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Final Report

Vehicle-to-grid in Switzerland

A first estimate of the value of vehicle-to-grid for the Swiss electricity system

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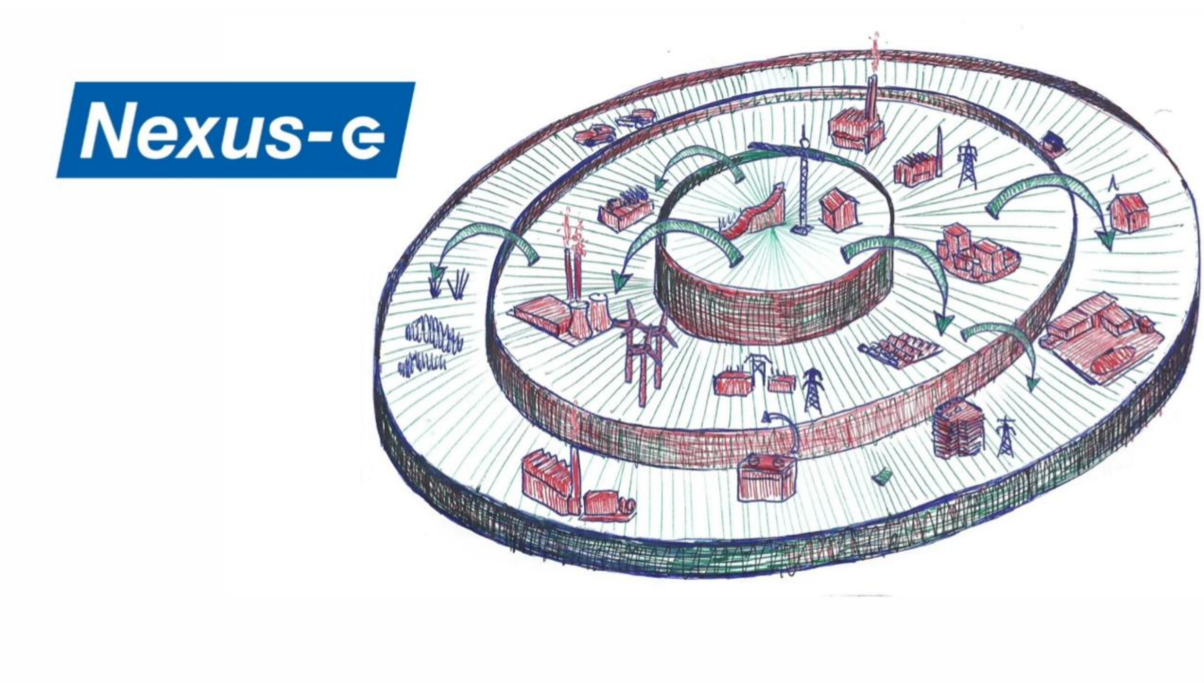

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Zusammenfassung

Die Elektrifizierung des Verkehrssektors wird einen erheblichen Einfluss auf das Schweizer Stromsystem haben. Einerseits wird die Elektrifizierung des Verkehrssektors die Stromnachfrage wesentlich erhöhen. Andererseits verfügen Elektrofahrzeuge über eine enorme Menge an Batterien, die an das Stromnetz angeschlossen werden können. Vehicle-to-Grid (V2G) – die bidirektionale Interaktion zwischen Elektrofahrzeugen und dem Stromnetz – ist eine Möglichkeit, die Batteriekapazität zu nutzen, um dem Stromsystem Flexibilität zu verleihen.

In dieser Studie machen wir eine erste Abschätzung der potentiellen Auswirkungen von V2G auf das Schweizer Stromsystem mit Hilfe von Nexus-e, einer Plattform zur Modellierung von Energiesystemen. Dabei nehmen wir an, dass V2G zum Ausgleich von Angebot und Nachfrage im Stromsystem eingesetzt wird. Andere Anwendungsfälle wie ein optimales Laden zur Minimierung des Verteilnetzausbaus oder die Bereitstellung von Systemdienstleistungen vernachlässigen wir. Wir untersuchen zwei Referenzszenarien: eines mit und eines ohne V2G, sowie vier Sensitivitätsanalysen zum eingeschränkten Stromhandel (NTC30), zu Entwicklungen in den Nachbarländern (TDE), zu höheren Gaspreisen (Gas) und zu einer erhöhten Verfügbarkeit von bidirektionalen Fahrzeugen (XL).

