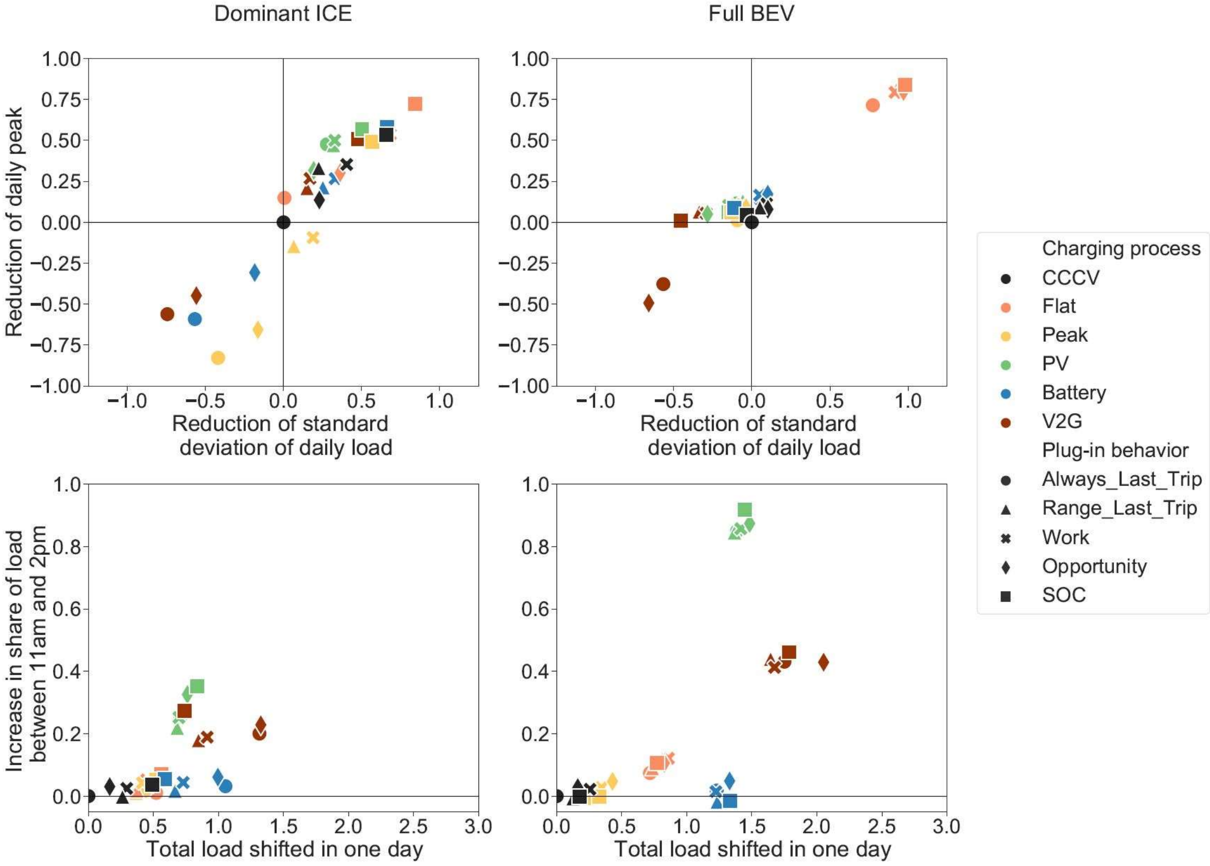

Figure 6 Overview of the average performance of combinations of plug-in behaviors and controlled charging processes for different flexibility metrics and the two frame-scenarios *Dominant ICE* and *Full BEV*. The upper right corner contains the most beneficial combinations. Source: Gschwendtner et al. (2023)[39]

3.4 The studies

In our studies[38,42],we simulated EV load profiles considering different driving and charging behavior and technology diffusion stages. For doing so, we developed an agent-based model, which allows us to consider specific characteristics of users such as their socio-demographics, heterogenous charging behavior, the interactions between EV users and with charging stations, as well as to include future technical developments and diffusion. More specifically, we develop four frame-scenarios covering different technology diffusion stages and developments such as battery capacities and charging station developments and deployment. We use simulated mobility data for passenger cars of a synthetic population of Switzerland[43] (provided by the Institute for Transport Planning and Systems at ETH Zurich), covering an average weekday for different time steps from today until 2050 and different EV use types. We consider different charging locations (home, work, public) and (grid) areas (urban, rural, suburban) and two components of EV charging, the plug-in behavior, and the charging process. We focus on three geographical cases, an urban agglomeration (Zurich), a rural multicentric (Freiburg) and a rural monocentric (Graubunden) case.

