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Assessing flexibility from electric vehicles using an open-source energy system model: trade-offs between smart charging, vehicle-to-grid and an extensive charging infrastructure

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ABSTRACT

The introduction of electric vehicles (EVs) is a key strategy to decarbonise the transport sector. However, the electrification of transport increases electricity demand, thus burdening electricity grids. EVs can also provide flexibility to the energy system to enable renewable energy through smart charging, vehicle-to-grid (V2G), and an extensive charging infrastructure with more charging opportunities away from home. This study analyses the complementarity among these three strategies by extending GRIMSEL, an open-source energy optimization model of Switzerland's energy system with its neighbouring countries. Our results show that implementing any flexibility option enables PV, reduces stationary battery installations, while also reducing overall system costs. Specifically, smart charging increases optimal PV capacity by 6 % and reduces storage needs by 19 %. Interestingly, V2G operates strategically by providing electricity during peak periods, and reducing battery storage needs between 21 and 37 % on average. Additionally, an extensive charging infrastructure including commercial, at work, and public charging, reduces the need for additional PV and battery storage by 12 % and 66 %, respectively, i.e. delivering congestion relieve. Overall, a combination of flexibility options can reduce overall system costs by up to 29 %. Policymakers and energy stakeholders may use these insights to tailor solutions depending on their specific policy targets.

1. Introduction

1.1. Motivation

The transport sector accounts for almost a quarter of CO_2 emissions globally [1]. Since passenger cars represent approximately 52 % of the total final energy demand of total ground transportation [2], the replacement of conventional cars by electric vehicles (EVs) is one of the key strategies for decarbonizing transportation [3]. Technological advancements, cost reductions, support mechanisms, and charging infrastructure are influencing the global adoption of EVs [4]. The number of electric cars continues to rise, globally surpassing 40 M, with 14 M new registrations in 2023 alone [4]. In Switzerland, the total number of EVs increased by 40 % from 2022 to 2023 (representing 3 % of the total passenger car stock), and trends indicate further growth [5].

At the same time, the electrification of transport leads to additional electricity demand, thus burdening electricity grids. This results in increased peak demand (as a consequence of EV charging use [6]), resulting in the need for electricity grid reinforcement [7]. On the other hand, EVs can provide flexibility through indirect (e.g., price signals [8]) and direct control (e.g., through a third party such as aggregators or utilities that determine the EV charging behaviour [9]). The flexibility through smart or flexible charging and vehicle-to-grid (V2G) can help mitigate the impact of EVs on the grid. Also, a widespread charging infrastructure including workplaces and public charging may help further [10].

The flexibility provided by EVs can benefit both the overall energy system and EV owners. In addition to a reduction of peak demand [11], EV can increase local PV self-consumption [12] and can lower carbon emissions [13]. Smart charging can provide ancillary services to the electricity system [14], while V2G can act as an additional battery storage. Although battery degradation is one of the key concerns related to V2G use for grid purposes [15], studies have demonstrated that the impact on battery degradation is minimal when infrequently used [16], and that V2G can even extend the lifespan of the battery of the vehicle

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Nomenclature

EV - Electric Vehicle
V2G - Vehicle-to-Grid
HP - Heat Pump
IND - Industrial sector
Li-ion - Lithium-ion battery
LCOE - Levelized cost of electricity
MFH - Multi-family house
NHTS - National Household Travel Surveys
OCO - Service sector (offices and commercial sector)
PV - Photovoltaics
SFH - Single-family house
VRFB - Vanadium redox flow battery

Notation/Symbols

P_{V2G_inst} - Installed V2G capacity [MW]
$P_{V2G\_charger}$ - Power charging of V2G [kW]
$C_{degradation\_V2G}$ - Degradation cost of V2G [€/MWh]
C_{bat} - Battery cost of EV [Euro]
L_c - Number of cycles
E_b - Battery capacity of EV [kWh]
DOD - Depth of discharge [%]

[17,18]. These benefits may also reduce the electricity bills of EV owners [19]. To further stimulate EV adoption, an extensive and distributed charging infrastructure is needed [20]. Therefore, a comprehensive analysis, using energy system modelling, on how to accommodate the rising uptake of EVs while minimizing their impact on the electricity sector through EV flexibility options (smart charging, V2G, and distributed charging) can be useful for policy makers, energy companies, and utilities.

1.2. Insights from literature

EVs can provide flexibility for the energy system in various ways. For example, a study conducted at the microgrid level shows that smart charging and V2G can increase self-consumption by 13–39 % and reduce peak demand by 27–67 % [11]. Dixon et al. assessed the role of V2G in the local distribution grid in Glasgow and found a 5–6 % reduction in carbon emissions and a 28–67 % decrease in EV charging costs [21]. However, integrating EVs into the distribution grid increases reinforcement requirements [7]. For instance, extensive EV adoption in California could require upgrades for 20 % of the distribution grid [22].

Table 1
A non-exhaustive list of energy system models integrating flexibility options of EVs (smart charging, V2G, and differences in charging locations, i.e. home, work, commercial, public charging).

Model	Smart charging	V2G	Charging locations	Open source	Reference
Balmorel	✓	✓	Home	✓	[23]
PyPSA	✓	✓	–	✓	[24]
LUT-ESTM	✓	✓	–	–	[25]
Simple Dispatch	✓	–	Home, work	✓	[10]
EnergyPLAN	✓	✓	–	✓	[26]
OSeMOSYS	–	–	–	✓	[27]
CentIv (Nexus-e)	–	✓	–	–	[28]
Swiss-Calliope	–	–	–	✓	[29]
GRIMSEL-EV	✓	–	Home	✓	[30,31]
GRIMSEL-EV (Extended)	✓	✓	Home, work, commercial, and public charging	✓	This study

Table 1 displays a non-exhaustive list of publications that have studied EV integration and the effects of EV flexibility options in energy system models. Gunkel et al. studied the impact of EV flexibility using the Balmorel energy optimization model [23]. They found that flexibility reduces system costs and emissions while increasing installed capacities of wind power. Similarly, the study by Xu et al. at the European level demonstrated that smart charging and V2G increase PV capacity compared to uncontrolled charging, reducing carbon emissions by 6 % for smart charging and 17 % for V2G [13]. Another pan-European study by Brown et al., using the PyPSA energy optimization model, shows that smart charging and V2G reduce the need for additional installed capacity and lower overall system costs [24].

Already in 2008, Lund and Kempton showed for Denmark that V2G could increase the installation of wind capacity and lower emissions in the power system [26]. For Japan, Bogdanov and Breyer, using the energy system model LUT-ESTM, found that flexibility options like smart charging and V2G lead to reduced system costs, optimized storage needs, and fewer curtailments [25]. Powell et al. showed that an extensive charging infrastructure can significantly reduce grid impacts by lowering storage requirements and emissions in California [10]. For Switzerland, V2G was found to reduce electricity imports with high carbon intensity (by 33–40 %) [32]. Another study for Switzerland by Liedekerke et al. concluded that V2G reduces both total system costs and curtailments. This study, conducted using the CentIv module within the Nexus-e model, focused exclusively on V2G, with other flexibility options not considered [28]. Previous studies using the GRIMSEL model have analyzed the role of smart charging with various charging strategies, finding that it increases the integration of renewable energy sources and reduces storage needs [30,31]. However, other flexibility options such as V2G or charging at different locations were not analyzed.

1.3. Novelty and key contributions

Overall, existing energy system models have considered some of the EV-related flexibility options (see Table 1). Several review studies have highlighted the need for a more detailed and holistic assessment of EV flexibility options within energy system models. Kachirayil et al. reviewed 116 studies and found that EV flexibility options are rarely considered [33]. Another review on energy system planning in the context of transport electrification emphasized the importance of including EV flexibility options in energy models to support EV adoption and provide benefits to the system [34].

Against this background, the novelty of this study is to provide a comprehensive assessment of EV flexibility options and their trade-offs in energy systems. To do so, this paper extends an open-source energy optimization model, referred to as GRIMSEL: a) to integrate multiple EV flexibility options, including V2G and distributed charging infrastructure (e.g., workplace, commercial, and public charging), beyond smart charging; b) to analyze the techno-economic trade-offs between EV flexibility options including optimal capacity expansion for PV and battery storage, and net system costs; c) to provide a detailed spatially distributed charging infrastructure framework that distinguishes between urban, suburban, and rural settings by considering various charging locations, as well as building archetypes, including home, work, commercial, and public charging; d) to assess the interplay between stationary battery storage and V2G.

The following section describes the methodology used to implement the EV flexibility options, alongside the energy system model and input data. The results are then presented and discussed in the third and fourth sections. Finally, we discuss the limitations of the study, followed by the conclusion.

