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Enabling Flexible Electric Vehicle Grid Integration - ErVIn

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Zusammenfassung

Der erwartete steigende Anteil an Elektrofahrzeugen (EVs) kann im Falle von unkontrolliertem sofortigem Laden die existierenden Verteilnetzte deutlich belasten. Jedoch können EVs auch Flexibilität bereitstellen und somit die Integration schwankender erneuerbarer Energien unterstützen. Trotz des Potenzials von kontrolliertem einwegigen Laden und zweiwegigem Laden (d.h. Be- und Entladen) werden EVs derzeit selten für Netzdienstleistungen genutzt.

Die Forschung hat bisher hauptsächlich auf technische Lösungen zur Integration von EVs in das Stromnetz fokussiert; sozioökonomische Aspekte wie Be- und Entladestrategien, unterschiedliche Fahrzeugnutzungstypen und Fahrprofile werden kaum berücksichtigt. Zudem existieren grosse Unterschiede in den individuellen Netzsituationen (z.B. Anteil erneuerbarer Energien, stationäre Speicher) der Verteilnetze. Dies kann, zusammen mit der aktuell geringen Diffusion netzdienlicher Lösungen zur EV-Integration, Anreize für kontrolliertes Be-/Entladen erfordern.

Das Forschungsprojekt «Enabling Flexible Electric Vehicle Grid Integration (ErVIn)» analysiert mit Hilfe unterschiedlicher, mehrheitlich quantitativer, Methoden wie der steigende Anteil an EVs in das Verteilnetz integriert werden kann, um letztendlich (Politik-) Massnahmen zu identifizieren, welche das Be-/Entladen von EVs netzdienlich steuern können. Nach einer Analyse des derzeitigen Standes von zweiwegigem Laden, sowie von vielversprechenden Lösungen und wichtigen Herausforderungen (Arbeitspaket 1), möchten wir mittels quantitativer bottom-up Modellierung die potentielle Flexibilität in verschiedenen Netzsituationen besser verstehen (Arbeitspaket 2) und untersuchen wie Be- und Entladestrategien mit unterschiedlichen (finanziellen) Anreizen in diesen Netzsituationen eine netzdienliche Integration von EVs ermöglichen können (Arbeitspaket 3).

Der Fokus des zweiten Projektjahres lag auf der Entwicklung des quantitativen bottom-up Modells zur Analyse des Flexibilitätspotenzials basierend auf dem Zusammenspiel verschiedener EV-Nutzungstypen und Netzsituationen, welches im dritten Projektjahr um (finanzielle) Anreize erweitert wird. Unser Modellierungsansatz besteht aus zwei Schritten: Der Simulation von (i) Lastprofilen von Gebäuden und (ii) Lastprofilen von EVs, welche wir dann kombinieren und unter einer Verteilnetzperspektive analysieren—für heute und unterschiedliche Szenarien in der Zukunft. In unseren Netzsituationen berücksichtigen wir unterschiedliche Gebiete (urban, sub-urban und ländlich) und Typen (z.B. Wohn- oder Industrieviertel) in unterschiedlichen Geographien. Derzeit erweitern wir unser existierendes Modell um ein agentenbasiertes Modell (ABM), welches die Analyse und die Relevanz unserer Resultate stärken soll. Zusätzlich dazu haben wir aufgrund der zentralen Rolle für unser Modell eine umfassende Literaturrecherche zu Ladestrategien durchgeführt.

Da sich das Modell noch in der Weiterentwicklungsphase befindet und die Resultate stark von den konkreten Modelleinstellungen abhängen, beinhaltet dieser Report exemplarische Resultate für beide Modellierungsschritte, sowie eine Zusammenfassung der Literatur. Beispielsweise zeigt die Analyse des gewählten exemplarischen Settings der Gebäudelastprofile die wichtige Rolle von EVs und Gebäudeanwendungen wie Beleuchtung und Belüftung für zukünftige aggregierte Lastprofile. Für die Simulation von EV Lastprofilen konnten wir mit Hilfe einer Analyse von schweizerischen Mobilitätsdaten Standzeiten und deren Ort (zu Hause, Arbeit, öffentlich) und Gebiet, welche mögliche Einsteckzeiten und -orte darstellen, sowie fünf Cluster der Autonutzung identifizieren. Auf Basis unserer Literaturrecherche konnten wir sowohl Bestimmungsfaktoren für Ladestrategien als auch beobachtete systemische Lademuster ermitteln.

Summary

The expected uptake of electric vehicles (EVs) can challenge existing distribution grids in case of uncontrolled instant charging. However, EVs can also provide flexibility, allowing for high shares of intermittent renewable power production. Despite the potential of controlled unidirectional and bidirectional charging of EVs, they rarely provide services to the grid.

Extant research has mainly focused on technical aspects, but less is known about socio-economic aspects, such as EV dis-/charging strategies, different vehicle use types and driving profiles. Moreover, grid settings (e.g., share of renewables, stationary storage) differ substantially between distribution grids. Together with the currently sparse diffusion of grid-friendly EV integration solutions, incentives for controlled dis-/charging might be necessary.

The research project «Enabling Flexible Electric Vehicle Grid Integration (ErVIn)» analyses how increasing shares of EVs can be integrated into distribution grid(s). Applying a mixed-method approach with a quantitative modelling focus, we aim to identify (policy) measures that can steer EV dis-/charging in a grid-friendly way. After analysing the current status of bidirectional implementations as well as identifying promising solutions and important challenges (work package 1), we use quantitative bottom-up modelling to better understand the potential of flexibility in different grid settings (work package 2) and investigate the interplay between dis-/charging strategies with (financial) incentives to enable grid-friendly EV integration into these grid settings (work package 3).