4 Incentives for leveraging the flexibility from EV charging

4.1 Executive summary

- Financial incentives, i.e., price signals, are found to be promising to motivate participation in controlled EV charging.
- We focus on different designs of static time-of-use (TOS) tariffs as they focus on both peak-load reduction and peak-load shifting and consider different price levels at different times and charging locations.
- Our findings show that TOU tariffs shift loads from expensive to low-price periods but can result in even higher peaks due to the over-coordination of EV charging.
- We find that different designs of TOU tariffs are suitable for different locations (i.e., home, work, public). These incentives could, for example, consider the specificities such as different peaks at different locations.
- Moreover, we find that user's reactions play a substantial role. More specifically, low user reaction, i.e., more users not and/or reluctantly reacting to incentives, results in less flexibility than high user reaction.
- Decision-makers in industry and policy designing incentives for EV charging flexibility should be aware of a potential over-coordination effect, i.e., a simultaneous start of charging of many EVs typically at the start of the low-price period resulting in a fast ramp-up and a high peak), increase the general attractiveness of certain incentive designs to EV users, and consider specificities of different charging locations in their incentive design.

4.2 The problem

To cope with climate change mitigation requirements, high shares of EVs are required, together with high shares of renewable power production[28]. While the increasing share of EVs can challenge existing grids, EVs can also provide flexibility—and hence support the integration of intermittent renewable power production[29,30] and/or potentially prevent or delay expensive grid investments[27]. Tapping into this flexibility potential requires controlled EV charging.

Typically, controlled EV charging has been approached as a technical issue and optimization problem[44–46]. However, controlling EV charging is also a behavioral issue; not all elements of controlled EV charging are fully controllable such as plug-in behavior. EV charging consists of two components, the plug-in behavior and the charging process[38,47]. While the charging process occurring within the dwell-time of an EV can be mostly automated—once it has been adopted by the EV user—the plug-in behavior, i.e., when and where the car is plugged in to charge, strongly depends on routines and is less controllable.

Incentives might be needed that attract EV users to participate in controlled EV charging and that steer EV charging in a grid-friendly way. These incentives have to be designed to shift EV charging load in time and space to correspond to the flexibility requirements of specific grid settings. In general, incentives can be based on information[48] or financial, i.e., price, signals[48]. While information such as informing the EV user about the benefits of controlled EV charging might work well for early adopters, financial signals such as different price levels at different times and/or locations are required especially at stages of higher EV diffusion. However, when estimating the effect of these incentives, the users' reactions have to be considered. EV user might rather act according to their routines regarding when and where to plug-in the car (e.g., always at home over night) than to purely economic decisions, and not all users might react and not all users might react similarly to incentives.

Extant work focusing on the technical flexibility potential of controlled charging and energy policy[49] typically neglects these aspects and, hence, results are likely to overestimate this potential, especially at high EV diffusion. To obtain a more realistic picture for controlled charging and the effect of incentives and their design, behavioral aspects such as plug-in behavior and the users' reactions have to be considered—in addition to optimizing the charging process itself. It is yet unclear which design of incentives in terms of prices, times and location could effectively leverage the flexibility potential and steer EV charging in a grid-friendly way.

4.3 The findings

We base our analysis a previously developed agent-based model simulating EV load profiles considering different driving and charging behavior and technology diffusion stages[38,47], which we extend with different designs of static time-of-use tariffs (TOU) and types of user reactions. TOU tariffs focus on both peak-load reduction and peak-load shifting and are found to be effective to reach certain flexibility goals[50]. We focus on three different designs of TOU tariffs that can be (1) the same for all charging locations or (2a) vary between different charging location by dis-/incentivizing a certain location or (2b) vary between different charging locations by considering the typical peaks of the different location types (Table 1). For charging locations, we distinguish between home, work and public. We consider low and high user reaction to the different incentive designs. Moreover, we distinguish between two different components of charging: plug-in behavior and the (controlled) charging process. Each of the reaction types consists of a combination of plug-in behavior and charging process. We selected the case of the Canton of Zurich in Switzerland covering different spatial areas, i.e., urban, suburban, and rural, and associated heterogeneous mobility behavior.