2. Methodology and input data

2.1. Energy optimization model (GRIMSEL)

GRIMSEL is a quadratic linear programming optimization model (due to the quadratic fuel cost function of thermal power plants). It is written in Python programming language (version 3.8), with mathematical and optimization equations formulated using the Pyomo package, while CPLEX (academic version 20.1) is used as the solver. The main objective of the model is to minimize total system costs (from the social planner perspective). Grimsel has a high temporal resolution (hourly) over an entire year, and it applies a multiple horizon optimization framework up to 2050, with a five-year step increase, allowing to capture long-term investment decisions. It is open source[1] and extendible to other countries and geographical areas depending on the node configurations (communal, city, country, or continental level). A detailed description of the model is provided by Soini et al. [35], while its validation was achieved by replicating the electricity system conditions of the base year (2015), as presented in the Supplementary Information (SI), S1. The model was subsequently extended to represent sector-coupling (heat [36], transport [31], and hydrogen [30]).

In this study, we build on the latest version of the model to analyze in detail the effect of EV integration and flexibility [30,36]. The model has a granular representation for Switzerland, where the demand-side is represented through various building archetypes which representant different type of consumers, namely single family houses (SFH), multi-family houses (MFH), offices and commercial buildings (OCO), and industry (IND) across urban settings (rural, suburban, and urban), as shown in Fig. 1. The building stock, for which statistical data are available from the building registry [37,38] is described by building archetypes developed by Streicher et al. [39]. Explanations about the features of the archetypes are provided in Ref. [40]. Building archetypes are linked with the central or national node (CH), representing Switzerland. Across the different urban settings, different constraints are defined for the distribution grid capacity (e.g., higher capacities in urban than rural area).

Here, we optimize the installed capacities of decentralised PV and stationary battery storage (Li-ion with 2h maximum discharge) and vanadium flow batteries (VRFB with (6h maximum discharge) at the level of various building archetypes. For Switzerland, PV is considered as the main future potential source of electricity production, since the other technologies such as wind is less accepted, and its capacity is provided exogenously based on the Swiss Energy Perspectives 2050+ [41]). The PV installations in Switzerland are expected to be integrated primarily in the built environment (in contrast, large-scale, open-space PV installations face various challenges such as high land cost and lack of social acceptance, similar to wind technology [42]). The costs for PV and battery storage are provided in the supplementary information.

The integration of heat pumps (HPs) was modelled previously by Rinaldi et al., thereby distinguishing between air/water (A/W) and brine/water (B/W) HPs [36]. The electricity demand of HPs is calculated based on the thermal demand of buildings using a bottom-up approach, and pre-defined COP values. These COP values depend on exergy efficiency (or thermodynamic efficiency) and the difference between source and sink temperature, with the latter being the outlet temperature (e.g., 60° for radiators and 35° for underfloor heating) [39]. The HP demand is provided with a daily (24h) temporal resolution.

The integration of EVs, specifically passenger cars, was studied in a previous publication by Syla et al. [31], where the modelling of EV charging demand profiles was conducted by capturing real mobility behaviour (e.g., arrival time, location, distance) using the National Household Travel Surveys (NHTS). EV demand is provided on an hourly basis with a weekly representation, which is scaled to the entire year. In this study, GRIMSEL is extended to represent an extensive distributed charging infrastructure: EVs can be charged at OCO and IND nodes, and public charging (marked in green in Fig. 1), in addition to residential building archetypes (SFH and MFH). The scenario used in this study assumes full electrification, with approximately 5 million EVs by 2050, representing an annual electricity demand of 10.45 TWh. Moreover, V2G is added as a new flexibility option for the energy system, in addition to battery storage, demand-side management and flexible heat pump operation. Details on the input data used in the model, for Switzerland and its neighbouring countries (Austria, France, Germany, and Italy), including installed capacities based on energy sources, energy demand, fuel and CO_2 prices, are provided in S6 of the SI. These input data have been updated using the latest projections from TYNDP2024 [43] up to 2050.

2.2. EV flexibility options

In this study, we assess three types of flexibility options from EVs. First, distributed charging, where charging occurs at locations such as workplaces, commercial buildings, and public charging rather than at home. Second, smart charging, where flexibility is provided within a specific charging time window. Third, V2G which serves as an additional flexibility source. This study focuses solely only on passenger cars, while other types of vehicles (e.g., commercial fleets, busses) are not considered.

2.2.1. Distributed charging

We used the National Household Travel Survey (NHTS) to assess the effect of extensive distributed charging across different building archetypes and urban settings. To model the potential of distributed charging, we start the process by assuming that EV charging primarily occurred at home, as described in our previous study [31]. This allows us to create the base scenario and calculate the potential for charging at other nodes, such as workplaces, commercial, or public charging (distributed charging). In both home and distributed charging scenarios, the total EV demand (10.45 TWh/year for 2050 in Switzerland) remains the same, but in the distributed charging option, this demand is shifted across different nodes (OCO, IND, and public charging). The process, outlined in Fig. 2, starts with the first module (load patterns for charging profiles), where representative charging profiles are generated based on charging locations. This module is important to represent the temporal charging patterns based on trip purpose and nodes (OCO, IND, and public charging). Next, the second module, which focuses on spatial distribution of cars across urban settings and trip purposes, distributes the cars across nodes and urban settings (e.g., from home to workplace charging). This step is important for estimating the amount of EV demand that is shifted based on spatial behaviour and trip purposes, as shown in Fig. 3.

The first module, charging profile load patterns, describes the steps applied to generate typical charging profiles based on the purpose of each trip (e.g., work, commercial, and leisure activities). We analyze travel behaviour data (such as distance, purpose, time of arrival, and day) from the Swiss NHTS to calculate the required energy demand and time to charge EVs, under the assumption that charging at nominal power begins immediately once the EV has reached the charging station (uncontrolled charging). The charging profiles of each EV are then aggregated to generate a representative charging load profile for the whole country. This process is repeated daily to represent a typical week, which is used to model charging demand across the entire year. Since the purpose of the car trips are known from the NHTS, charging profiles for different charging locations can be distinguished, i.e. at work, commercial areas, and public charging. For home charging, this results in the three charging profiles depending on the urban setting, namely rural, suburban, and urban [31].

The second module, distribution of cars across urban settings and trip purpose, determines the share of cars that move across nodes, and it

[1] https://github.com/sylaarven/GRIMSEL-EV.

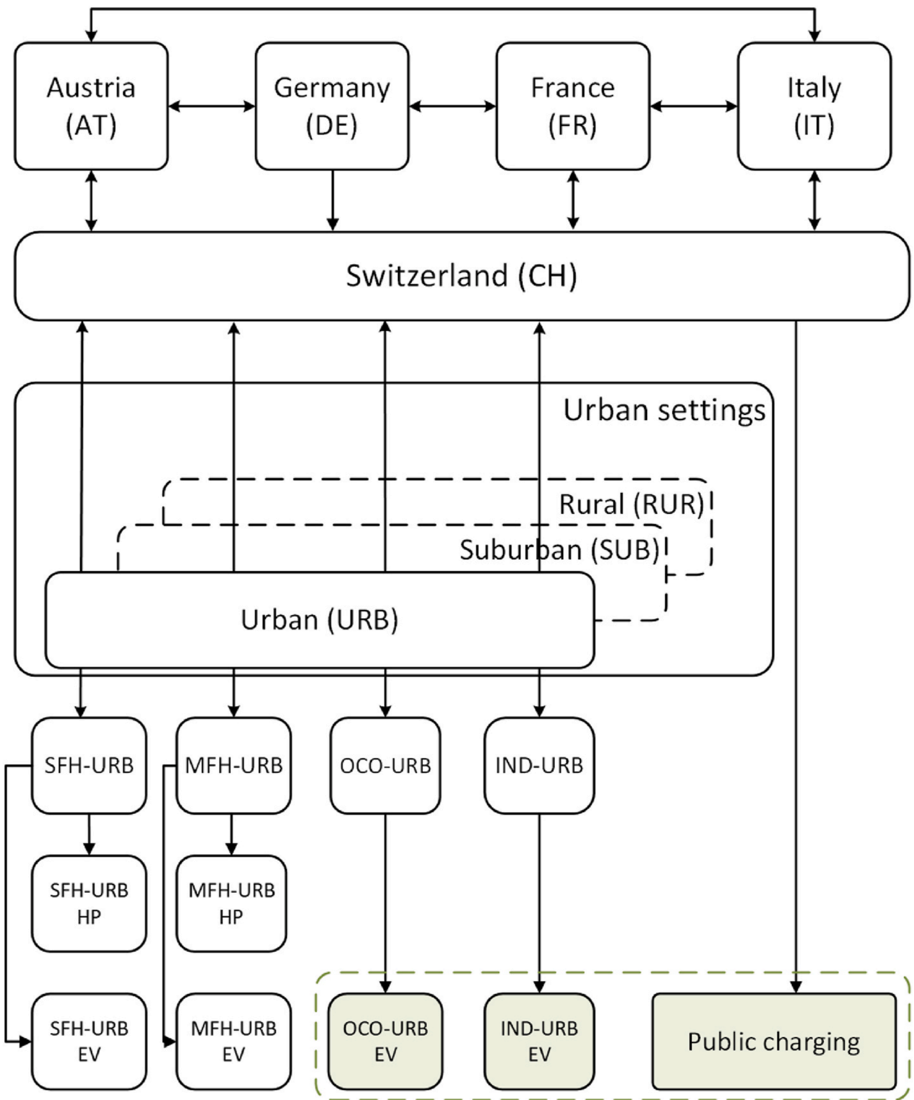

Fig. 1. Graphical representation of the energy optimization model (GRIMSEL) with building archetypes (SFH, MFH, OCO, and IND) across urban settings (rural, suburban, and urban). The national node, Switzerland (CH), is coupled with its neighbouring countries, namely Austria (AT), Germany (DE), France (FR), and Italy (IT) along with their respective transmission capacity constraints. Each national node includes key technologies (e.g., nuclear, gas, PV, wind) and electricity demand. The extension of the model for distributed charging at OCO, IND, and public charging nodes is highlighted in green.