During the second project year, we have focused on developing a quantitative bottom-up model for analysing the flexibility potential based on the interplay of different EV users and distribution grid settings, which will also serve as basis for the integration of incentives during the third project year. Our modelling approach consists of two steps: the simulation of (i) building load profiles and of (ii) EV load profiles, which we then combine and analyse from a distribution grid perspective—for today and different scenarios in the future. We focus on different typical grid settings that cover different areas (urban, rural, suburban) and types (e.g., industrial, residential) in different geographies. We have started to extent our existing model by an agent-based model (ABM), which we expect to strengthen the analysis and yield in more relevant results. Due to its important role for the modelling, we conducted an extensive literature review on EV charging strategies.

Given that the model is still under development and that the results depend on the specific model settings, we present selected exemplary results for the two modelling steps, and a summary of the literature review in this report. For example, our results for the presented exemplary setting show the important role of EVs and building appliances such as lightning or ventilation for future loads. By analyzing Swiss mobility data for simulating EV load profiles, we identified car dwell-times, and their locations (home, work, public) and areas, which represent possible plug-in times and locations of (flexible) EV dis-/charging, and five different clusters of car use. Finally, our literature review on charging strategies revealed both determinants for charging strategies and observed systemic charging patterns.

Contents

Abbreviations

ABM	Agent-based model
EV	Electric vehicle
PV	Photovoltaic
V2G	Vehicle-to-grid
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 share of EVs is planned to increase to 20% (2035) and 41% (2050) for passenger cars, and 15% (2035) and 29% (2050) for light-duty vehicles[2], starting from currently very low shares (e.g., 0.6% for passenger cars in 2019[3]). Although the uptake of EVs can challenge existing grids in case of uncontrolled, instant charging[4], EVs can also provide flexibility and frequency services to distribution and transmission grids[5,6]. Hence, EVs can help to integrate high shares of intermittent renewable energy production, such as wind and photovoltaic (PV) power[7,8], and in doing so, contribute to the decarbonisation 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[9,10]. 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 favour the storage capabilities of EVs[11]. 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)[10]. While the former charging strategy puts an additional burden on grid reliability by potentially increasing peak load, the latter two allow for a beneficial integration of EVs[8]. However, EVs rarely provide these services to the grid today; specifically bidirectional charging technology is still in its pilot phase[12]. The potential of EVs as flexibility source for the grid “has not yet been seriously explored”[13].

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[14], such as different EV dis-/charging strategies and/of different vehicle use types. Moreover, grid settings (e.g., share of renewables and stationary storage) differ substantially between individual distribution grids[15]. Together with the currently sparse diffusion of grid-friendly EV integration solutions, specific incentives for smart dis-/charging might be necessary[16–18].

Extant work has begun to evaluate how to better model EV user behaviour[9]. However, they fall short in modelling the behavioural nuances that were evaluated empirically[19]. Extant work has also begun to evaluate how to best incentivize both consumers and businesses to allow for smart charging[16] or participate in electricity markets[17,18]. Yet, studies that have started to consider some form of economic incentive typically focus, separately or in selected combinations, on specific grid settings[9,11,16,20,21], charging strategies and/of user types[9,11,20], and flexibility services[16], 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[9,20] lacks a detailed understanding of the interplay of incentives and user behaviour, overlooks the potential diffusion of other technologies such as stationary storage 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[14] –, (ii) a comparison between a broader variety of arrangements of vehicle types, user profiles, and grid settings[10], and (iii) future developments such as the diffusion of stationary storage[22]. Therefore, we aim 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, renewable power generation and stationary storage technologies can become an attractive solution for different distribution grid(s). 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 analysed 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, which are each allocated to individual work packages with individual deliverables.

Research question

(1) What are promising settings of 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 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)

Deliverables/outputs

Work package 1:
- A list of the analysed projects and relevant information
- A documentation of the conducted interviews
- A scientific review/overview paper on different EV integration solutions, including their drivers and barriers
- A practitioner article on different EV integration solutions, their drivers, and barriers

Work package 2[1]:
- A techno-economic bottom-up model that allows the assessment of the flexibility potential based on an interplay of different EV users and distribution grid settings
  A techno-economic bottom-up model will be developed that allows the assessment of the flexibility required based on an interplay of different EV users and distribution grid settings
- A scientific paper in a peer-reviewed journal with a focus on the flexibility potential based on an interplay of different EV users and distribution grid settings
  A scientific paper in a peer-reviewed journal with a focus the flexibility required based on an interplay of different EV users and distribution grid settings
- A practitioner article on the flexibility potential based on an interplay of different EV users and distribution grid settings
  A practitioner article on the flexibility required based on an interplay of different EV users and distribution grid settings

[1] While we still respond to the same research questions, we sharpened the focus of work package 2 during the second project year. We adapted the deliverables of work package 2 accordingly. The original versions of the deliverables are given in italics.

Work package 3:

- A techno-economic bottom-up model that allows the assessment of how different incentive measures affect different EV integration solutions in different distribution grid settings
- A scientific paper in a peer-reviewed journal with a focus on how policy and other incentive measures could steer different EV dis-/charging strategies and their interplay
- A practitioner article on how policy and other incentive measures could steer different EV dis-/charging strategies and their interplay

2 Procedures and methodology

To fulfil the project's purpose, we apply a mixed-method approach with a quantitative focus. While the first work package is explorative and aims to develop a holistic and global understanding of promising settings for bidirectional EV integration solutions, the second and third work package focus on the interplay of technical and socio-economic aspects. We hence chose different methodological approaches with a qualitative focus for the first and a quantitative focus for the second and third work package. In the following, we describe the method and procedures as well as the current status of the different work packages with a focus on work package 2—being our core activity during the second project year.