Table 1 Different designs of time-of-use tariffs considered, charging locations can be home, work or public. Source: Gschwendtner (2023)[51]

Designs of time-of-use tariff	Description
(1) Same for all charging locations	Different price levels at different times, e.g., high prices in the evening and medium prices in the morning and the afternoon
(2a) Different for different charging locations by dis-/incentivizing certain locations	Different price levels at different times, constant high/low price levels at certain locations
(2b) Different for different charging locations considering typical peaks	Different price levels at different times considering the different peaks at certain locations

We find that different price levels shift charging load away from expensive time periods, typically to the cheap price periods. While high price signals can successfully decrease (evening) peaks, our results show that these incentives can lead to even higher peaks potentially resulting in grid constraints. These high peaks typically occur at the beginning of the cheap price periods due to an over-coordination effect, in particular when the charging process aims to optimize charging cost. We also find that user's reactions play a substantial role; low user reaction to prices results in less flexibility than high user reaction. This effect is particularly strong when charging the EV during times of high PV production, i.e., during midday. Moreover, we also find that designs of TOU tariffs that consider the specificities of different locations result in high flexibility.

Hence decision-makers in policy and industry have to be aware that steering EV charging with different price levels might result in new peaks at cheap price periods due to an over-coordination effect. These peaks can even be higher than the peak that should be decreased and might result in congestion problems. Moreover, and more generally, they should increase the attractiveness of certain designs of incentives to EV users to stimulate high reactions to incentives. For example, tariffs could be tailored to certain user groups (assuming regulatory feasibility), e.g., different price levels could be slightly staggered in time for different users. This scheduling should avoid the simultaneity of charging and prevent the over-coordination effect. However, decision-makers have to be aware that besides the price level also other factors such as guarantees, or trust might play a role. Finally, incentives considering the specificities of different locations can result in high flexibility. However, this can come with adverse effects such as ethical issues that should be considered.

4.4 The study

In our study[51], we extend a previously developed agent-based model, simulating EV load profiles considering different driving and charging behavior and technology diffusion stages[38,47], with financial incentives and types of user reactions. More specifically, we focus on three different designs of static TOU tariffs that can be (1) the same for all charging locations or (2a) vary between different charging location by dis-/incentivizing a certain location or (2b) vary between different charging locations by considering the typical peaks of the different location types. We consider low and high user reaction to the different incentive designs. In the low user reaction scenario, less users react to incentives, and the reaction itself is more reluctant than in the high user reaction scenario. Moreover, we distinguish between two different components of charging: plug-in behavior and the (controlled) charging process. Each of the reaction types consists of a combination of plug-in behavior and charging process. We selected the case of the Canton of Zurich in Switzerland covering different spatial areas, i.e., urban, suburban, and rural, and associated heterogeneous mobility behavior.

5 Conclusions

The overall purpose of the research project ErVIn was to understand how the increasing share of EVs can be beneficially integrated into distribution grids. More specifically, this project aimed to (RQ1) identify promising settings of and challenges (technical, social, and regulatory) for the bidirectional integration of EVs as a promising flexibility source in electricity grids, and understand (RQ2) how the interplay between different EV dis-/charging strategies, user types and grid settings affects the attractiveness for EVs as flexibility option in different distribution grids, and (RQ3) how different incentives affect the integration of EVs as a flexibility option.

Regarding bidirectional charging (RQ1), we find that current trials for bidirectional charging focus on commercial EVs that charge at work as well as the provision of V2C and transmission services. While this indicates that these settings are promising for commercial application, future trials should test broader combinations of user types, charging stations and services to leverage the flexibility potential of V2X and reduce risks. We also find that several technological, social, and regulatory challenges such as uncertainties regarding future demand and supply of flexibility, user participation and future market and tariff structures hamper commercial implementations. To enable and support further and commercial V2X implementation, decision-makers in policy and industry need to remove these barriers. While industry players should develop relevant technologies e.g., platforms that allow for an economically viable service provision and monitoring systems that collect distribution grid data to allow for a better evaluation of business opportunities and the development of business models. Policy makers need to remove regulatory barriers. These include the uncertainties regarding the design of markets or mechanisms (e.g., tariffs, tenders, auctions) for flexibility provision at distribution grid level, current prequalification processes, which impede participation for small providers due to minimum bid sizes, or the lack of incentives supporting the implementation of smart solutions rather than grid reinforcement. Moreover, policy makers should enable the cooperation between the different related actors such as the automotive and electricity industry, e.g., via funding conferences or subsidizing joint projects.