considers the starting and ending points of respondent, based on urban settings and trip purpose. This process is iterated for the seven representative days of the week, across trip purpose and urban settings, as depicted in Fig. 2. The output of this module determines the share of cars moving across building archetypes (e.g., home to work) and urban settings (e.g., urban to suburban), as shown in the Sankey diagram in Fig. 3. As observed in Fig. 3, for SFH, we assume that EVs will primarily charge at home and work, while for MFH, we assume a more distributed charging, including OCO and the public charging node. Lastly, we consider the EV demand by residential building archetypes, e.g., home charging, to calculate the electricity demand for EVs in a scenario with extensive distributed charging infrastructure [31]. This baseline demand is adjusted using the outputs from both modules, which account for the shift of charging across different urban settings and trip purposes. Typical weekly load curves for home and distributed charging are shown in Fig. 4.

2.2.2. Smart charging

Smart charging is modelled endogenously, with specific charging time window given exogenously. For example, we assume a 24h time window for home charging (SFH and MFH), and an 8h time window for work charging (IND, OCO)), based on typical idle time for EVs at different places. Smart charging ensures that EV demand is satisfied within these time windows in a system-optimal way, i.e. minimizing the total energy system costs. For the public charging node, no flexibility is provided as we assume that EV owners expect immediate charging.

2.2.3. V2G

V2G is modelled as an additional battery storage with installed capacities and variable costs calculated exogenously. The V2G capacities are calculated across residential building archetypes (SFH and MFH) and urban settings, based on the number of EVs and their level of participation (e.g., no participation, biweekly, weekly, and twice-per-week or 2x/week), as shown in equation (1). For instance, weekly participation corresponds to 14.25 % participation (52 days out of 365) for an EV over the course of a year. The installed capacities are then calculated by multiplying the participation percentage by the total number of EVs, assuming a 7 kW, charger V2G capacity with a 90 % efficiency.

Fig. 5 provides the V2G installed capacities across residential building archetypes. The installed capacities remain constant

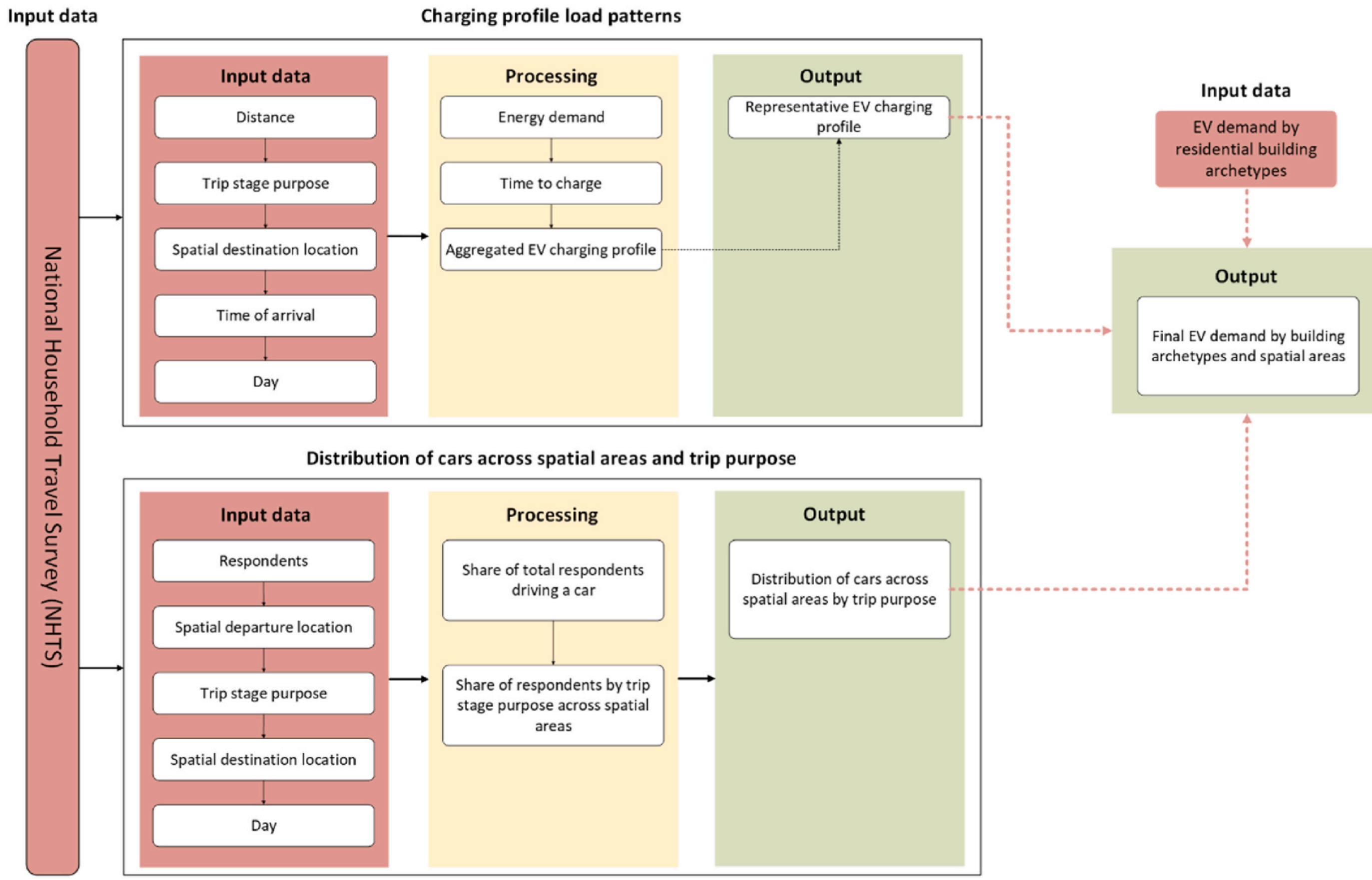

Fig. 2. Flowchart diagram depicting the steps for modelling EV charging profiles and demand based on trip stage purpose and urban settings. The input data for the EV demand by residential building archetypes has been calculated in a previous publication [31] and is provided in appendix.

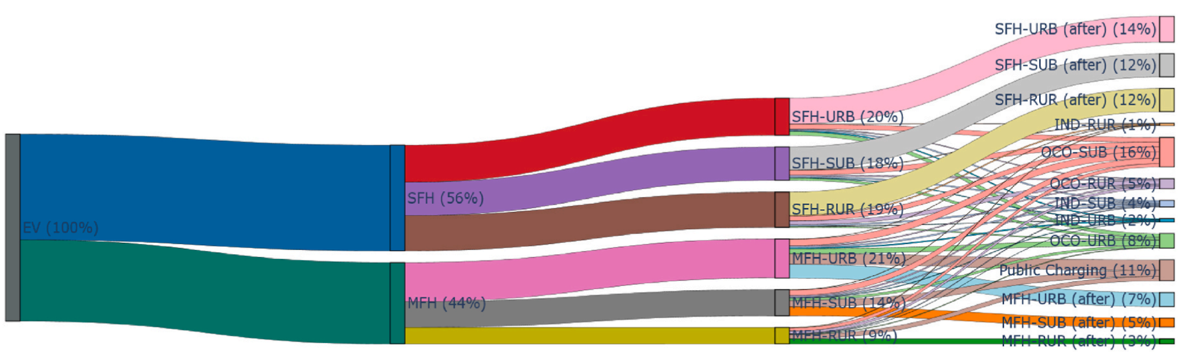

Fig. 3. The distribution of cars across urban settings and trip purposes. The nodes in the third link represent the scenario of home charging only, while the nodes in the fourth link depicts distributed charging for building archetypes and public charging.

throughout the year, based on the level of participation. Energy market actors like virtual power plants or aggregators are expected to coordinate these units to provide the required capacities. The estimation of V2G capacities in this study aligns with the availability of EVs in the system (i.e., the share of cars that are not used during the day). This availability was quantified by Syla et al. by calculating driving frequency using the data from Swiss NHTS [31]. On average, at least 32 % of cars remain at home at any given moment, and therefore, could potentially be used to provide V2G services. In this context, even in the scenario with the highest installed V2G capacity (2x/week scenario - 10 GW), the corresponding EV participation rate remains 28.5 %, thereby aligning with the minimum share of available cars in the system.