2.1 Work package 1

To develop a holistic and global understanding of promising settings for and challenges of bidirectional EV integration solutions, we combined insights from academic and practical literature, an analysis of completed and ongoing EV integration projects, i.e., trials, and interviews with experts from industry and academia. We focused on bidirectional charging, i.e., vehicle-to-X (V2X), solutions because they represent the most innovative approach for EV integration. More specifically, we conducted a literature review, using the "Web of Science" database, and categorized 168 focus articles (which we selected out of 12.000 initial articles) into the most prevailing topics: technical, social, economic, and overview. In addition, we categorized mostly ongoing V2X trials collected in the online database "V2G Hub"[23], which comprised 80 projects worldwide, into the characteristics: provided services, charging locations, and vehicle use types. We ultimately categorized 47 trials, which were the ones that contained data for all three characteristics. We complemented this publicly available data with 47 semi-structured interviews with experts from different stakeholder groups to explore technical, social, and regulatory challenges for V2X implementation. We focused on the countries with the highest V2G trial activity, i.e. Germany, the Netherlands, the UK, and the USA[12]. We added interviews with experts from Denmark, France, Spain, and Switzerland to increase diversity. A detailed description of the method and procedures of work package 1 can be found in the interim report of the first project year[24] and in the published academic paper[25].

2.2 Work package 2

We respond to the second, i.e., work package 2, research question by applying a quantitative bottom-up modelling approach, which provides the basis for work package 3 and represents the core of the overall project. With our quantitative bottom-up analysis, we can provide and analyse the flexibility potential of different charging strategies of different EV users in different grid settings (work package 2) and evaluate how incentives can affect different EV user types and/or EV dis-/charging strategies (work package 3). While, in work package 2, we focus on the flexibility potential of EV charging mainly determined by EV driving profiles, we plan to consider bidirectional charging, i.e., also discharging, in work package 3 when including incentives. These insights could be used by policymakers and/or other power sector players such as utilities or grid operators to manage EV dis-/charging of different users/groups in specific grid settings.

Our model consists of two steps: the simulation of (1) building load profiles and of (2) EV load profiles, which we will combine and analyse under a distribution grid perspective covering different potential distribution grid settings (Figure 1). We identified the most relevant variables, their interplay, and input data based on an extensive literature review with a particular focus on charging strategies due to its important role for the project. We also discussed our approach with experts from industry, policy, and academia, such as in our advisory board meetings.

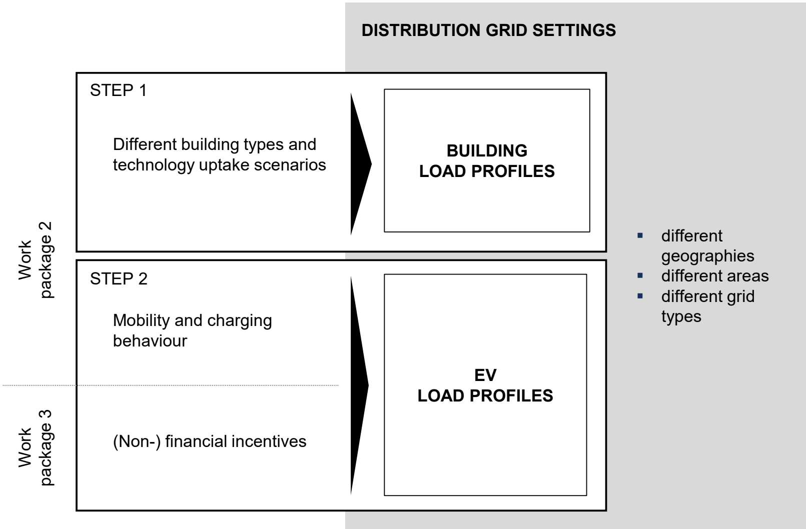

Figure 1 Modelling approach for work packages 2 and 3

Building load profiles

In the building load profiles step, we simulate the impact of different clean energy technologies on the load profiles of different building types in different settings in Switzerland—today and for two different scenarios in the future. More specifically, we consider different technologies (heat pumps, domestic and commercial EVs, PV and small-scale stationary batteries) and building types (households and small businesses) under different conditions (seasons, weather, levels of urbanization). While we analyzed single days in a 15 minute resolution, we also conducted a Monte Carlo analysis to cover variations in input parameters such as technology penetrations and efficiencies. More details on our approach, including the dimensioning and operation of the different technologies considered can be found in the master thesis Schnydrig (2021)[26]. The thesis has been sent to the SFOE; (technical) details could be provided upon request.

EV load profiles

The target of the EV load profiles step is to simulate EV load profiles for different socio-demographic and commercial user types and/or clusters of EV driving profiles. Our analysis is based on a database containing the driving profiles of more than 600 commercial vehicles over three weeks on average[27] and Swiss transport simulation data of internal combustion engine cars for a typical weekday, which are generated by the agent- and activity-based transport simulation tool (MATSim)[28] with the extension of using discrete choice models [29,30]. While we, firstly, employed an analysis of the mobility data including a clustering approach (see below for a more detailed description), we, secondly, started to develop an agent-based model (ABM), which was originally planned only for work package 3. The ABM allows for a more detailed geographical analysis of the data, the consideration of interactions between the individual agents (e.g., modelling the occupancy of charging stations and hence potential waiting times for EV charging) and an easier implementation of the incentives in work package 3 in the third project year. We pre-processed and transformed the original data, e.g., from a person to a car focus, to serve the purposes of our analyses.