Regarding the interplay between different EV dis-/charging strategies, user types and grid settings (RQ2), we find that different charging strategies differ in their effectiveness for flexibility provision. This depends on the goal of the flexibility (e.g., flattening load curves vs. reducing load peaks), technology development and diffusion (in particular, infrastructure deployment) and the grid area (e.g., urban, rural, suburban). In addition, some charging behaviors can address several flexibility goals while others perform very well regarding one flexibility goal but come with strong tradeoffs for others. For example, they allow for shifting a large share of the load but increase the overall peak. Moreover, we find that controlled charging processes show higher impact on the flexibility metrics than plug-in behaviors. The beneficial impact of plug-in behavior depends on the flexibility goal, technology diffusion, and the controlled charging scenario that it is combined with. Regarding different EV use types, we find that high peaks are typically caused by certain use types such as EV users using their car very often and those driving long distances—despite their relatively low share in the overall car fleet, e.g., about ~20% in the Canton of Zurich. Hence, decision makers in policy and industry should be aware of the flexibility needs of specific grid settings. Incentives that steer charging behavior into the desired direction might be required. These incentives should consider potential trade-offs between flexibility goals. Moreover, incentives probably have to be adapted over time with increasing technology diffusion and the accompanies changes in user behavior. This requires to closely monitor technology diffusion and a good understanding of user behavior at different diffusion stages. While in general, charging processes show higher flexibility potential than plug-in behavior, incentives for plug-in behavior allow for a temporal and *spatial* distribution of charging load, and might be more effective in rural than in (sub)urban areas.

More specifically regarding incentives (RQ3), we find that different designs of time-of-use tariffs result in different effects on charging loads. We identify the effectiveness of certain incentive designs for specific flexibility goals by considering different price levels for different time periods and charging locations (i.e., home, work, public), as well as different user reactions. For example, the typical evening peak at home locations can be substantially reduced with expensive price levels. However, the following low-price period might result in an over-coordination effect, causing an even higher peak. Decision-makers in industry and policy can use these insights to design incentives for flexible EV charging. Moreover, they should be aware of a potential over-coordination effect, increase the general attractiveness of certain incentive designs to EV users, and consider different charging locations in their incentive design.

We think that the findings of this project are highly relevant—for the academic community as well as for decision-makers in policy and industry. In our view, the acceptance to present this work at several academic conferences and the publication of several scientific papers in internationally renowned peer-reviewed journals (three peer-reviewed publications at the time of this report, see also section 9), which—in addition—have already been frequently cited, indicate the relevance for the academic community. Moreover, the project's studies are part of a dissertation at ETH Zurich, which has been defended in December 2022. We think that the high interest of our industry partners and the interviewees in our findings as well as several invitations to present and discuss the findings in industry events and seminars (eight at the time of this report, see also sections 7 and 8) indicate the value and relevance of this project also for decision makers in practice. Moreover, our findings allowed to derive implications for decision-makers in policy. We consider these implications relevant for supporting the beneficial integration of the increasing number of EVs into the electricity grid.

6 Outlook and next steps

The findings of this project yield in implications for decision-makers in practice, i.e., policy and industry, that want to foster the beneficial integration of EVs into electricity grids as well as for research. While the implications for decision-makers in practice have been summarized in section 5, we recommend further research in the following three areas. First, further research should extend our work and enhance the understanding of the effect of incentive schemes on EV charging load. This can include investigating further designs of financial incentives or combinations of financial and non-financial incentives. Second and related, future research should investigate the willingness of different user groups to participate in controlled EV charging, including V2X, and how to increase their acceptance in real-life, e.g., in trials. EV users' acceptance as well as high user reaction to incentives can be crucial for leveraging the flexibility potential. Third, future research should use real-life data—once available—in modelling approaches and investigate the service requirements of different grid types and their interplay with flexibility services, in particular bidirectional charging.