$$P_{V2G\_inst} = \frac{Level\ of\ participation}{Days\ of\ the\ year} \times Number\ of\ EVs \times P_{V2G\_charger} \tag{1}$$

Secondly, the variable costs for V2G are calculated to represent battery degradation, as this is the primary factor affecting the cost-effectiveness of V2G [44]. To calculate these costs, we use equation (2), proposed by Kempton et Tomić [45], also used in other studies such as Parra et Patel [46], which takes into account battery costs, the number of cycles, capacity, and depth of discharge (DOD), as shown in Table 2. The values assumed for Switzerland result in variable costs for V2G of 78.12 €/MWh.

$$C_{degradation\_V2G} = \frac{C_{bat}}{L_c \times E_b \times DOD} \tag{2}$$

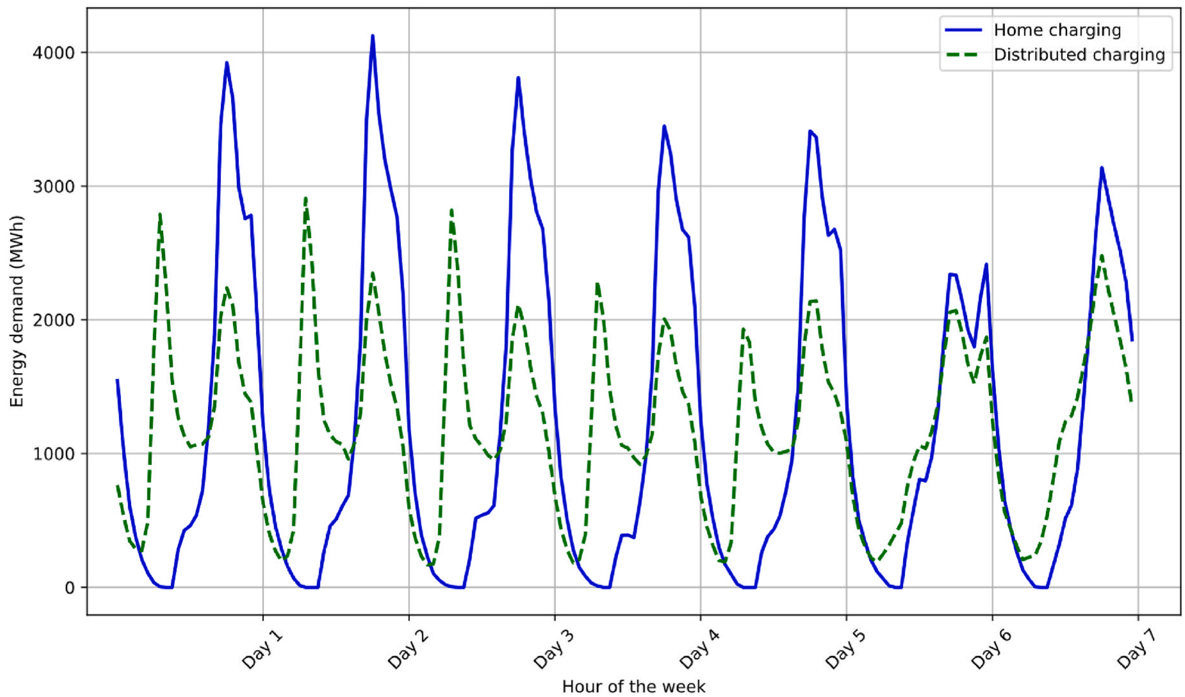

Fig. 4. Weekly representation of EV electricity demand in 2050 for charging at home (blue) and distributed charging (green). The profiles are provided for uncontrolled charging.

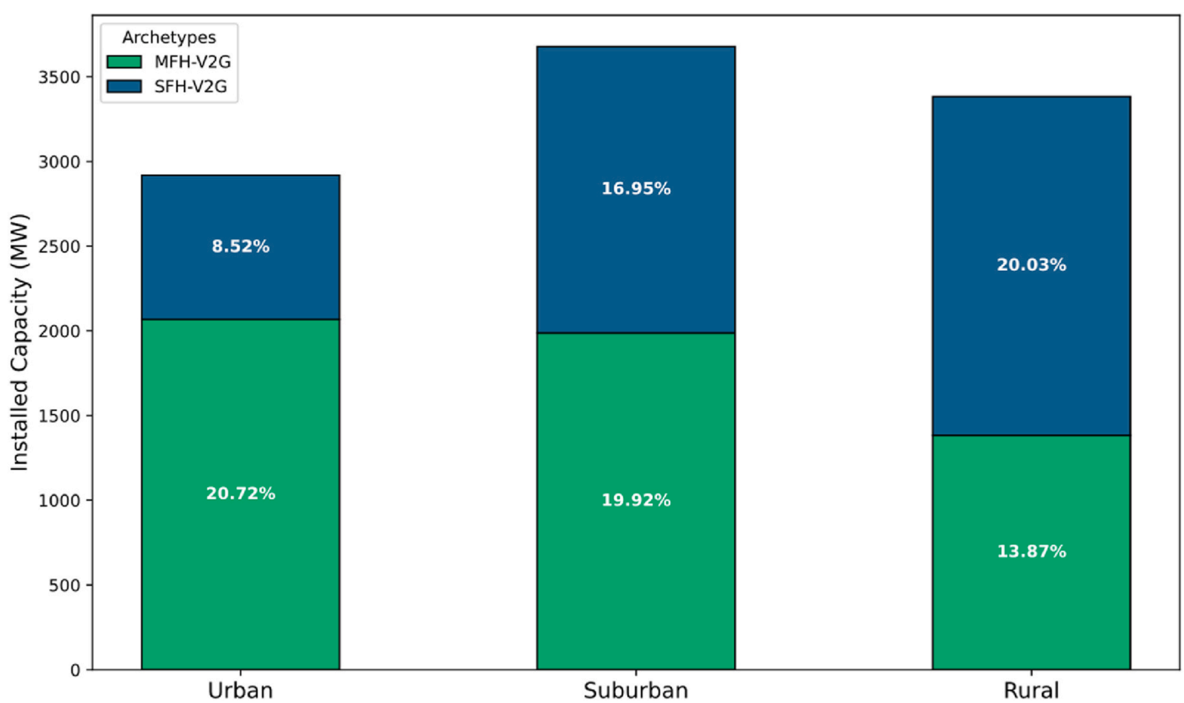

Fig. 5. V2G installed capacity, in nominal power, by 2050 across building archetypes and urban settings. In particular, installed capacities when EVs participate twice per week (2x/week, equivalent to 28.5 % participation annually) are depicted. The installed capacities are approximately 10 GW for 2x/week, with 5 GW and 2.5 GW for weekly and biweekly participation, respectively. The percentages represent the distribution of V2G installed capacities across different building archetypes.

2.3. Scenarios

To assess the effect of EV flexibility options, we study and run the model for different scenarios. For the EV charging location, we distinguish scenarios with EV home charging and distributed charging (charging away from home, i.e., at IND, OCO, and public charging). For smart charging, we consider a daily flexibility with time window of 24h for home charging (SFH and MFH), and 8h time window (08:00–16:00) for work. In contrast, for scenarios without smart charging (i.e., for uncontrolled charging), the EV demand is represented on an hourly (1h) basis, with charging occurring immediately upon plugging in. To

Table 2
Techno-economic parameters used to calculate V2G battery degradation.

		Source
Battery cost (C_{bat})	15000 €	[47]
Number of cycles (L_c)	4000 cycles	[48,49]
Battery capacity (E_b)	60 kWh	Own assumption
Depth of discharge (DOD)	80 %	[47,49]

analyze the role of installed capacities for V2G, we differentiate four scenarios depending on level of EV participation ranging from no V2G participation (noV2G), biweekly, weekly to twice per week participation (2x/week). In total, a combination by 16 scenarios is considered (i.e., resulting from the multiplication of two for smart vs. uncontrolled charging times two for charging location (home and distributed charging) times four V2G scenarios).

3. Results

The result section is divided into three parts following the raised research question. First, we show the effect of EV flexibility options, namely V2G, smart charging, and distributed charging on optimal installed capacity (PV and stationary battery storage) across building archetypes. Secondly, the interplay between stationary battery storage and V2G is depicted, and lastly, we discuss the effect of EV flexibility options on net system costs.

3.1. The effect of EV flexibility options on optimal installed capacity

Fig. 6 illustrates the increased levels of V2G (see grouped bar charts consisting of 4 bars each, from left to right) slightly reduce the optimal installed capacities of PV and significantly reduce battery storage capacities across scenarios. Importantly, V2G acts as a peak shaving plant, thereby strongly decreasing the battery storage needs. This is discussed further in the subsequent section. More specifically, compared to scenarios without V2G, battery storage decreases by up to 21 % (6.3 GW) and 37 % (3.8 GW) for Home and Distributed charging, respectively (percentages refer to V2G case 2x/week). Conversely, the reduction in optimal PV capacity is less significant, e.g., up to 1.8 % (340 MW) and 4.5 % (730 MW) for Home charging and Distributed charging, respectively. The effect of V2G on installed capacities of PV and battery storage is primarily noticeable in residential nodes, where V2G is added, rather than in other building archetypes (compare legend in Fig. 6).