In our analysis of the mobility data, we calculated driving and dwell-times and locations for car dwell-times because they represent possible plug-in times and locations of (flexible) EV dis-/charging. In addition, we clustered different car uses into representative driving profiles based on 8 features: the maximum dwell-time, the average dwell-time, the standard deviation of the dwell-times, the number of different destinations, the number of trips, the total travel time, the total distance travelled, and the latest arrival time of the day. We use the clustering algorithm k-means[31,32], which we chose due to its low computational cost and used the elbow method[33] to determine a suitable number of clusters k. More details regarding our method can be found in Gschwendtner & Stephan (2021)[34]. We will use these mobility data as input data for the ABM to determine charging strategies and assess their flexibility potential under the assumption that car use for mobility will not change with EVs.

For the ABM, we have so far created two agent classes: dwell-time locations and domestic EVs; a third class will be created for commercial EVs. In doing so, we account for the loads of every EV individually at its specific charging location. The dwell-time locations have different characteristics, such as the location type (e.g., work, home, shop, leisure, and education), charging station availability and possible charging power as well as potential occupation and waiting agents. Based on the mobility data, the EV agents conduct their trips and decide at the beginning of every dwell-time start whether they want to charge or not. This decision is based on different criteria, such as the current state of charge of the EV battery, the remaining distance to the home location or the next dwell-time location, the dwell-time duration and location type, and possible charging power. We apply different decision criteria to different EV users, e.g., based on socio-demographic characteristics, such as early-adopters. Overall, this approach allows integrating diverse social factors of charging behavior while accounting for interactions between agents.

Given its importance for the analysis of work package 2, we conducted an extensive literature review on charging strategies. We focused on observations of charging behaviour during trials (revealed preferences) in different countries and on charging behaviour collected by survey studies (stated preferences). In doing so, we decided to base our analysis on empirical (primary) data—as opposed to extant simulations, which are either also based on empirical data[33] or on assumptions. Hence, our approach allows us to ensure a good representation of real-world behaviour and to be fully aware of all assumptions underlying, and affecting, our results. We focused on those studies in contrast to studies employing a modelling approach because we prefer to base the assumptions for our modelling approach on empirical rather than simulated data. In total, we collected 46 academic studies from 2013 to 2020—which is the period since relevant empirical data exists—using a snowball approach. We analysed the studies in detail on the relevant characteristics of charging behaviour and distinguished information on full battery EVs from plug-in hybrid EVs.

Distribution grid settings

We will analyze our data with a distribution grid perspective. Based on interviews with experts from industry and academia, the expertise in our group, and data availability, we decided to focus on different typical grid settings in different geographical cases, and aggregated load profiles as opposed to a detailed load flow analysis including grid lines, transformers etc. To analyze different grid settings, we consider different areas and grid types. We apply these different grid settings to different geographical cases to cover different building types, mobility behavior, and spatial structures[35]. Hence, our case selection is targeted to identify similarities or differences in dis-/charging strategies and/or flexibility potential. Table 1 shows the different grid settings and geographical cases and their distinctive features. For the aggregation of load profiles, we will combine the EV load profiles (simulated in the modelling step *EV load profiles*) and the building load profiles (simulated in the modelling step *Building load profiles*), accounting for different levels of heat pump, PV, and domestic storage uptake.

Table 1 Grid settings and geographical cases that we plan to investigate

		Geographies: Cases		
		Urban agglomeration: Canton Zurich	Rural mono-centric: Canton Graubünden	Rural multi-centric: Canton Fribourg
Grid settings	Areas: Urban, sub-urban, rural	x	x	x
	Grid types: Residential, industrial, mixed, …	x	x	x

2.3 Work package 3

We will respond to the third research question in work package 3 by sequentially extending the model developed in work package 2 to cover different incentives for grid-beneficial dis-/charging strategies, such as the uptake of controlled (dis)charging options, (non-)financial incentives and users' constraints (see also Figure 1). In doing so, bidirectional charging might also become a relevant option and a potential source of flexibility. As a preparation, we conducted a literature search focussing on different purposes of incentives (e.g., plug-in behaviour, load control) and types of incentives (e.g., classical incentives, marked-based incentives, price incentives) already in the second project year. We discussed the findings and the suitability of different incentives with the SFOE and the industry partners in our second advisory/monitoring meeting in March 2021.

3 Activities and results

Figure 2 shows the current work plan of the project. While the decision to employ an agent-based modelling approach already in the second project year delayed the timing of the publications for work package 2, we expect to benefit from this decision in work package 3 with a shorter model extension phase. Figure 2 also includes the conference paper that we developed and presented during the second project year. We conducted a second advisory/monitoring meeting together with the SFOE and the industry partners in March 2021—a year after the first advisory board meeting—to provide updates on the project's process, discuss results and receive feedback regarding the current and subsequent work package. Below, we focus on **the preliminary results of work package 2**.