7 National and international cooperation

The project has been supported by partners from the Swiss industry and research. While IWB and novatlantis gmbh have accompanied the project from the beginning, EKZ and energie360° have joined during the first project year. Besides informal interactions, the project partners form the advisory group to discuss preliminary findings and provide feedback. These meetings with the monitoring/advisory group allowed to include an industry perspective and identify possible deep dives for the upcoming project phases. Over the entire project phase, six meetings with the monitoring/advisory board group (incl. the kick-off meeting) were conducted; a final meeting after the project`s finalization is planned. In addition, we discussed our approach with researchers from our and other groups of ETH Zurich, as well as with experts in national and international academic conferences and at industry events, to validate our assumptions and methodological choices (see also section 8).

8 Communication

The project's progress, (preliminary) results and next steps have been communicated to and discussed with the SFOE and the industry partners. In addition, we have been in regular exchange with researchers from the Center for Energy and Environment at the ZHAW School of Management and Law, who work on related projects, and to whom the SFOE has connected us. We furthermore discussed our approach multiple times with researchers from ETH focusing on related and relevant technical issues to validate our approach, as well as with experts in national and international academic conferences and via talks at industry events and seminars.

Presentations at national and international academic conferences

- Christine Gschwendtner presented parts of the project at the 34th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS), Online, 2021
- Christine Gschwendtner presented parts of the project at the 14th International Renewable Energy Storage Conference (IRES), Online, 2021
- Christine Gschwendtner presented parts of the project at the 12th International Sustainability Transitions (IST) Conference, Online, 2021
- Christine Gschwendtner presented parts of the project at the 6th Network of Early Career Researchers in Sustainability Transitions (NEST) International Conference, Online, 2021
- Christine Gschwendtner presented parts of the project at the 6th International Conference on Smart Energy Systems (SES), Online, 2020
- Christine Gschwendtner presented parts of the project at the 5th Network of Early Career Researchers in Sustainability Transitions (NEST) International Conference, Online, 2020

Talks at industry events and seminars

- Christine Gschwendtner presented parts of the project at the Fraunhofer Institute for Systems and Innovation Research ISI, Karlsruhe, Germany, 2022
- Christine Gschwendtner presented parts of the project at the meeting of the Network Management Commission of the Association of the Swiss Electric Power Industry (VSE), Aarau, Switzerland, 2022
- Christine Gschwendtner presented parts of the project at the Fachtagung Elektromobilität of the Association of the Swiss Electric Power Industry (VSE), Baden, Switzerland, 2022
- Christine Gschwendtner provided insights on electric mobility for the general public in an ETH Zurich Podcast episode with Anthony Patt and Christian Schaffner, 2022
- Christine Gschwendtner presented parts of the project at the Building Excellence TechOutlook 2022 of the Switzerland Innovation Park Central (an independent platform to connect science, industry, and policy to foster innovations in the built environment), Online, 2022
- Dr. Annegret Stephan presented parts of the project at the Energy Week @ ETH 2021, Zurich, Switzerland, 2021
- Christine Gschwendtner presented parts of the project at the Innovation Forum Mobility, a 2-day conference to provide an independent platform for Swiss decision-makers in policy and industry to exchange recent insights for the transport transition, Rüschlikon, Switzerland, 2021

- Dr. Annegret Stephan presented parts of the project at the plenary meeting of the P&D project “V2X Suisse” (financially supported by the SFOE), Risch-Rotkreuz, Switzerland, 2021

Our results will be further disseminated via the (upcoming) publications of the scientific papers and the practitioner articles.

9 Publications

9.1 Scientific publications

Vehicle-to-X (V2X) implementation: An overview of predominate trial configurations and technical, social and regulatory challenges

Gschwendtner, C., Sinsel, S.R., Stephan, A.

2021, Renewable and Sustainable Energy Reviews, Vol. 145, 110977

Available at: https://doi.org/10.1016/j.rser.2021.110977

Abstract

The uptake of electric vehicles supports decarbonization and increasingly interconnects the electricity and transport system. While the integration of electric vehicles could challenge electricity grids, bidirectional power flows between vehicles and grids could support grid operations. Despite the globally increasing number of Vehicle-to-X trials, including Vehicle-to-Grid and Vehicle-to-Customer, an in-depth understanding of trial implementations and expert experiences has largely been overlooked although they are both crucial for technological development and deployment. Based on our analysis of a global Vehicle-to-X trial database and 47 interviews with experts from industry and academia, we (i) provide an overview of the implementation status of Vehicle-to-X and analyze predominate trial configurations, i.e., combinations of characteristics, (ii) identify important technical, social and regulatory challenges for the implementation of Vehicle-to-X and assess and discuss expert evaluations of these challenges and (iii) derive implications for different actors.