Secondly, the use of distributed charging (without smart charging, i.e., the first and third groups of bar charts on the x-axis of Fig. 6) leads to a substantial reduction in the total optimal installed capacities of PV and, even more so, for battery storage. In the Home charging scenario, high battery storage needs, especially in MFH, are a consequence of limited PV potential and high EV demand in combination with grid constraints, and subsequently limited imports from the grid. Therefore, shifting EV charging from residential to non-residential nodes significantly reduces battery storage capacity. Compared to the Home charging scenario, the optimal installed battery storage capacity decreases by up to 53 % (3.7 GW) for SFH and 86 % (20 GW) for MFH (see Fig. 6). PV capacities decrease by less, namely by 50 % (2.2 GW) and 28 % (2 GW) for SFH and MFH, respectively. Conversely, the Distributed charging scenario results in additionally installed capacities at OCO and IND nodes, particularly at OCO, where the majority of EV charging occurs (2.9 out of 3.6 TWh of EV demand). For the total of all OCO and IND nodes, PV capacity in the Distributed charging scenario increases by up to 1.9 GW and stationary battery storage by up to 3.8 GW. Capacity additions in IND are very limited (due to space limitations for PV) or even close to zero, with the changes primarily observed in the additional battery storage capacity.

Thirdly, for the smart charging scenario (i.e., second and fourth group of four on the x-axis of Fig. 6), due to temporal flexibility in charging (with a time window of 24h), EV demand is shifted towards sunny hours, which enables higher PV installations and reduced battery storage. Both the Home and Distributed smart charging scenarios show a 6 % increase in PV capacities (compared to their counterparts with uncontrolled charging). In both scenarios, higher PV additions are predominantly observed in SFH compared to MFH due to the greater PV potential. In the case of Home charging, smart charging does not enable any additional PV on MFH due to limited potential. In contrast, the

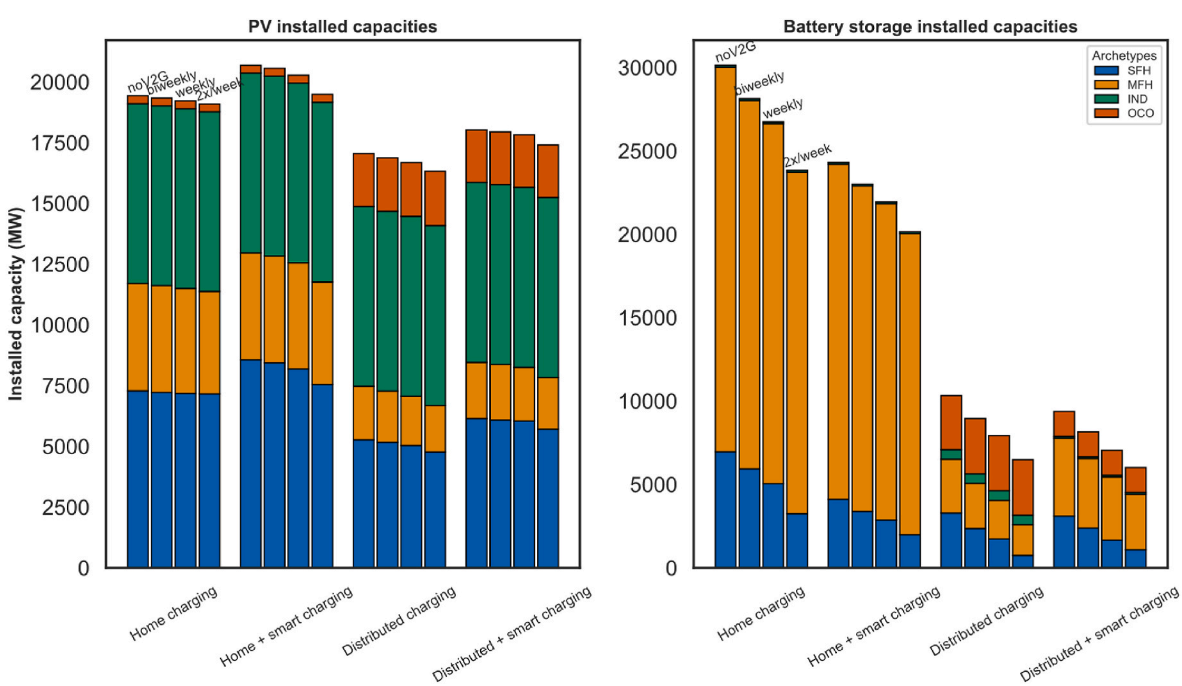

Fig. 6. Optimal installed capacity for PV (left) and battery storage (right) across four scenarios (x-axis). Each bar plot represents a different level of V2G participation, ranging from noV2G (left) to 2x/week participation (right). For Home and Distributed charging scenarios the charging profiles are uncontrolled (no flexibility).

installed battery storage decreases by up to 19 % (6 GW) and 9 % (1 GW) for the Home and Distributed smart charging scenario, respectively (when compared to their counterparts without smart charging). Storage reductions are also noted in IND and OCO nodes for the Distributed smart charging scenario (compared to just Distributed charging). However, in SFH and MFH, the reduction of storage is less pronounced compared to the Home charging scenario (with and without smart charging scenarios) due to the shift in EV demand. When charging at work (e.g., IND and OCO), new electricity peaks emerge in the early morning, typically between 08:00 and 10:00 a.m., due to the simultaneous arrival of vehicles, necessitating significant storage to meet demand (due to limited imports from the grid and low PV production during these hours). Shifting charging towards sunny hours significantly reduces storage requirements, with a 54 % reduction in OCO (from 3.2 GW to 1.5 GW) and a 92 % reduction (from 570 MW to 105 MW) in IND.

3.2. The interplay between stationary battery storage and V2G

To assess the interplay between stationary battery storage and V2G, we next analyze the annual energy output from both battery storage and V2G and their operation. Fig. 7 shows the energy discharged from battery storage (left) and V2G (right) across various scenarios (see the Methodology on the V2G capacity used).

We observe that with increased EV flexibility options, such as V2G (with increased power availability), smart charging, and distributed charging, the amount of energy provided by battery storage strongly decreases (in line with capacity decrease according to Fig. 6). Notably, this reduction is achieved with a relatively small amount of energy supplied by V2G, as observed in Fig. 7 (right). For instance, in the Home charging scenario (Fig. 7, left), the energy provided by the battery storage is approximately 10 TWh annually without V2G, which decreases to 6.5 TWh for the 2x/week scenario V2G participation. In contrast, the energy provided by V2G for the 2x/week scenario is only 0.35 TWh. While hence energy from battery storage decreases by 3.5 TWh, the energy provided by V2G only amounts to 0.35 TWh. This significant reduction in battery storage usage, with the support of V2G, highlights the importance of V2G's power availability. The results indicate that V2G is strategically used as a peak-shaving plant during critical periods, thereby avoiding additional storage needs.

Fig. 8 shows the hourly operation of battery storage and V2G. While battery storage is used throughout the year, V2G is mainly utilized during critical winter days, which are characterised by low PV production. On these days, the energy provided by V2G supports the system by reducing the need for additional storage capacity. The reason for battery storage use throughout the year is that it is practically cost-free to operate once installed. In contrast, V2G is used during critical winter periods and when electricity prices exceed the calculated variable cost of V2G (see Methodology) of 78 €/MWh (i.e., these periods occur when there are energy deficits, with expensive fossil fuel power plants being activated). During summer, battery storage operates more frequently due to higher PV production, and it decreases during seasons with less sunny hours. Both storage types follow a similar daily operation pattern, charging during sunny hours and discharging during evening peak times.

3.3. The effect of EV flexibility options on net system costs

In addition to modifying the annual energy balance for the whole energy system, EV flexibility options contribute to lower system costs. Fig. 9 presents the net system costs and levelized cost of supplied electricity (LCOE) for Switzerland in 2050 across different EV flexibility options (x-axis). The grouped bar plots indicate various levels of V2G participation. The stacked bar plots (primary y-axis) show the net system costs, comprising energy costs (related to electricity production, exports, and imports) and investment costs (including PV and battery storage). The secondary y-axis shows the LCOE.

