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Analysing charging processes of electric vehicles to reduce grid load and emissions

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Abstract

Private electricity production and consumption are expected to increase in the forthcoming years due to the growing number of electric cars, the replacement of oil-based heating systems with heat pumps, and the rise of locally produced energy from solar panels. This poses a challenge to the existing grid as well as the entire energy sector of Switzerland, particularly during peak load periods and when surplus photovoltaic energy is lost unused. This thesis investigates the flexibility of electric car owners in relation to charging sessions and proposes a data-driven optimised charging management system that minimises grid load and emissions.

A combination of data from charging sessions, transformer stations, emissions from electricity production and weather is used to assess the flexibility of charging sessions and define the framework of such a system. The analysis focuses on a demonstration site in St. Gallen, providing predictions and visualisations to measure the impact of electric cars on a local scale. The results contribute to the goals of the ENFLATE project and Switzerland's climate neutrality targets.

The findings reveal that electric vehicle owners exhibit heterogeneous but long-term regular charging behaviours. Peak load occurs when individuals return from work and start charging immediately, although low energy tariffs can shift the charging start time. The proposed system allows electric car owners to book a timeslot when the car is plugged in and needs charging. The charging management system selects the optimal charging time based on the availability of surplus energy and low emission times. To effectively shift charging, the system must incorporate dynamic pricing linked to emissions. This approach ensures optimal use of renewable energy and increases grid stability, supporting Switzerland's transition to a user friendly and sustainable energy future.

Introduction

The consumption of electricity in private households has increased in the last few years and is expected to rise further in the future. This is due to the replacement of oil heating with heat pumps and the shift towards cars driven by electricity instead of fossil fuel. Furthermore, the amount of electricity generated by photovoltaic systems is also increasing [1]. These factors pose a challenge to the power grid in the upcoming years, as the consumption and the input continue to rise and put additional pressure on the transformer. Especially on cold winter or sunny summer days, it may come to temporary bottlenecks on the local transformer.
The ENFLATE project aims to address these challenges by the shifting electricity flows resulting from the growth of local renewable energy sources and battery electric vehicles (BEV). The current grid was not designed to handle these changes and requires flexibility, particularly during peak load periods. Expanding the existing grid is too expensive and would have to be paid by private individuals, further increasing the already rising electricity prices.
Peak load is reached in two ways. Excessive electricity consumption or strong feed-in from photovoltaic systems on sunny days can potentially overload the transformer. The trading platform used in the project allows individuals to sell their flexibility, such as not charging their electric cars at a certain time when maximum load could be reached [2]. In general, fixed appliances such as electric boilers and heat pumps are better suited to dissipate excess energy than electric vehicles. This is because BEVs need to be plugged in to receive electricity and have a battery that is not yet fully charged. Implementation of efficient and flexible charging infrastructure for BEVs is crucial in decreasing the load on the grid and achieving carbon neutrality by 2050.
The EKZ has provided charging infrastructure data of Zurich. This data is used to understand the current behaviour of charging processes. With knowledge of the behaviour, the flexibility potential of charging sessions is investigated. In addition to analysing historical emission and energy consumption data, various visualisations are created to present the data objectively and build a charging management system in a way that minimises the impact on the grid and environment. Overall, the ideas aim to reduce the impact of BEVs on the grid, which will be a topic of great interest in the next years with increasing inflow of electricity from solar panels and growth in BEVs.

1. Planned analysis and discussions

The first step is to explore all the data. The central objective is to model the charging behaviours of electric cars based on charging infrastructure data from Zurich. Possible patterns are researched using visualisations to identify differences or coherences among various types of electric car owners. These results are considered as the basis for modelling the behaviour, assessing flexibility, and defining the framework of the charging management system to solve the problems.
After getting an overview on how currently BEVs are charged, a search to limiting factors on basis of the greenhouse gas (GHG) emissions per kWh and future grid limits is conducted. Modelling the charging behaviour and finding limits in emission and the grid is fundamental to creating appropriate and realistic charging implementation ideas. These findings are then discussed in the chapter after the results, to determine how well they work and how much capacity can be reserved for BEVs in the upcoming future. They are essential for the adoption of their energy management technology. A short overview of the whole process from data preparation to the final product is shown in figure 1.