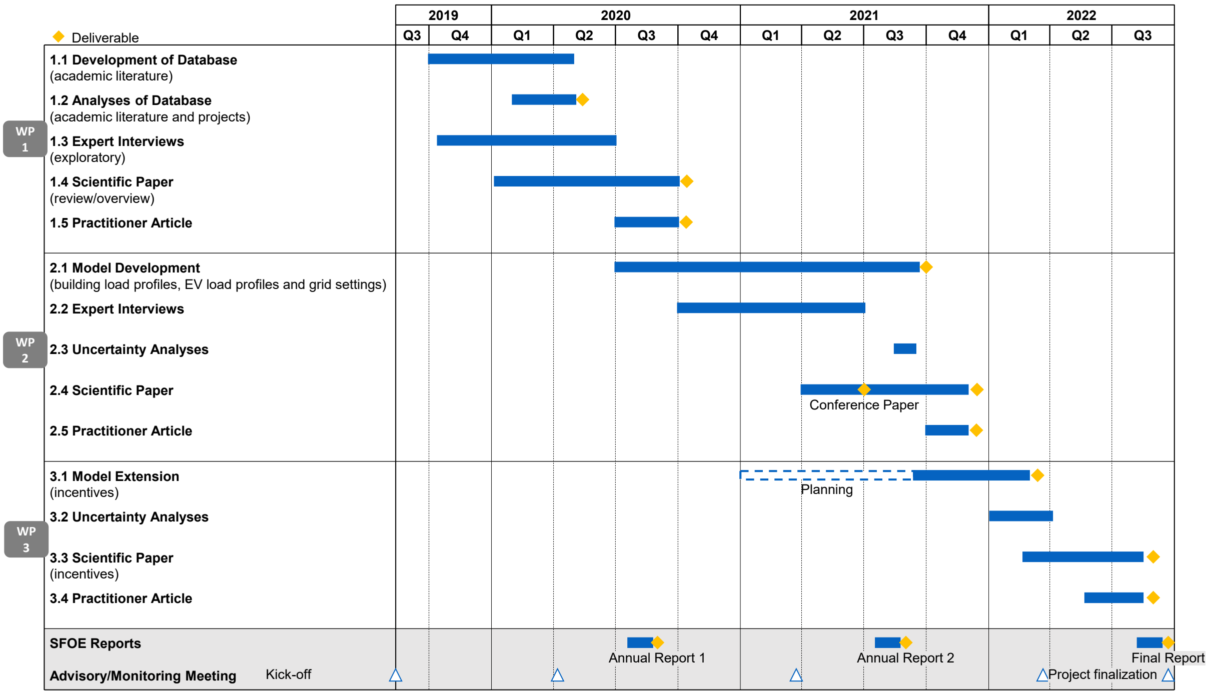

Figure 2 Work plan

3.1 Work package 1

In work package 1, we developed a holistic and global understanding of promising EV integration solutions. We also focused on technical, social, and regulatory challenges of V2X, i.e., V2G and vehicle-to-customer, implementations. Besides a literature search, we used a database analysis and expert interviews to analyse the current status of V2X implementation, i.e. completed and ongoing trials, and identify technical, social, and regulatory challenges relevant for future V2X implementation, which yield in implications for future trials, industry, policy and research. More details can be found in the interim report of the first project year, and the related academic paper and practitioner article that have been published during the second project year (see also section 8).

3.2 Work package 2

As publications are in active development, results are still preliminary. The main target of work package 2 is to understand how the interplay between different EV user types and grid settings affect the attractiveness for EVs as flexibility option in different distribution grids. To achieve this, we have simulated the load profiles of different buildings in different exemplary distribution grid settings in Switzerland, have analysed Swiss mobility data to be able to determine charging strategies and assess flexibility potential, and have conducted an extensive literature review on different charging strategies. Given that the model is still under development and that the results depend on the specific model settings, we focus on selected exemplary results in the following.

Building load profiles

Figure 3 depicts the aggregated load profiles of an exemplary setting (50 buildings in an urban area in winter, see Table 2 for the selected input parameters) at different years and under two different scenarios: slow and fast technology development. The slow development scenario (slow_dev) is based on the business-as-usual scenarios of the Energy Perspectives 2050 and 2050+, whereas the fast development (fast_dev) scenario is based on the new energy policy scenario and ZERO basis scenario of the Energy Perspectives 2050 and 2050+. The EV load profiles shown in Figure 3 are simplified (e.g., for domestic EVs, only home charging during night is considered) and will be refined using the modelling step *EV load profiles* once this has been finished. The total load curve (Figure 3, magenta line) shows the electricity consumption minus production by PV and the supply by a stationary battery operating at the building level. This curve represents the most representative load curve from a simulation of 100 different load curves (Monte Carlo analysis).

Figure 3 shows an increase in peak power in all years and scenarios considered. It also shows that—despite its general increase—PV production cannot compensate electricity demand in either of the scenarios shown. While this might be subject to the specific setting chosen, especially the low solar irradiation in winter, we found similar patterns also for settings in which we simulated a day in summer. Figure 3 also shows a decrease in the electricity demand for heating over time. This can be explained by building retrofits, replacement of inefficient resistance heating systems, and the partial supply of heat by district heating systems in the future. In addition, appliances such as lighting and mechanical ventilation (Figure 3, Buildings: other) play and will play a more important role than heating. While Table A1 in the Appendix presents the results of this exemplary setting in a numerical way; more details and the results of other settings and a Monte Carlo analysis can be found in Schnydrig (2021)[26].