The most predominate trial configurations are Vehicle-to-Customer and transmission-level services provided by commercial fleets that charge at work due to current practical advantages of centralized approaches. From a technical standpoint, we find that although Vehicle-to-X can defer or even mitigate grid reinforcement at the distribution level, this potential is highly dependent on local conditions. Regarding social aspects, incentives and Vehicle-to-X operations need to be tailored to different vehicle users. Concerning regulation, it is imperative to avoid double taxation of electricity, simplify market participation for small providers, and further develop Vehicle-to-X standards. Implications for actors include the evaluation and enablement of portfolios with different flexibility assets and stacking of services to increase revenue streams and reduce risk resulting from variations in driving patterns and charging behavior.

The impact of plug-in behavior on the spatial–temporal flexibility of electric vehicle charging load

Gschwendtner, C., Knoeri, C., Stephan, A.

2023, Sustainable Cities and Society, Vol. 88, 104263

Available at: doi.org/10.1016/j.scs.2022.104263

Abstract

While electric vehicles (EVs) are expected to support decarbonizing transport, EVs can challenge the electricity system. Investigating the EV charging load and its flexibility, e.g., by shifting load, is therefore crucial to ensure a secure and sustainable energy system. We develop an agent-based model to investigate how different plug-in behaviors can affect (future) EV charging load profiles and their spatial–temporal flexibility. We contribute to extant literature by (1) revealing the effect of diverse plug-in behaviors on EV load profiles, particularly the flexibility potential resulting from different plug-in behaviors; (2) presenting the (future) charging load in different spatial structures, i.e., urban, rural, or suburban, and home, work, or public charging locations; and (3) demonstrating the effect of detailed driving profiles in high spatial and temporal resolution. We implement three future scenarios regarding EV and charging infrastructure diffusion and technology developments. We find that the impact of potential changes in plug-in behavior on EV charging load would be highest for urban areas and increases as charging infrastructure becomes more spatially diversified. Decision-makers in policy and industry can use these insights to evaluate the impact of EV charging on distribution grids and design incentives to leverage the flexibility potential of EVs.

Mind the Goal: Trade-offs between Flexibility Goals for Controlled Electric Vehicle Charging Strategies

Gschwendtner, C., Knoeri, C., Stephan, A.

2023, iScience, Vol. 26, 105937

Available at: doi.org/10.1016/j.isci.2023.105937

Abstract

Electrification is one of the main decarbonization strategies for transportation. While uncontrolled electric vehicle (EV) charging can challenge the electricity system, controlled EV charging can offer flexibility. Using an agent-based model, we simulate combinations of two elements of EV charging, plug-in behaviors and controlled-charging processes, and measure flexibility goals with four metrics: total load shift, increase in midday load, peak reduction, and flatness of the load curve. We reveal trade-offs between these flexibility goals, which indicates that the most beneficial combinations are specific to spatial areas and their flexibility goals. Furthermore, we find that controlled-charging processes show higher impact on the flexibility metrics than plug-in behaviors, particularly with high EV and charging-station diffusion, but less so in rural areas. Incentivizing beneficial combinations can increase the flexibility potential of EV charging and potentially avoid grid reinforcements.

Incentives for leveraging the spatial-temporal flexibility of controlled electric vehicle charging

Gschwendtner, C., Knoeri, C., Stephan, A.

2023, Working paper as part of Doctoral Thesis ETH Zurich

Available at: doi.org/10.3929/ethz-b-000600983

Abstract

While EVs can stress existing grids in case of fast and cumulative charging, controlled EV charging can provide flexibility for distribution and transmission grids and hence, help to integrate high shares of intermittent renewable power production. Extant work has typically focused on technical aspects of flexibility provision and has neglected behavioral aspects, which are typically not fully controllable, such as plug-in behavior. Therefore, incentives for EV users might be required to stimulate their participation in controlled EV charging. We investigate how different designs of static time-of-use tariffs affect EV charging load with the goal of leveraging its flexibility. More specifically, we extend a previously developed agent-based model. This paper contributes to extant work by (1) integrating both behavioral aspects and automated reactions to tariffs; (2) considering different reactions to price levels; (3) investigating location specific tariffs; and (4) revealing the effects of incentives in cases of high EV diffusion considering heterogeneous driving and charging behavior and future technology developments Based on these insights, we derive implications for decision-makers in policy and industry to incentivize the spatial-temporal flexibility of controlled EV charging.