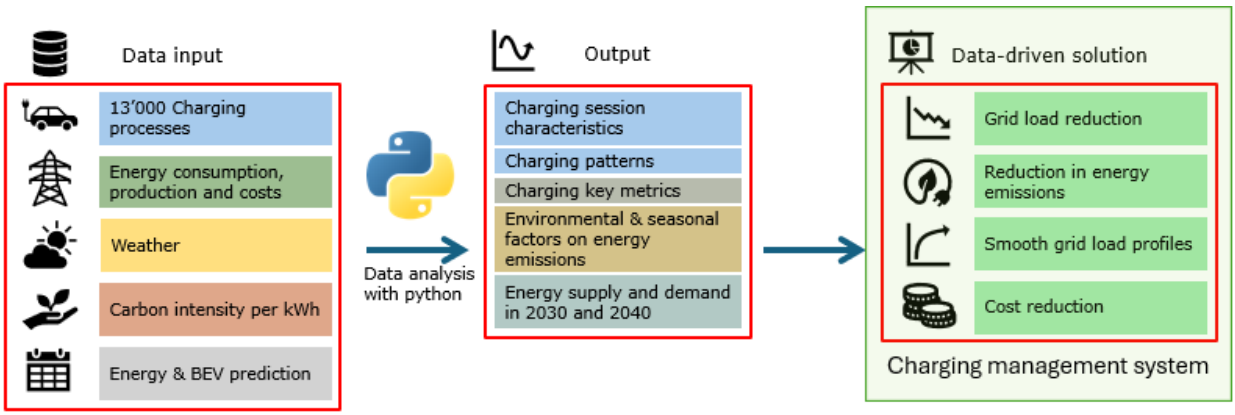
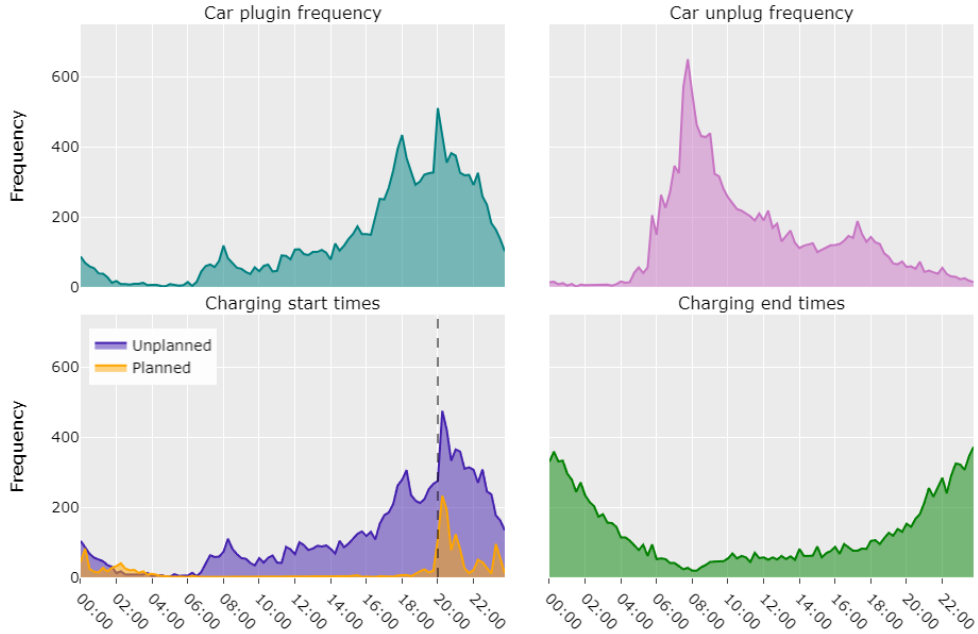


Figure 1 - Data-driven process roadmap

2. Characteristics of charging sessions and energy mix emissions

An in-depth analysis of the data has yielded valuable insights into the characteristics of charging processes. The data received from the EKZ revealed additional insights beyond those initially anticipated.