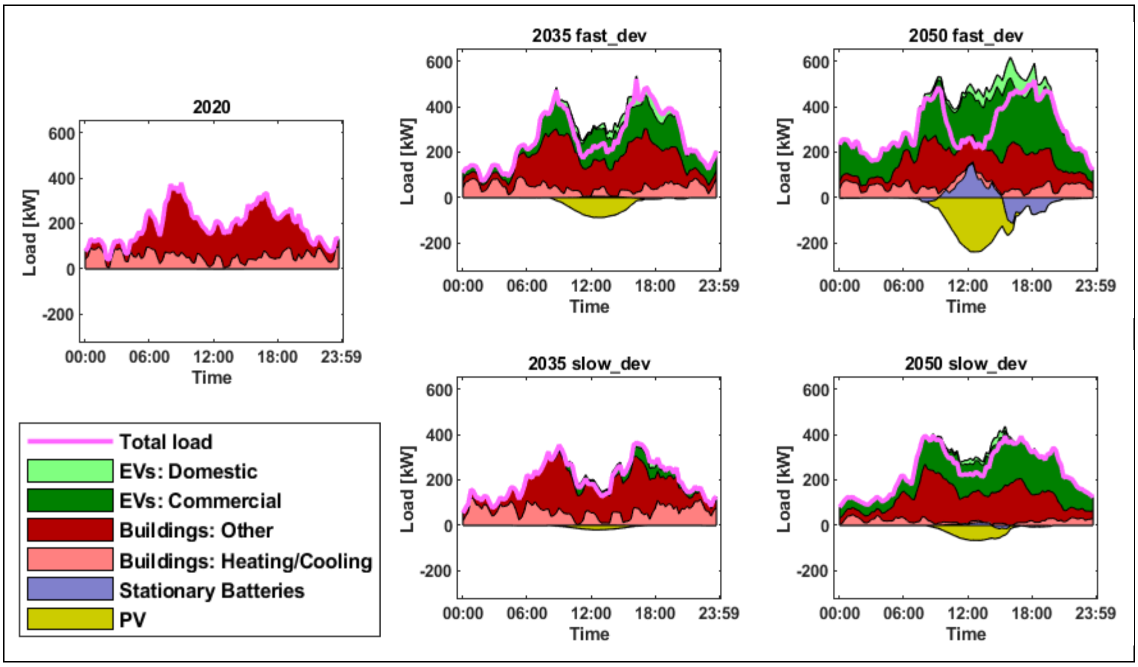

Figure 3 Load curves and technology split for an exemplary setting at different years and under two different technology development scenarios, source: Schnydrig (2021)[26].

Table 2 Input parameters for exemplary setting

General parameters	Input
Number and types of buildings	50 buildings: 20 multi-family-houses, 20 offices, 6 shops, 4 others
Level of urbanization	Urban
Season	Winter
Weather	Sunny
Day of the week	Weekday

EV load profiles

Figures 4a-c[2] show the car dwell-time durations at different levels of aggregation. These dwell-times are likely to represent possible plug-in times and locations of (flexible) EV dis-/charging (see also section 2.2). While Figure 4a shows the dwell-time durations in an aggregated way, splits of the sample into different locations (i.e., home, work, and public) and areas (i.e., urban, sub-urban, and rural) are shown in Figure 4b and Figure 4c, respectively.

On average (Figure 4a), dwell-times start between 6am and 7am, and last between 8 and 10 hours. While dwell-times during the day last below 4 hours, dwell-times starting from 5pm onwards last between 10 to 12 hours. Figure 4a also demonstrates (see second y-axis) that the majority of dwell-times starts in the evening (e.g., 8% at 5pm), followed by dwell-times in the morning (e.g., more than 6% at 7am) and during lunch time (e.g., almost 6% at noon). Regarding locations (Figure 4b) we find that dwell-times at public locations typically last below 2 hours at any time of the day while the majority of dwell-times at work locations lasts between 6 and 10 hours, starting in the early morning between 4am and 9am. At home, few dwell-times start in the morning with a duration of more than 16 hours, i.e., the car is not used during the day. Cars arriving at home between 11am and noon are typically used again in the evening. While few cars arrive at 1, 2 or 3pm without being used again later, the majority of cars arrives between 5pm and 6pm. Regarding the areas (Figure 4c), our analysis shows that –despite larger variations during a few hours—there are no substantial differences between the areas except for the cars not used at all (Figure 4c, left-hand side with given start of dwell-time at 1am), which are more likely in urban areas.

[2] These results are preliminary and can be seen as a first indication. They base on a selected subset of the data due to computational reasons, which might not necessarily be representative.