9.2 Practitioner articles

Mehr Flexibilität durch zweiwegiges Laden?

Gschwendtner, C., Sinsel, S.R., Stephan, A.

2020, VSE Bulletin 12/2020, 25-28

Available at: https://www.bulletin.ch/de/news-detail/mehr-flexibilitaet-durch-zweiwegiges-laden.html

Abstract

Obwohl zweiwegiges Laden die Integration von Erneuerbaren unterstützen könnte, bleibt dessen Zukunft unsicher: Eine Analyse von Expertenmeinungen zeigt unterschiedliche Einschätzungen und Wissenslücken im technischen, sozialen und regulatorischen Bereich. Wie könnte die Implementierung von zweiwegigem Laden aussehen und welche Herausforderungen bestehen?

Flexible Integration von Elektroautos: Wie können Einsteckverhalten und Ladevorgänge unterschiedliche Flexibilitätsziele erreichen?

Gschwendtner, C., Knoeri, K., Stephan, A.

2023, Energiewirtschaftliche Tagesfragen (forthcoming)

Abstract

Die zunehmende Anzahl an Elektroautos kann sowohl eine Herausforderung darstellen als auch Flexibilitätsziele, wie z.B. die Verringerung von Lastspitzen, unterstützen. In einem 3-jährigen Forschungsprojekt haben wir untersucht, wie das Zusammenspiel von unterschiedlichen Einsteckverhalten und Ladevorgängen verschiedene Flexibilitätsziele erreichen kann. Dieser Artikel zeigt Trade-offs zwischen diesen Zielen auf und identifiziert besonders vorteilhafte Ladestrategien—je nach Eigenschaften der Netzgebiete.

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11 Appendix

11.1 Frame Scenarios

Table 2 Assumptions for frame-scenarios, based on literature, expert interviews, and own assumptions. Source: Gschwendtner et al.[38]

Parameter	Current state	Dominant ICE	Dominant EV	Full BEV
Share of EVs in the car fleet	2%	50%	60%	100%
Share of BEVs in EV fleet consisting of BEVs and PHEVs	65%	75%	85%	100%
Battery capacity	100%	130%	160%	180%
Energy consumption	100%	-1%	-2%	-3%
Charging station availability[a]				
Home[b] (urban)	75%	80%	85%	100%
Home (rural)	95%	95%	95%	100%
Home (suburban)	80%	85%	90%	100%
Work (urban)	15%	20%	50%	90%
Work (rural)	5%	15%	40%	70%
Work (suburban)	10%	18%	45%	80%
Public (urban)	10%	20%	40%	70%
Public (rural)	5%	8%	15%	40%
Public (suburban)	8%	15%	25%	50%
Charging capacity: Home and work chargers, public chargers in brackets				
3.7 kW	35% (15%)	30% (5%)	10% (5%)	0% (0%)
7.2 kW	35% (15%)	50% (15%)	20% (10%)	5% (5%)
11 kW	25% (5%)	15% (15%)	60% (10%)	75% (5%)
22 kW	5% (45%)	5% (45%)	10% (45%)	20% (30%)
50 kW	(10%)	(5%)	(5%)	(10%)
80 kW	(0%)	(5%)	(5%)	(10%)
100 kW	(0%)	(5%)	(10%)	(15%)
150 kW	(10%)	(5%)	(10%)	(20%)
350 kW	(0%)	(0%)	(0%)	(5%)
Charging efficiency	85%	85%	87.5%	90%
Approx. number of EV agents				
Zurich	400	4,250	13,175	21,125
Freiburg	120	1,125	4,115	7,045
Graubunden	70	645	1,900	3,030

[a] Percentages refer to the probability that a location at which an EV stops has at least one charging station.

[b] Categories refer to the location, i.e., “home” includes one-street public charging in residential areas.