The majority of BEVs are connected to a wall box and begin charging immediately following the end of a workday. This peak happens twice: once at 18:00 and again at 20:00. It is notable that 86.4% of users employ a dumb charging approach, whereby the car is charged immediately after the cable is connected. The remaining charging sessions are planned, with users scheduling the start time to occur after 20:00 in order to take advantage of the lower electricity tariff offered by the EKZ. Some users even schedule charging at the middle of the night. Most cars are unplugged at 7:45 in the morning. However, some car owners unplug their cars as early as 6:00. The aforementioned facts

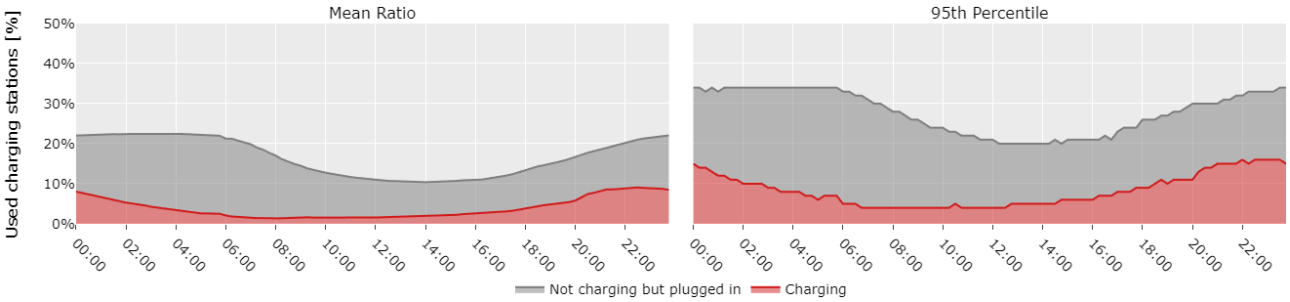


are derived from figure 2.

Figure 2 - Daily trends in BEV charging behaviour

Figure 3 illustrates the connection probability between charging stations and BEV divided into charging and not charging but plugged in events. It is observed that there is a notable increase in the number of cars charging during evening times at 17:00, which coincides with the period when many users return from work. The number of cars charging increases

until it peaks at 21:00, after which it remains stable until midnight. Following midnight, the number of cars charging decline as a lower necessity for charging is required given that the cars are then fully charged. Between 6:00 and 17:00, the number of cars charging remains constant. 23.2% of the total charging session is spent charging the car, with the remainder spent in a plugged-in state without charging. Charging sessions derived from the data exhibit a distinct character. Once the vehicle has reached a fully charged state, it



remains connected to the power source until the car is required for use again.

Figure 3 - Connection probability of BEVs in a 24-hour cycle

The connection probability between charging times and the number of available stations was also measured in order to ascertain the number of charging stations in use for each hour of the day. At the highest peak, from midnight to 5:00, 20% of all charging stations are in a plugged-in state. Over the course of this period, the proportion of cars that are charging decreases from 9% to 2%. This connection probability is very similar to that from the evaluations from the university of Stuttgart, where the ratio fluctuates daily between 19% and 9% [3].

In addition to the graphical analysis of charging times, statistical evaluations were conducted to extract numerical values from the data. Table 1 displays the distributions of selected metrics, which provide an overall understanding of certain distributions in charging processes. The data presented includes the first quartile (Q1), median, mean (μ), and third quartile (Q3) for each metric.

Table 1 - Summary of key metrics from 13'000 charging processes

	Q1	median	μ	Q3
Charging sessions per week	0.62	1.23	1.43	1.85
Energy flown per charging session [kWh]	13.03	26.5	28.24	39.86
Charging duration [h:m]	1:45	3	3:10	4
Plugged in time [h:m]	10	13	13:46	17
GHG emissions per charging session (gCO_2/kWh)	1'117	2'511	3'379	4'651
Costs per charging session [CHF]	2.19	4.97	5.33	7.73
Time in between charging sessions [days]	0.58	2.22	3.12	4.53

When the average energy input for each charging session is scaled down to the energy needed for each day, this equates to 29.5 km driven by each BEV, if each car consumes 19 kWh per 100 km. The observed variation in GHG emissions per charging session is attributed to the differing emission profiles observed at different times of the day and year.