First, the results indicate that the investment costs in PV and stationary battery storage constitute the primary component of the Swiss net system costs in 2050. On average, these investment costs account for 66 % and 57.3 % of the total costs in Home and Distributed charging scenarios, with the remainder attributed to energy costs. Secondly, implementing EV flexibility options reduces both the total net system

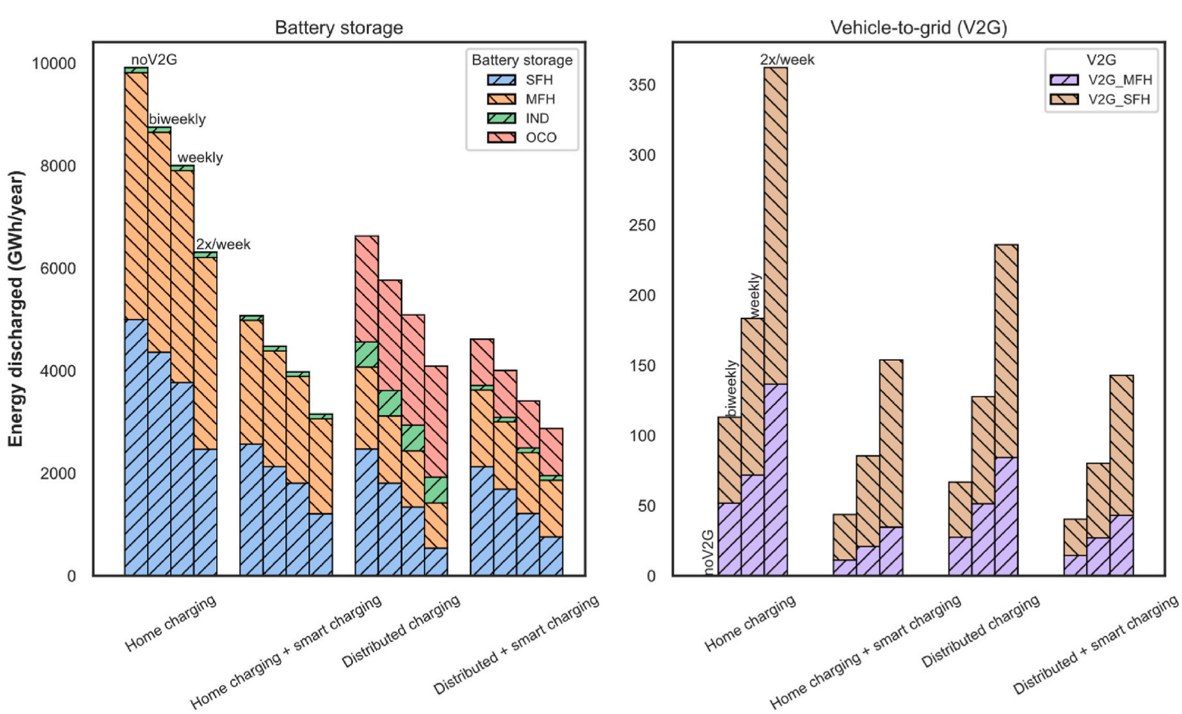

Fig. 7. Energy discharged from battery storage (left) and V2G (right) across four scenarios (x-axis). Each bar plot represents a different level of V2G participation, ranging from noV2G (left) to twice-per-week participation (right). In the right graph, only 3 bars are displayed across four scenarios, since for the scenario noV2G, no energy is provided by V2G.

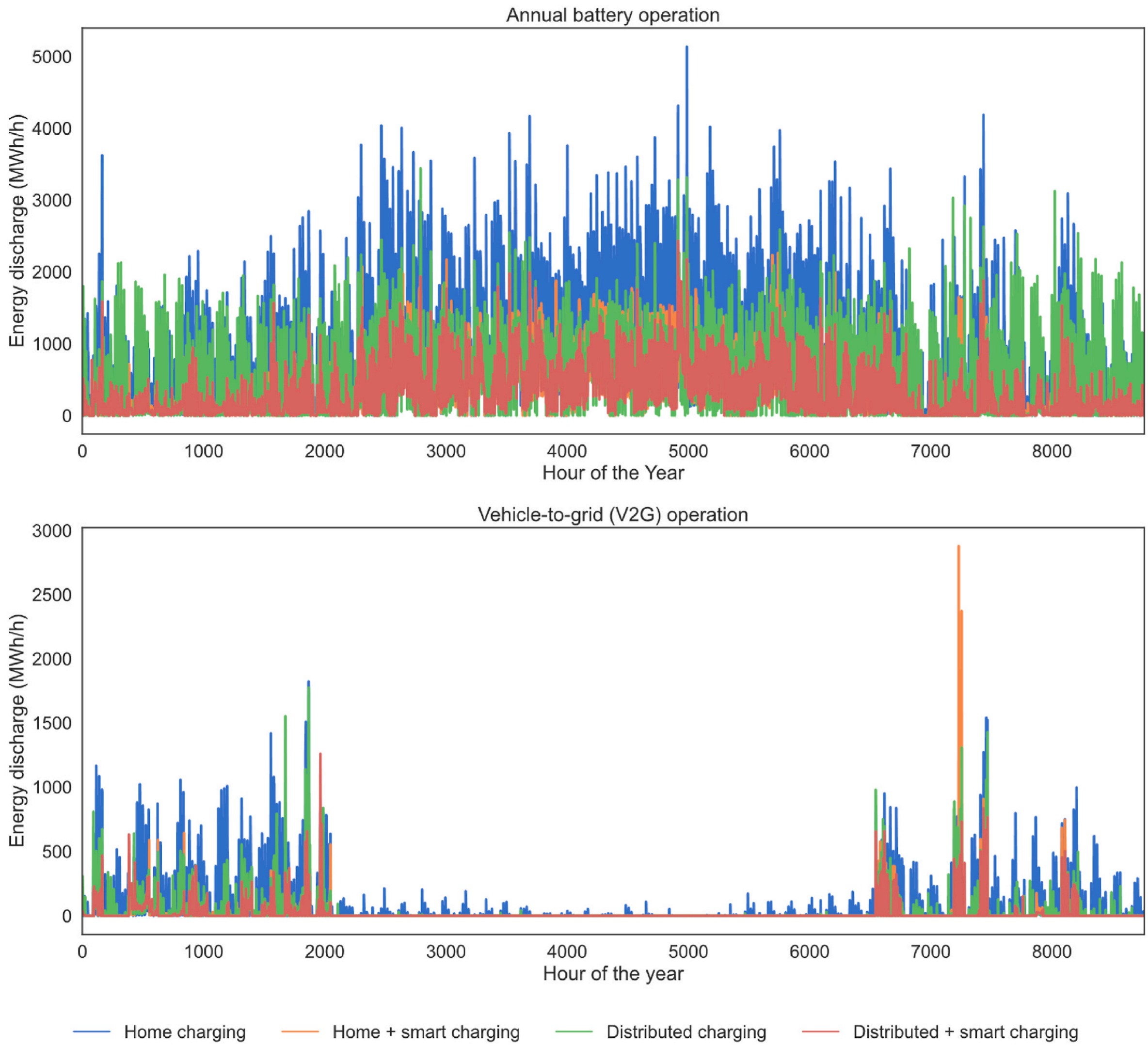

Fig. 8. Hourly operation of battery storage (top) and of V2G (bottom) across four scenarios (see legend). Here the V2G operation is given for the scenario 2x/week.

costs and the LCOE. The cost reduction is mainly to the consequence of avoided installed capacities. For example, comparing the Home and Distributed charging scenarios, system costs decrease by an average of 21 % (equivalent to 2.5 billion €), while LCOE drops from 133 €/MWh to 110 €/MWh (see Fig. 9). Similar cost savings are observed if Home and Distributed charging include similar levels of smart charging and/or V2G. Smart charging enables somewhat higher PV investments but shifting EV charging to sunny hours results in lower storage investment and reduced energy costs, achieved by reducing imports during peak price periods and increased self-consumption. Also, V2G allows to substantially reduce system costs. For example, comparing scenarios with V2G (right stacked bar plot) to those without V2G (left stacked bar plot), system costs are reduced by 1.3 B€ (10.4 %) and 500 M€ (5.2 %) in the Home and Distributed charging scenarios, respectively. Additionally, electricity prices (LCOE) decrease by 12 % (16.5 €/MWh) and 6 % (6.5 €/MWh), respectively.

Regarding energy costs, the differences among scenarios are not substantial. However, it is important to highlight the effects of flexibility options at the national level. Differences in energy costs between scenarios are influenced by increased imports from neighbouring countries due to lower optimal PV and battery storage installed capacities. For example, energy costs (Fig. 9, in blue) are lower in Home charging scenarios compared to Distributed charging. This is influenced by higher installed capacities (PV and battery storage), resulting in greater self-sufficiency and lower imports. However, Home charging also leads to significantly higher investment costs than other scenarios. With increased flexibility options, such as Distributed charging or V2G, energy costs relatively increase due to higher imports from neighbouring countries, resulting in lower domestic optimally installed capacities and energy production. Generally, slightly higher energy costs are also observed in uncontrolled charging scenarios, which require more imports during peak hours at noon, aligning with higher electricity prices. In contrast, smart charging scenarios shift demand to sunny hours, aligning with periods of high PV production and lower prices.

4. Discussion

This section discusses the key findings and implications of EV flexibility options, including smart charging, V2G, and distributed charging. It also provides recommendations for energy stakeholders, such as grid utilities and policymakers, and addresses the limitations of this study.