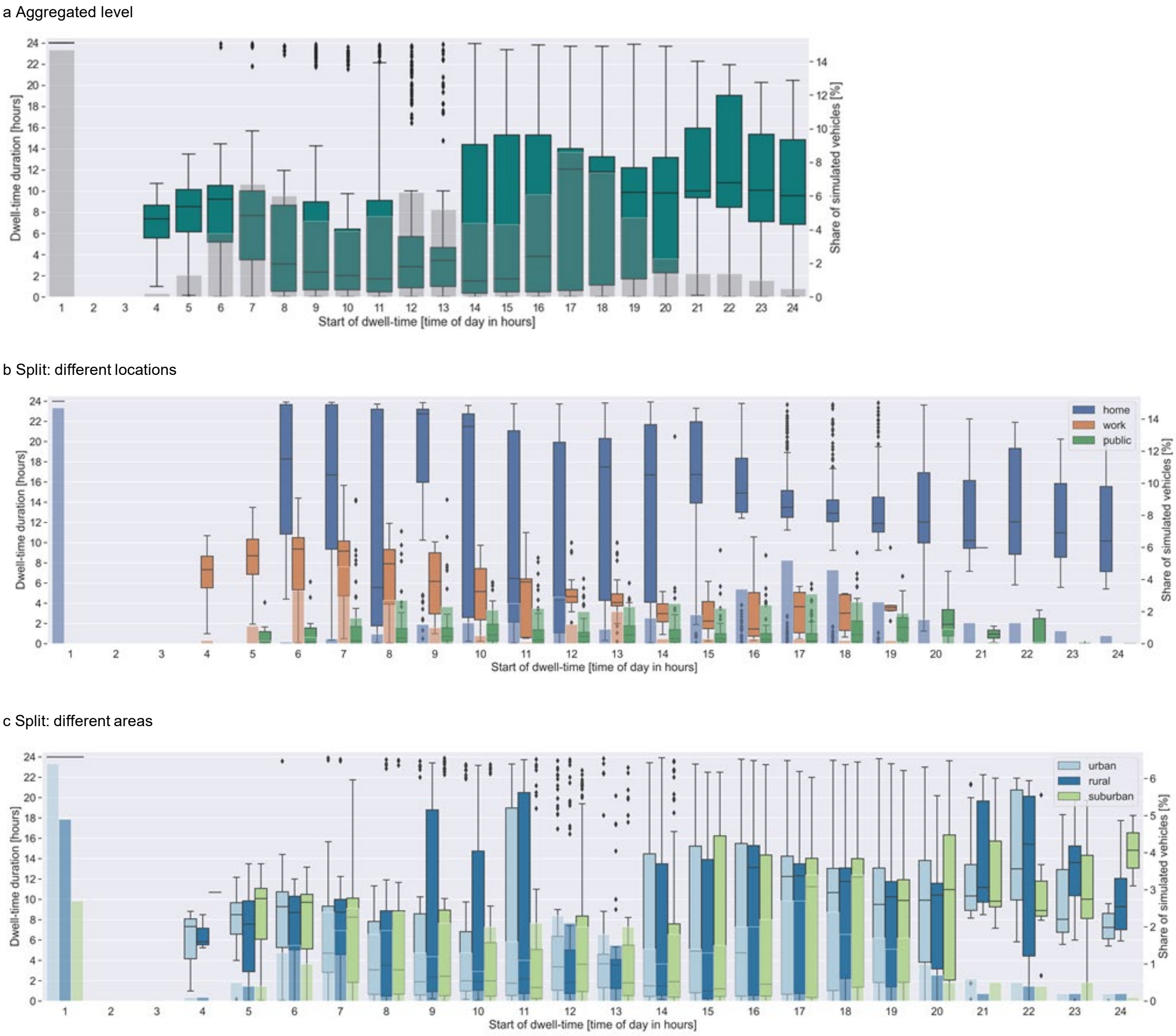

Figure 4 Car dwell-times during simulated day at different levels of aggregation, source: Gschwendtner & Stephan (2021)[34], second y-axis (bar chart) shows share of simulated vehicles

Table 3[3] summarizes the results of our cluster analysis. We clustered the car uses into 5 driving profiles (clusters 0 to 4) – plus one for the cars not used at all during the simulated day (cluster 5). For example, Table 3 shows that only about 20% of car use can be classified as typical commuters (cluster 3), which are often the focus when investigating EV integration. This means that commuting as main driving profile for EV charging prediction might be misleading. The results also show that about a third of the cars (35.6%) are not used during the day (cluster 5). Almost half of these cars belong to urban areas (45.6%), which indicates a high potential for flexibility in urban areas. In contrast, only 0.7% of the simulated cars exhibit exceptionally high car use (cluster 1), which are typically located in rural areas. Cluster 4 also represents a cluster with a low share of cars (6.7%) but high share in rural areas and is characterized by medium car use and long distances. Therefore, cars in rural areas tend to be more used for mobility and thus, show lower potential for flexibility. In addition, we analyzed the different clusters regarding distinctive socio-demographic characteristics of the related car users. While unemployment could be an indication of low car use and early in the day, we did not find a clear relation between socio-

[3] The results for the clustering base on a selected subset of the data due to computational reasons, which might not necessarily be representative. Hence, the results are preliminary and can be seen as a first indication.

demographics to clusters – and hence, driving profiles. More details regarding the descriptive analysis and the clustering can be found in Gschwendtner & Stephan (2021)[34].

Table 3 Clusters of car use, source: Gschwendtner & Stephan (2021)[34]

Cluster	Simulated cars [%]	Urban [%]	Rural [%]	Suburban [%]	Description
0	21.1	33.3	25.6	41.1	**Medium car use with short distances:** relatively low mean dwell-time with medium variation, medium maximum dwell-time of about 13h, typical latest arrival time at around 6pm, short total distance below 50km, more than 2 trips, and high variety of destinations
1	0.7	36.4	63.6	0.0	**Exceptionally high car use**: low variation of dwell-times, lowest mean and maximum dwell-time of all clusters, latest arrival time after 10pm, longest total distance with more than 300km, highest number of trips, and high variety of destinations
2	16.2	33.9	28.5	37.6	**Low and early car use:** very high maximum dwell-time of more than 22h but high variation of dwell-times and mean dwell-times of around 12h, latest arrival time is typically early at around noon, shortest total distance below about 25km, low number of trips, and low variety of destinations
3	19.5	36.6	29.1	34.3	**Commuter:** low variation of dwell-times, mean dwell-time of about 14h, typical latest arrival time at round 6pm, short total distance below 50km, 2 trips, and 2 different destinations
4	6.7	27.2	41.3	31.5	**Medium car use with long distances:** medium mean dwell-time and variation, medium maximum dwell-time of about 13h, typical latest arrival time at around 6pm, relatively long distances of more than 100km, more than 2 trips per day and typically 2 or 3 different destinations
5	35.6	45.6	34.8	19.7	**No car use**: 24h dwell-time at home

Literature review on charging strategies

Our literature review focuses on revealed preference, i.e., observed patterns such as in trials[36–38], and stated preference, e.g. via surveys[39–41] data. Our literature collection covers BEVs and PHEVs and considers different locations such as public, home and work charging. The literature can be clustered regarding two aspects: (i) determinants for charging strategies and (ii) observed systemic charging patterns.

While many extant studies have focused on or identified individual parameters as determinants for charging strategies such as the preferred charging location[39,42,43], the time passed or the distance driven since the last charging[44], the state-of-charge of the battery[39,45] and the availability of charging stations[39], others have considered a mix of parameters. For example, the latter studies have investigated the prioritization of different parameters such as charging need and charging price for more or less risk-averse users[46] or income levels[47]. In addition, extant work has also identified different user types with different charging strategies[48].

Regarding the observed systemic charging patterns, studies have investigated the time used for charging such as the energy consumption per charging event [49,50], the charging[49–52] or connection[36] duration, the charging location[39,42,52–54], or the frequency of charging[39,50,55,56].