A study of 45'000 charging processes from 480 households in Germany revealed that an electric car is charged on average 2.2 times a week. The average time spent plugged in is 11.4 hours. The frequency of charging is significantly higher, and the plug-in time is shorter than the results presented in this thesis [4]. One possible reason for these large deviations can be explained by the difference in car-dependency, geography and daily driving distance between Switzerland and Germany [5][6].

It is not possible to extract and cluster charging patterns with a times series clustering algorithm due to the vast differences between all charging stations, which prevent the algorithm from identifying similarities. The patterns are not in similar shapes that could be meaningfully divided into groups by an algorithm. Therefore, a manual approach is applied. Upon manual inspection of the data, as shown in figure 4, it becomes clear that each station shows a regular charging pattern over time, but the charging patterns varies between each charging station. The upcoming figure presents a visual representation of the charging sessions from nine stations over a three-month period.

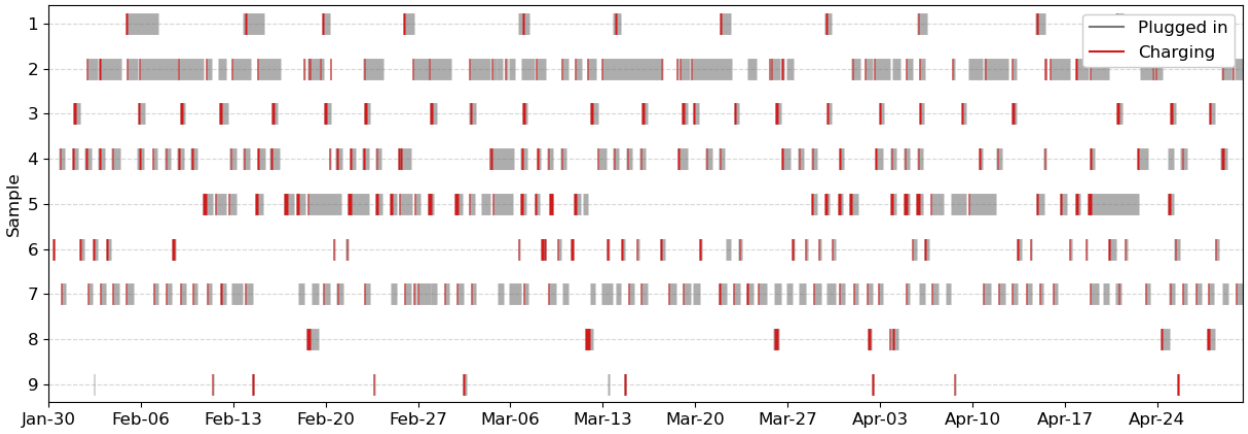


Figure 4 - Charging sessions of a sample of charging stations

Some individuals regularly plug in and charge their BEVs after work. Others always leave their car plugged in, even when it does not need to be charged. Some only charge it when it is necessary. There is no relationship between weather or season and charging behaviour. Holidays and weekends result in the same amount of charging processes and postponed unplugging times. Furthermore, it has been demonstrated that the frequency of charging has a direct impact on the consistency of the charging process over time. This implies that the predictability of subsequent charging process increases with the frequency of charging events, as opposed to longer periods in between charging events.

The average GHG emissions per kilowatt-hour in Switzerland is 85 gCO_2 eq/kWh. Figure 5 illustrates the change in gCO_2 eq/kWh emissions during a day, also incorporating the life cycle of the energy generators. The differences within the seasons were labelled with confidence bands, which demonstrate the variation from the 1st quantile to the 3rd quantile. During spring and autumn, there is minimal variation in emissions throughout the day. The emissions of the energy mix are stable at 64 gCO_2 eq/kWh during the summer and at 71 gCO_2 eq/kWh during spring and autumn. However, during winter, there is a notable discrepancy in emissions, with fluctuations occurring throughout the day and reaching elevated levels of over 200 gCO_2 eq/kWh during the night.