I. Impact of flexibility options on optimally installed capacities

First, EV flexibility options can strongly influence the optimal installed capacities of PV and battery storage. In scenarios without EV flexibility, such as Home charging, our results show a higher need for installed capacities, particularly for battery storage. High PV and battery

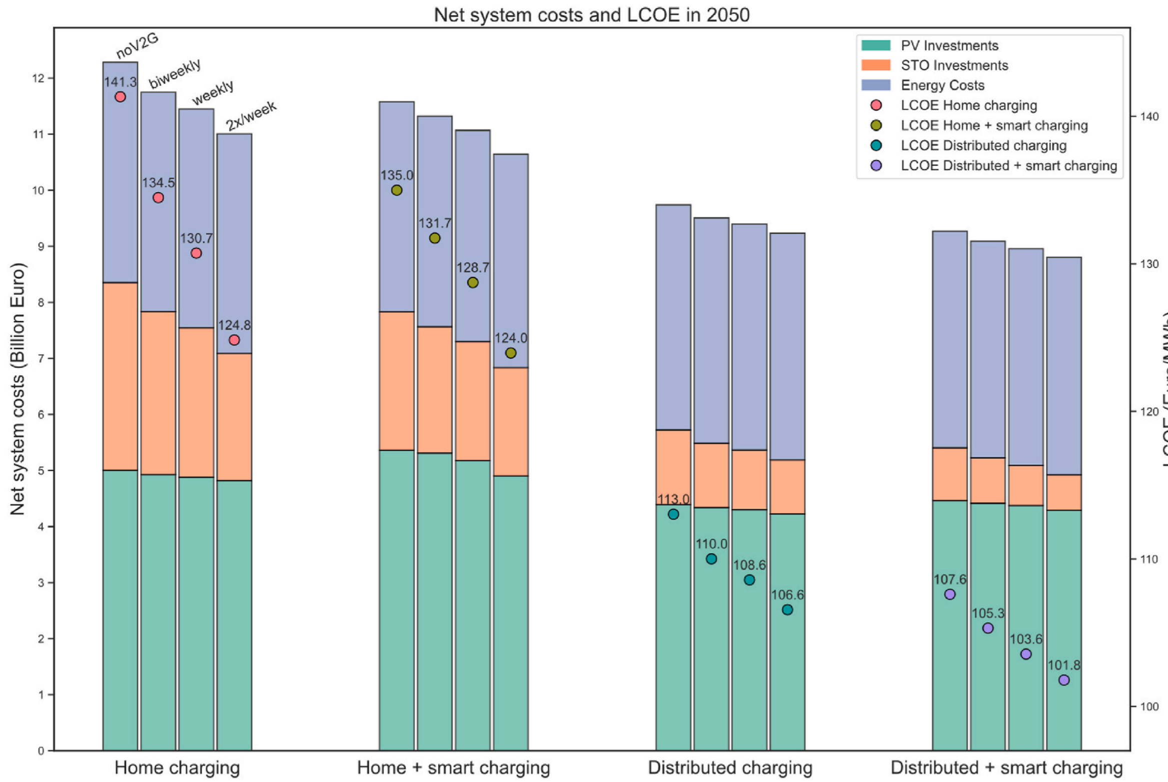

Fig. 9. Total net system costs for various EV flexibility options in 2050. The four grouped bars represent Home charging and Distributed charging, each with and without smart charging, with each bar indicating a different level of V2G participation from no V2G (left) to twice-per-week participation (right). The primary y-axis depicts net system costs, including investment in PV and battery storage (CAPEX and OPEX) and energy costs. The secondary y-axis shows the levelized cost of electricity per MWh consumed. The results are provided for Switzerland.

storage capacities are primarily driven by increased demand in residential nodes due to EV and HP, leading to grid constraints. Previous studies by Jenn et al. [22] and Gupta et al. [7] have highlighted the need for substantial grid reinforcements to accommodate electrification. Jenn et al. found that integrating 5 M EV in California (approximately 83 % of the total passenger car fleet) could significantly impact the distribution grid, with 20 % of feeders requiring capacity upgrades [22]. Our results suggest that EV flexibility options can mitigate such grid impacts. For instance, establishing an extensive distributed charging infrastructure is crucial to prevent feeder congestion resulting from increased EV adoption (particularly in residential areas). In the Distributed charging scenario, our findings show a substantial reduction in capacity needs, particularly in battery storage, which decreases by up to 66 % (20 GW). This reduction is based on the shift of EV demand from residential nodes (SFH and MFH) to workplaces, commercial, and public charging locations, alleviating grid overload in residential areas. However, the installation of charging infrastructure in other places than at home faces challenges. Jochem et al. showed that the associated costs are relatively high [50]. Therefore, incentives should be provided to support the development of an extensive distributed charging infrastructure.

Furthermore, while Distributed charging can be highly beneficial in technical and economic terms, it will most likely need to be combined with smart charging to avoid new demand peaks due to simultaneous arrival times at workplaces (between 08:00 and 10:00 a.m.). Existing electricity tariffs do not provide sufficient incentives for smart charging. The study by Hildermeier et al. reviewed smart charging tariffs across Europe, identified barriers within existing tariffs, and recommended concrete technical and regulatory measures to remove these barriers, alongside considering real-time tariffs [51]. The results here and those by Gschwendtner et al. [52], indicate that incentivising smart charging is crucial for reducing storage needs and potentially avoiding grid reinforcements, particularly in workplaces, commercial or public charging locations.

Moreover, EVs can provide greater flexibility to the energy system (ranging from daily to weekly). With an average daily travel distance of 45 km per vehicle and a battery range of approximately 325 km, smart charging with flexibility windows above 24 h is plausible [53,54]. We also showed in the previous study by Syla et al. that increased time window flexibility (such as 60h and 120h) leads to further PV installations and reduces storage needs [31]. The effects of flexibility on renewable additions vary depending on the energy system configuration. For instance, Gunkel et al. found that in Northern Europe, smart charging leads to lower PV additions but increased wind capacity due to the more favourable techno-economic characteristics of wind energy in that region [23].

II. The interplay between battery storage and V2G

Secondly, this study highlights the interplay between battery storage and V2G regarding power capacity and energy provision to the system. We show that V2G allows to reduce the (stationary) battery storage by up to 21 % and 37 % for Home and Distributed charging, respectively. A study for the energy system of Japan in 2050 leads to similar findings, where V2G reduced storage capacity by 35 % [25]. Also Brown et al. demonstrated for a pan-European sector coupled energy system that increased V2G participation could not only significantly reduce the need for stationary battery storage but also reduce investments in expensive power plants such as offshore wind [24]. In this study, V2G is found to be essential in providing power capacity during critical periods (e.g., winter days characterised by low PV production), acting as a peak shaving resource rather than supplying large amounts of energy (see Fig. 7). Consistently, our results indicate that V2G does not significantly contribute to load shifting (e.g., mitigating the duck curve) but rather serves as a strategic peak shaving resource. Instead, battery storage plays a crucial role in both load and supply shifting (SI, Figure S.6). Similar findings were also reported, highlighting the importance of V2G in peak shaving and reducing the battery storage needs [55].

A critical aspect of modelling V2G is the variable costs, which based on our own calculations was 78 €/MWh (see above in Methodology), whereas, according to Taljegard et al., the variable costs need to be even below 30 €/MWh in order for V2G to become competitive [56]. Bogdanov and Breyer established by means of a sensitivity analysis that V2G continues to be operated even with at operational costs above 50 €/MWh [25]. Overall, the findings from this study and previous research point out the importance of V2G in optimizing storage needs, even at high operational costs (e.g., 78 €/MWh, as shown here). Therefore, energy policymakers and grid operators should consider V2G as an important plant resource in long-term planning. In case of high operational costs, V2G can play the role of peak-shaving unit. For that, in view of the benefits of V2G, it is adequate to incentivize its implementation with remuneration schemes, such as resource adequacy or capacity payments, as discussed by Thompson and Perez [57].

V2G also offers potential benefits over shorter operational periods (e.g., providing ramping services due to its rapid response time), which is important in coping with the increased complexity of energy systems (due to electrification and intermittency of renewable energy sources). The introduction of new market mechanisms, such as flexible ramping products (e.g., those introduced in California, USA, in 2016 [58]), could provide additional incentives for V2G to increase its year-round operation. This is crucial, given the importance for proper remuneration to EV owners for V2G services, as highlighted by Gschwendtner et al. [59] and Kester et al. [60]. Additionally, addressing user-related barriers, e.g., maintaining a minimum state of charge [61] and regulatory barriers, e.g., utility reluctance [59], next to offering tailored programs [62] and privacy guarantees [63] to increase social acceptance, is crucial to encourage V2G participation, including smart charging of any kind.

In addition, our results underscore the importance of stationary battery storage and are consistent with current trends in stationary battery storage, while V2G is not yet widely commercialized. For instance, in Switzerland in 2023, half of the prosumers who installed PV systems also opted for stationary battery storage [64]. Furthermore, several studies have highlighted the importance of stationary battery storage in deferring or avoiding grid reinforcements due to electrification and renewable integration, a consideration that grid operators should include in long-term planning [7].