11.2 Dwell-time locations

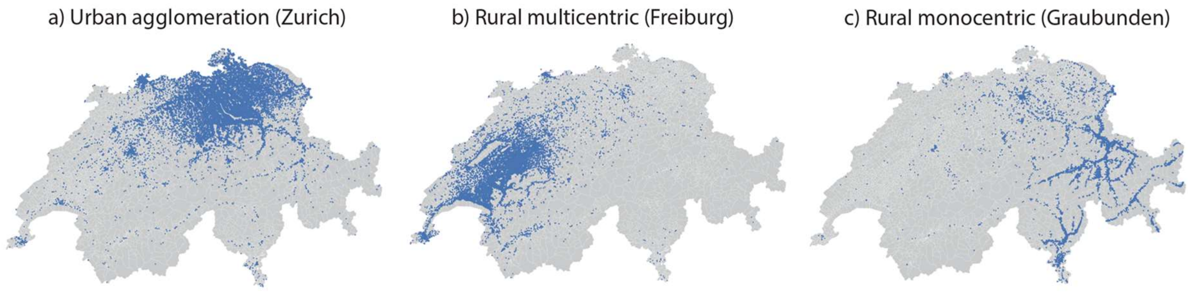

Figure 7 Dwell-time locations (blue dots) of the three geographical cases. Source: Gschwendtner et al.[38]

11.3 Driving clusters

Table 3 Identified driving clusters. Source: Gschwendtner et al.[38]

Driving profile	Description	Share of simulated cars
Low and early car use	High maximum dwell-time of more than 22h and high mean dwell-times of around 12h, latest arrival time is typically early at around noon, shortest total distance below about 25 km, typically 2 trips, and 2 different destinations	16%
Medium car use with short distances	Relatively low mean dwell-time of less than 6h, medium maximum dwell time of about 13h, relatively short total distance below 50 km, highest number of trips with about 5 on average, and at least 3 destinations	21%
Medium car use with long distances	Medium maximum dwell time of about 13h, typical latest arrival time at around 6pm, relatively long distances of more than 100 km, typically 4 trips per day and 3 different destinations	7%
Commuter	High mean dwell-time of about 12h, typical latest arrival time at round 6pm, short total distance below 50 km, typically 2 trips, and 2 different destinations	20%
Exceptionally high car use	lowest maximum dwell-time of less than 12h on average, latest arrival time is typically late at around 8pm, longest total distance with about 300 km on average, 4 trips on average	1%
No car use	Car is not used during the simulated day	36%

11.4 The effect of different charging behaviors on flexibility provision in rural areas

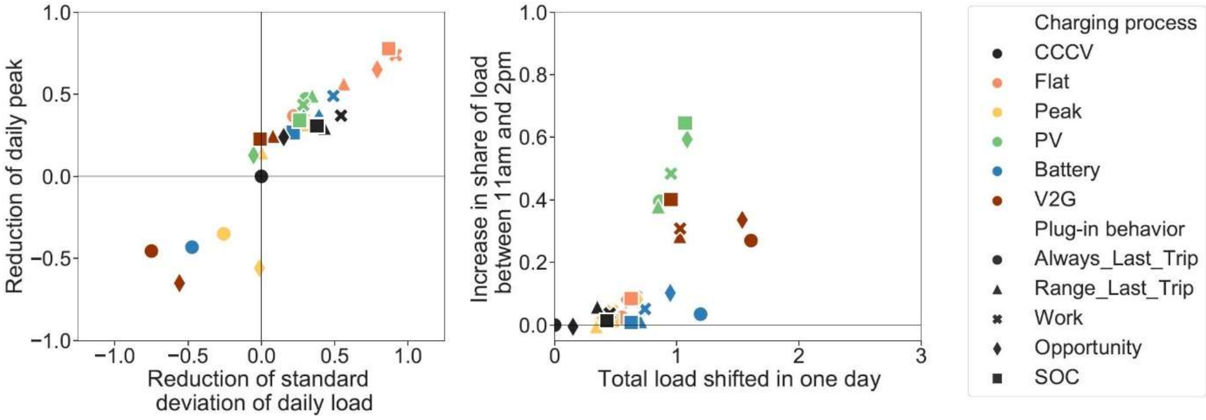

Figure 8 Overview of the average performance of combinations of plug-in behaviors and controlled charging processes for different flexibility metrics and the two frame-scenarios *Dominant ICE* and *Full BEV* for rural areas only. Source: Gschwendtner et al.[42]