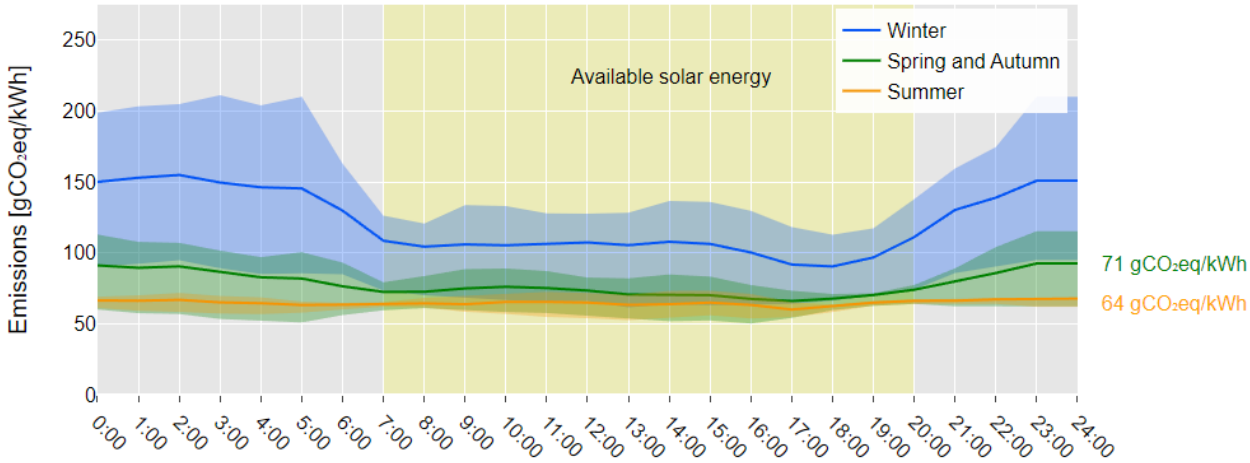


Figure 5 - Seasonal gCO_2eq/kWh emissions throughout the day

The generation of local energy from solar panels results in an emission of 30-50 gCO_2 eq/kWh, a figure that is dependent upon the photovoltaic panel technology employed and the consideration of the entire lifecycle of the photovoltaic panel [7][8][9]. Using only energy from locally produced sources results in a reduction of 22% to 58% of CO_2 equivalent emissions per kWh. However, this reduction is contingent upon the availability of sufficient global solar radiation during specific hours on sunny days.

Figure 6 illustrates that Switzerland relied on German electricity during the night on a period of low temperatures between the 23rd and 27th of January 2023. It is also notable that, on such winter nights, there is a high jump from 70 gCO_2eq/kWh to over 300 gCO_2eq/kWh after 20:00. This presents a significant challenge when postponing the charging of large quantities of batteries into winter nights, particularly in the context of the change to the low tariff. It is also noteworthy that on such days, there is not enough available sunlight to even charge a car by a household plug. The temperature on these days was at -2.9°C in St. Gallen. It is therefore imperative to closely predict such situations throughout the year and to exercise control over the charging of BEVs during such periods.