III. **Effects of flexibility options on net system costs**

Third, EV flexibility options contribute to significant reductions in system costs. These savings mainly come by avoiding additional PV and battery storage capacity. For instance, even a modest operation of V2G (0.32 TWh/year) with high-capacity availability resulted in system cost reductions of 10.4 %, which are equivalent to 1.3 B€, and a decrease in LCOE from 141 to 125 €/MWh (for Home charging scenarios with and without V2G participation, respectively). These values may be considered as optimistic values, as our study does not account for the costs of developing an infrastructure to enable V2G. Further reductions in V2G variable costs and increased capacity availability could potentially yield greater savings. Brown et al. [24] demonstrated a 22 % cost reduction by V2G for the European energy system by reducing the need for additional capacity expansion. Similarly, Ownes et al. [65] showed system cost savings in New England ranging from 2.2 to 20.3 %, depending on V2G participation levels (5–80 %).

Smart charging is key for reducing the energy or operational costs of the system (costs linked with domestic production, imports, and exports) by shifting consumption to periods with lower prices. For instance, in California, smart charging resulted in annual savings of 690 M$, based on the study conducted by Szinai et al. [66]. Our results are consistent with these results, showing that smart charging can reduce operational costs by 155 M€ annually. The savings from smart charging could be even higher in energy systems with higher electricity prices. However, in the context of energy systems with higher renewable availability in neighbouring countries, flexibility options such as distributed charging or V2G resulted in higher operational costs due to increased imports. For instance, updating scenarios from previous projections (e.g., TYNDP2020) to more recent ones (e.g., TYNDP 2024), as done in this study, resulted in lower domestic capacity installations (PV and battery storage) in Switzerland. Compared to the previous study by Syla et al. [31] and this study, approximately 10 GW less PV capacity are installed, reducing domestic production by around 14 TWh/year (see supplementary information).

Lastly, the robustness of the results is assessed by performing a sensitivity analysis on EV adoption rates, considering two additional scenarios (Basis and Sustainable Society (SS) scenario) in line with the Transport Outlook of Switzerland [67]. Our results show that the lower the EV adoption rate, the lower the technology capacity requirements. Specifically, PV and battery storage capacities decrease by 25 % and 62 %, respectively, in the Basis scenario, while 17 % and 42 % less capacity are required for the SS scenario when compared to the Full electrification scenario. Additional details are provided in the SI (S5).

4.1. Limitations and future research

Although this paper is the first to analyze, using energy system modelling at the national scale, all flexibility which could be provided by EV to the energy system, the findings of this study are subject to several limitations that may influence the results and need to be considered when drawing conclusions. First, only passenger cars are included, while other vehicle types, such as light and heavy-duty vehicles, are beyond the scope of this study. A previous study by Rinaldi et al. estimates that other EV types would increase electricity demand by 33 % compared to the demand from passenger cars in this study (10.5 TWh in 2050), yet passenger cars represent the highest share of energy demand [30]. This increase would lead to additional capacity requirements, thereby influencing the results presented here (specifically for other building archetypes such as IND and OCO). Therefore, future studies should integrate modelling of other EV types both in smart charging and V2G. Second, the modelling of charging profiles in this study is based on data from the National Household Travel Survey (NHTS) [68]. Although the NHTS provides a strong base for modelling EV charging profiles [69], in particular at the national scale, we assume that mobility habits remain largely unchanged throughout the energy transition. However, future mobility trends like remote work or carsharing may influence EV charging profiles [70]. For instance, remote work may allow to shift EV charging toward sunny hours, aligning with PV production. Other behavioural or technological choices such as car sharing, autonomous vehicles, and changes in the share of the various transportation modes could also influence the electricity needs, their timing and the flexibility options. Some EV manufacturers provide smart charging services through automated scheduled times for charging, implying an additional form of implicit or indirect control flexibility for the system [8]. These aspects are outside the scope of this paper and can be addressed by future research. Further, the representation of smart charging could be improved by assessing the flexibility potential using data from the NHTS (e.g., with tools like VencoPY [71]) rather than modelling it endogenously.

Third, V2G is modelled as an additional battery storage with a fixed installed capacity throughout the year, depending on the level of participation (biweekly, weekly, 2x/week). This approach is valid from a system and electricity market perspective, as units must be aggregated to participate in electricity markets. Virtual power plants (or aggregators) can facilitate this by aggregating and coordinating vehicles based on EV users' feedback (e.g., accounting for the state of charge or planned future trips) to provide a specified power capacity to the system. However, accounting for a constant power provision and the corresponding participation rate of V2G is challenging. Future studies should, therefore, focus on understanding the EV owners' requirements (state of charge or battery range, financial compensation) to ease the participation of V2G [59]. Moreover, studies focusing on how to account for the coordination of vehicles to utilize them for flexibility purposes in large-scale energy systems remains important, particularly for the energy system modelling community. Furthermore, the study does not include costs associated with developing the infrastructure required to implement flexibility options (e.g., costs related to hardware, software, or charging facilities).

Fourth, the net system costs studied here correspond exclusively to energy or operational and investment costs, and other costs are not included (transmission and distribution infrastructure or balancing costs). Fifth, the energy system model used in this study, GRIMSEL, is subject to certain limitations. For instance, flexibility options (e.g., home versus distributed charging) have been predefined exogenously, while they may be endogenously optimized. Furthermore, future research should focus on the integration of cooling, which is becoming increasingly important, as a consequence of climate change. Another interesting topic would be the inclusion of more battery technologies in the model, such as sodium and solid batteries, with different cost and technologies characteristics along with their potential innovation trajectories, which may emerge as an attractive solution for future installations, such as sodium based. Additional limitations are discussed in previous studies [31,72].

Finally, the results of this study are subject to various future uncertainties, which is a limitation intrinsic to all energy system models. Events such as new market mechanisms or shock events such as further energy crises could result in various political outcomes, significantly changing the context. For Switzerland, ongoing discussions with the EU may affect the electricity sector. For example, reductions in interconnection capacities with neighbouring countries could affect the results of this study by necessitating additional PV and battery storage capacities within Switzerland to ensure energy security. In response, new options would need to be considered, such as further expanding renewables (e.g., increasing wind capacity targets) or developing seasonal storage options (hydrogen and thermal). For example, hydrogen could play a key role as seasonal storage, especially as Switzerland imports electricity during the winter and exports during the summer. However, further advancements in hydrogen conversion efficiency and cost reduction are needed [30]. While the flexibility options analyzed in this study remain crucial for the short-term (day-ahead or intra-day), they do not address seasonal flexibility needs. Nonetheless, the fundamental insights and importance of flexibility options in optimizing energy systems and reducing costs remain relevant in Switzerland or other countries, regardless of future developments.

5. Conclusion

This paper assesses the role EVs can provide to a national energy system throughout the energy transition, such as smart charging, V2G, and distributed charging. The open-source energy optimization model GRIMSEL is extended to incorporate and analyze the effect of these flexibility options.

Our findings show that EV flexibility options can provide substantial benefits to counterbalance the impact of EVs on the reliability of the power system. An extensive charging infrastructure (distributed charging) notably reduces the need for capacity expansion in photovoltaics (PV) and stationary battery storage. Specifically, battery storage capacities are reduced by 66 % (20.2 GW), and installed PV capacity by 12 % (2.4 GW). This is enabled by better alignment of charging profiles with PV production in scenarios with extensive charging infrastructure (workplaces, commercial, and public charging). Smart charging enables the increase of installed PV capacity installations, and it reduces storage needs by shifting the EV charging toward sunny hours.

The study also shows the interplay between stationary battery storage and V2G, which is important to assess due to their different techno-economic characteristics. Stationary battery storage is primarily characterised by fixed capital expenditures, while V2G is characterised by operational expenditures. Our findings show that V2G allows to drastically reduce stationary battery storage capacity and acts strategically as a peak-shaving plant during critical periods. This can result in battery capacity reduction by up to 37 % (3.8 GW).

Various EV flexibility options significantly lower total energy system costs, mainly by reducing the need for additional installed capacities, with distributed charging achieving the highest savings (21 %, while the national LCOE decreases from 141 to 113 €/MWh). The availability of V2G capacity remains crucial, resulting in further cost reductions (5–10 %) with a moderate energy discharge (0.15–0.3 TWh per year).

Overall, a combination of flexibility options provides large benefits while mitigating impacts on the energy system. Our study shows that these flexibility options optimize PV and reduce battery capacity needs, improve system efficiency, and reduce overall system costs. These insights can guide policymakers and grid operators to understand the potential of EV flexibility and tailor specific flexibility strategies to achieve specific targets, e.g., design of new market products, such as capacity payments, flexible ramping products, and smart tariffs.

CRediT authorship contribution statement

Arven Syla: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **David Parra:** Writing – review & editing, Supervision, Conceptualization. **Martin K. Patel:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2025.136236.

Data availability

The input data and energy system model used in this manuscript are available in the following repository: https://github.com/sylaarven/GRIMSEL-EV.

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