3.3 Work package 3

Work package 3 will be the focus of the third project year. Hence, there are no results for work package 3 yet. However, during the second project year, we have conducted a literature search and started the planning of the extension of the quantitative model. Our literature search resulted in the identification of different purposes, such as plug-in behaviour, load control, and types of incentives, such as classical incentives (e.g., direct load control), marked-based incentives (e.g., biding markets), and price incentives (e.g., time-of-use tariffs, peak pricing). Based on insights from the literature and the discussions with the SFOE and industry partners, we will most likely focus on price incentives in work package 3.

4 Evaluation of results to date

During the second project year, the progress of the project has mostly followed the original planning. Slight deviations from the original work plan such as the development of the ABM earlier than planned are shown in Figure 1. In general, all major objectives have been or are expected to be met.

4.1 Work package 1

While work package 1 proceeded well during the first project year, we finalized work package 1 successfully in the second project year with the publication of the practitioner article in the Swiss periodical VSE bulletin in December 2020 and the publication of the scientific paper in the internationally renowned journal Renewable and Sustainable Energy Reviews in May 2021. The positive feedback to the practitioner article as well as the successful publication of the scientific paper in a widely read journal indicate the relevance and value of our results for both academia and practice.

4.2 Work package 2

Work package 2 has made good progress during the second project year. More specifically, the findings of the simulation of building load profiles strongly indicate the important role that EVs can play—especially in future times with high EV uptake. While this confirms the relevance of the overall project's target, it also supports our decision to employ EV charging in a more detailed way via already developing an ABM in work package 2. The intermediate results of the EV load profiles, i.e., the analysis and clustering, has been of great interest in different academic communities, which we approached and will approach at different conferences with transportation, energy, and/or modelling focus. In addition, our industry partners also showed high interest in the results. Hence, we think that the final results, particularly the identification of different charging strategies and flexibility potential in different distribution grid settings are not only of high value for academia, but also practice; we are confident to be able to publish the results in a scientific paper and a practitioner report and, in doing so, attract a large audience.

4.3 Work package 3

Earlier than planned, we have started with the planning of the model extension for work package 3. More specifically, we conducted an extensive literature research, discussed first insights with the SFOE and industry partners, and started the planning for implementation in the model.

5 Next steps

The main focus of the coming project year will be on finishing work package 2, and on work package 3. We plan to finish work package 2 with finalizing the model, i.e. the simulation of the EV load profiles and their combinations with the building load profiles, and the submission of the two publications during the next months. While we expect rounds of revisions for the academic paper of work package 2, we will start with work package 3 in parallel. The dominant part of the third project year will be the extension of the model (Figure 2, Task 3.1), followed by an uncertainty analysis (Figure 2, Task 3.2), and the preparations of the scientific paper (Figure 2, Task 3.3) and practitioner article (Figure 2, Task 3.4). More specifically, the steps towards the model extension will include the selection of incentives, the implementation of these incentives into the model, and the analysis of how these incentives steer EV dis-/charging in a grid-friendly way. In addition, and in a continuous process, we will further develop our focus; the many configurations of the parameters considered, such as the different EV charging strategies of different EV users, incentives, grid settings and geographies, and years, require a careful selection in order to identify the most interesting and relevant results for decision-makers in academia, policy and industry.

6 National and international cooperation

The project has been supported by project partners from the Swiss industry. 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 for the upcoming project phases. A first monitoring/advisory board meeting was conducted after seven months into the project; a second one was conducted after 1.5 years into the project. Besides insightful discussions on the preliminary results of work packages 1 and 2, respectively, these meetings allowed to identify possible deep-dives for the upcoming project phases. For the second and third project year, these included the discussion of charging strategies and different scenarios, grid settings, and incentives. In addition, we discussed our approach with researchers from our and other groups of ETH, as well as with experts in five international conferences, to validate our assumptions and methodological choices (see also section 7).

7 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 form ETH focusing on related and relevant technical issues to validate our approach, as well as with experts in five international conferences.

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

8 Publications

We published the results of work package 1 in a paper that appeared in the internationally widely-read academic journal Renewable and Sustainable Energy Reviews[25] in May 2021 and in a practitioner article in the Swiss periodical VSE bulletin in December 2020[57]. We plan to submit the scientific paper of work package 2 to a peer reviewed academic journal and the practitioner article to a widely read periodical during the next months. A conference paper, which serves as a basis for both publications, has been sent to the SFOE in addition to this report.

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Appendix

Table A1: Results of building load profiles: Power and electricity in the exemplary setting considered, source: Schnydrig (2021)[26]

	2020	2035		2050	
		slow_dev	fast_dev	slow_dev	fast_dev
Peak power [kW]	364.5 [a] (0%) [b]	374.3 (+3%)	488.9 (+34%)	440.9 (+21%)	579.7 (+59%)
Daily net electricity demand [kWh]	4576.8 (0%)	4811.9 (+5%)	6235.8 (+36%)	5874.9 (+28%)	7463.9 (+63%)
Daily electricity production of PV [kWh]	39.2 (0%)	193.0 (+393%)	460.8 (+1076%)	245.9 (+528%)	911.0 (+2225%)
Daily electricity demand for heating/cooling [kWh]	1823.1 (0%)	1541.7 (-15%)	1569.2 (-14%)	1332.2 (-27%)	1114.2 (-39%)
Daily electricity demand for EVs [kWh]	3.6 (0%)	761.7 (+21276%)	2660.1 (+74558%)	2192.8 (+61442%)	5005.4 (+140377%)

[a] The reported numbers represent the mean values of the 100 Monte Carlo simulations, not the numbers from the most representative load curves.

[b] The percentages indicate the deviation from the 2020 value.