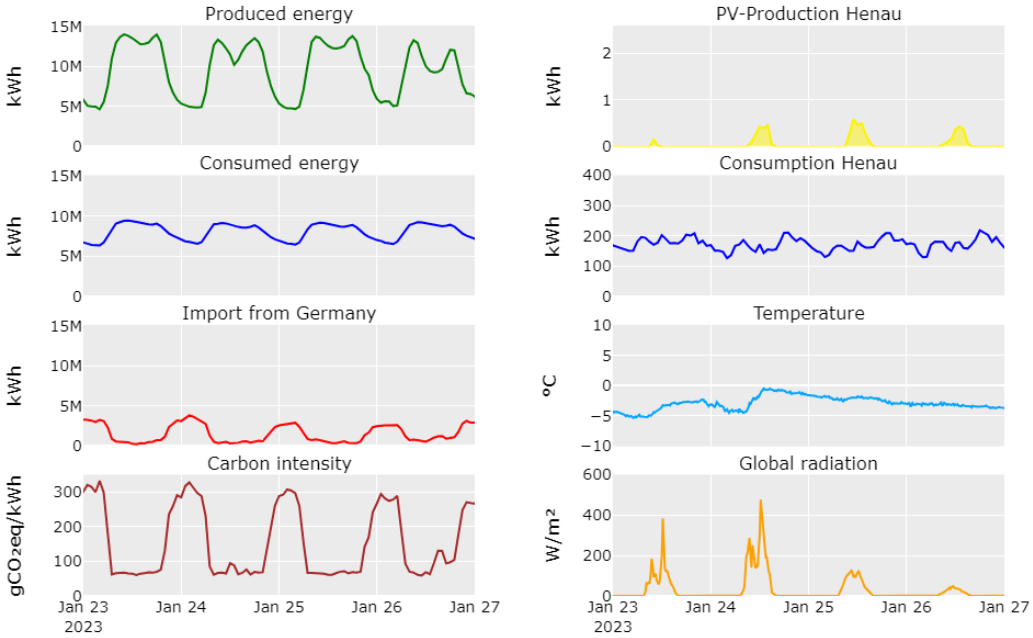


Figure 6 - Energy, weather, and emission metrics over four days

In the most unfavourable circumstances, the charging of a BEV results in the emission of 18kg of CO_2, compared to 64 kg for a diesel car over the same period. This means BEVs have running emissions more than 3.55 times lower than comparable gasoline cars. This aligns closely with the ICCT's life cycle emissions estimates, which show BEVs having 2.94 to 3.23 times lower emissions over their lifetime compared to internal combustion engine cars [10].

3. Added Values/Conclusion

The daily routines, charging needs and the electricity pricing of BEVs are the main factors influencing the charging behaviour. It is discovered that there are no similar charging patterns decipherable across BEV owners, which can be generalised in behaviour groups. However, it is encouraging to note that each user appears to remain consistent in their behaviour over a long period of time. The more frequently a BEV owner charges their vehicle, the more consistent and predictable upcoming charging processes become. The analyses have enabled a more comprehensive understanding of the charging demand of electric vehicles. This, in turn, enables the development of ideas for more effective energy infrastructure and energy management strategies.

In general, there is a high availability of surplus solar power from March to October during the day after 7:30 until 20:00. In winter, there is not enough solar power to get an excessive amount. Therefore, solutions must avoid charging during high emissions times in winter, which occur mainly during very cold nights. The availability of plugged-in electric cars is unfortunately better at nighttime based on the analyses. The charging capacity at early mornings and evenings can be increased by turning off boilers and heat pumps for a few hours until the excess energy accumulated exceeds reheat energy needs. The additional electricity generated is insufficient to charge multiple vehicles and is therefore in this case not a viable solution.

Optimising charging of BEVs means optimising GHG emissions and energy costs. These need to be linked together in the solution. When locally produced solar power is available, there are no costs associated with electricity procurement, and the GHG are lower than those resulting from the use of the electricity mix from Switzerland at these times. However, the costs due to the low tariff in the winter months play against the GHG emissions. The electricity costs decrease at 20:00 and at the same time, the GHG emissions explode on cold nights. This is due to the fact that the missing electricity is imported from Germany, where 24% of energy is still produced with coal [11]. The results of the study indicate that small cost incentives, such as the switch to a low-tariff rate, have a significant impact on the charging start time. The price per kWh decreased by 18%, and 13.6% of all BEV owners changed their charging start time to after 20:00. The findings of the study suggest that cost adjustments in the electricity price could be a useful lever to influence charging behaviour.

As soon as the production of solar energy is greater than the local electricity consumption, an electric car can be used to absorb the otherwise lost energy. Controlling the charging infrastructure of electric vehicles is more complex than that of a heating pump or boiler. An intervention into vehicle charging would be noticed by the user, in contrast to the heat generators. The time flexibility of a BEV is low. This is because it is linked to the plugged-in time, the individual driving behaviour, and the current situation of the owner. Additionally, available battery storage is required to charge flexibly. Plugged-in and fully charged cars cannot be used to dissipate energy anymore. Once they are charged, only V2G solutions are effective. V2G solutions could also increase the local flexibility. They can be charged at a place with high solar energy input, for example at work, and at home this electricity can be fed for the operation of household appliances during low sunlight.

It is also crucial to highlight the significant potential for solar energy generation at the workplace. During typical working hours, solar radiation levels are high, which translates to a correspondingly high energy generation potential.
In order to enhance the flexibility of charging processes, it is essential to address the cost approaches and to grant vehicle owners the autonomy to organise their charging processes according to their preferences. This also encompasses the option of not having the charging process entirely controlled by a management system, as this may not always be the optimal solution due to the multitude of behaviours.

To promote the flexibility of BEVs, a solution is proposed for integration into the ENFLATE Strompilot energy management system. This solution involves a local management system capable of controlling boilers, heat pumps, and charging stations. It also requires a flexible electricity pricing structure to accommodate the diverse lifestyles of BEV owners, allowing them complete freedom to choose their charging times.
BEV owners can schedule a charging window of when their vehicle is at home and plugged in but not fully charged. The management system identifies the most optimal charging times, initially prioritising excess solar power to eliminate costs and then focusing on charging BEVs during periods of minimal GHG emissions.
To motivate BEV owners to adapt their charging behaviour, pricing incentives are crucial. Charging during high-emission periods or predicted high grid loads should be priced higher, encouraging users to charge during off-peak times for price benefits. Additionally, a system could be introduced, rewarding users with a lower energy tariff for charging during periods of lesser GHG emissions per kWh. Charging when excessive energy from solar panels is available remains free. The height of the tariff would depend on factors such as time of charging, the size of the entered charging window, the use of excess energy, and avoided GHG emissions. Early planning and reservation of charging times would yield higher returns, while last-minute changes would incur higher costs.
The charging management system maintains considerable flexibility in managing electric vehicle charging schedules based on entered time slots. Initially, the system monitors the electrical grid to prevent overload, which occurs from charging multiple vehicles simultaneously. Additionally, the system prioritises charging based on the cost of electricity. Charging during periods when excess solar power is available is highly prioritised, as this reduces the cost of electricity to zero and also relieves the grid load as a side effect. This further reduces the risk of sudden load peaks and power interruptions. The system then prioritises charging during times of lower carbon dioxide emissions when there is no excess solar energy available, as higher emissions correlate with higher electricity costs in the pricing strategy. Users are notified about the expected charging times for their vehicles, the predicted price, and saved costs. By the end of each individually defined time slot, the vehicle is fully charged.
This approach not only provides flexibility but also minimises the impact of BEVs on the local and national energy grids by better distributing the use of energy across the day. This could reduce the need for costly grid capacity expansions and significantly lower GHG emissions.

The solution's most significant strength lies in its scalability. It can be introduced on a single home scale, or it can be expanded to encompass a wider area, making it versatile for managing large fleets. Additionally, it supports a wide range of BEVs, from small-scale personal vehicles to large fleet vehicles or even trucks, ensuring broad applicability.
The solution addresses three key challenges of today simultaneously. High, rising energy prices, smoothing grid load, and reducing emissions in line with the climate neutrality goals of Switzerland. It promotes self-produced solar energy and prevents the transformer from

reaching its technical limits, preventing potential fires and heavy wear. This results in reduced infrastructure costs and enhanced safety.
With this solution, the BEV owner is always focussed and takes the full responsibility of their car, preserving their autonomy without intrusive system interference. A user has always the option to charge the car spontaneously at the standard energy price without an intervention from the management system. However, this charging behaviour would always be strategically priced higher, to encourage using the management system. Otherwise, users would revert to their previous habits of charging their vehicles on the spot.
BEVs that are not plugged in or are already fully charged when the user reserves a timeslot do not present a challenge to the infrastructure and therefore do not require any solutions to this potential issue.

This solution also has drawbacks. It is important to consider direct, indirect, and macroeconomic rebound effects that could result from behaviour changes due to the lower electricity costs. The system's reliance on solar energy also introduces vulnerability to sudden weather changes, such as overcast conditions that reduce solar panel efficiency. Legal compliance is another essential factor, including ensuring that there is no discrimination in access based on human or regional differences, and meeting data protection and other relevant laws.
Moreover, the effectiveness of this concept must be tested on a large scale, which involves significant costs. Infrastructure updates are necessary, including the installation of smart meters to support the management system. Ultimately, the benefits derived from the management system must justify these expenditures.
The charging management system should create a situation in which a lesser number of vehicles charge at a fewer daily frequency, rather than many BEVs charging a small amount of energy at the same time. The latter places a much greater load on the grid than the former. To address this problem the system should therefore know the number of remaining battery charge of each BEV.
This paper presents an abridged version of a bachelor's thesis written at the Lucerne University of Applied Sciences and Arts for the degree programme in mobility, data science and economics. The complete version is available upon request from the authors.

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