Unsere Ergebnisse deuten darauf hin, dass die vermehrte Nutzung von E-Fahrzeugen in V2G zu geringeren Stromsystemkosten führen kann. In unseren Szenarien und Sensitivitätsanalysen sinken dank einer intelligenten Integration der Autobatterien in das Energiesystem die Stromsystemkosten um 1,7 bis 6,6 Mrd. CHF (siehe Abbildung 1b). Dies entspricht einer Reduktion von 2 bis 14 Prozent. Hierbei muss jedoch beachtet werden, dass die Kosten für den benötigten Ausbau des Übertragungs- und Verteilnetzes noch nicht berücksichtigt sind.

Für den Wert von V2G für das Stromsystem gibt es drei Haupteinflussfaktoren:

1. V2G ermöglicht eine bessere Verwertung des erneuerbar produzierten Stroms, indem die Batterien der E-Fahrzeuge während der Spitzenzeiten der Stromerzeugung aufgeladen und zu Zeiten mit geringerer Erzeugung Erneuerbarer Energien oder hoher Nachfrage entladen werden. Letztendlich führt eine solche verbesserte Nutzung zu weniger Abregelungen von Erneuerbarer Energien. Abbildung 1c zeigt die jährlichen Abregelungen von 2020 bis 2050. Es wird deutlich, dass je mehr E-Fahrzeuge an V2G teilnehmen können, desto geringer werden die Abregelungen. Zwischen 2020 und 2050 können dadurch insgesamt 55,3 TWh mit einem Wert von 1,1 Mrd. CHF zusätzlich in das Netz eingespeist werden.

2. V2G ermöglicht das Ausnutzen von Marktpreisunterschieden zwischen Stunden und Tagen. So kann das System mit Hilfe von V2G zum Beispiel Exporte von Stunden mit niedrigen Strommarktpreisen auf Stunden mit hohen Preisen verlagern. Das Gleiche gilt für Importe, die in Zeiten hoher Marktpreise vermieden werden können. Entsprechend wird der Stromhandel lukrativer. Die Einschränkung des Handels schmälert diesen Vorteil von V2G und ist der Hauptgrund für den niedrigsten Wert von V2G im NTC30-Szenario. Relevant für die Nutzung der zeitlichen Unterschiede in den Marktpreisen ist die Höhe und Volatilität dieser Preise. Abbildung 1d zeigt die Jahresdurchschnittswerte für die Marktpreise. Wir sehen, dass das Szenario mit hohen Gaspreisen die höchsten Strompreise aufweist (und auch mit einer hohen Preisvolatilität gekennzeichnet ist), was den Wert von V2G massiv steigert.

3. V2G kann weiter auch dazu beitragen, den Einsatz teurer, auf fossilen Brennstoffen basierender Notstromaggregate zu vermeiden, beispielsweise in Situationen, in denen die auf erneuerbaren Energien basierende Stromerzeugung im Inland und Importe nicht ausreichen würde, um die Nachfrage zu decken. In der Sensitivitätsanalyse des NTC30-Szenarios trägt die Einbindung von V2G in das System dazu bei, den Einsatz von Kraftwerken basierend auf fossilen Brennstoffen

vollständig zu vermeiden.

Die Ergebnisse dieser Studie sollten als Szenarien verstanden werden und nicht als Prognosen. Die Modellierung von V2G und des Schweizer Stromsystems unterliegt vielen Annahmen und Vereinfachungen, welche massgeblich den Wert von V2G für das Schweizer Stromsystem beeinflussen können. Vor allem wie sich das Einsteckverhalten der Nutzer von E-Fahrzeugen entwickelt ist in der Wissenschaft und Praxis umstritten.

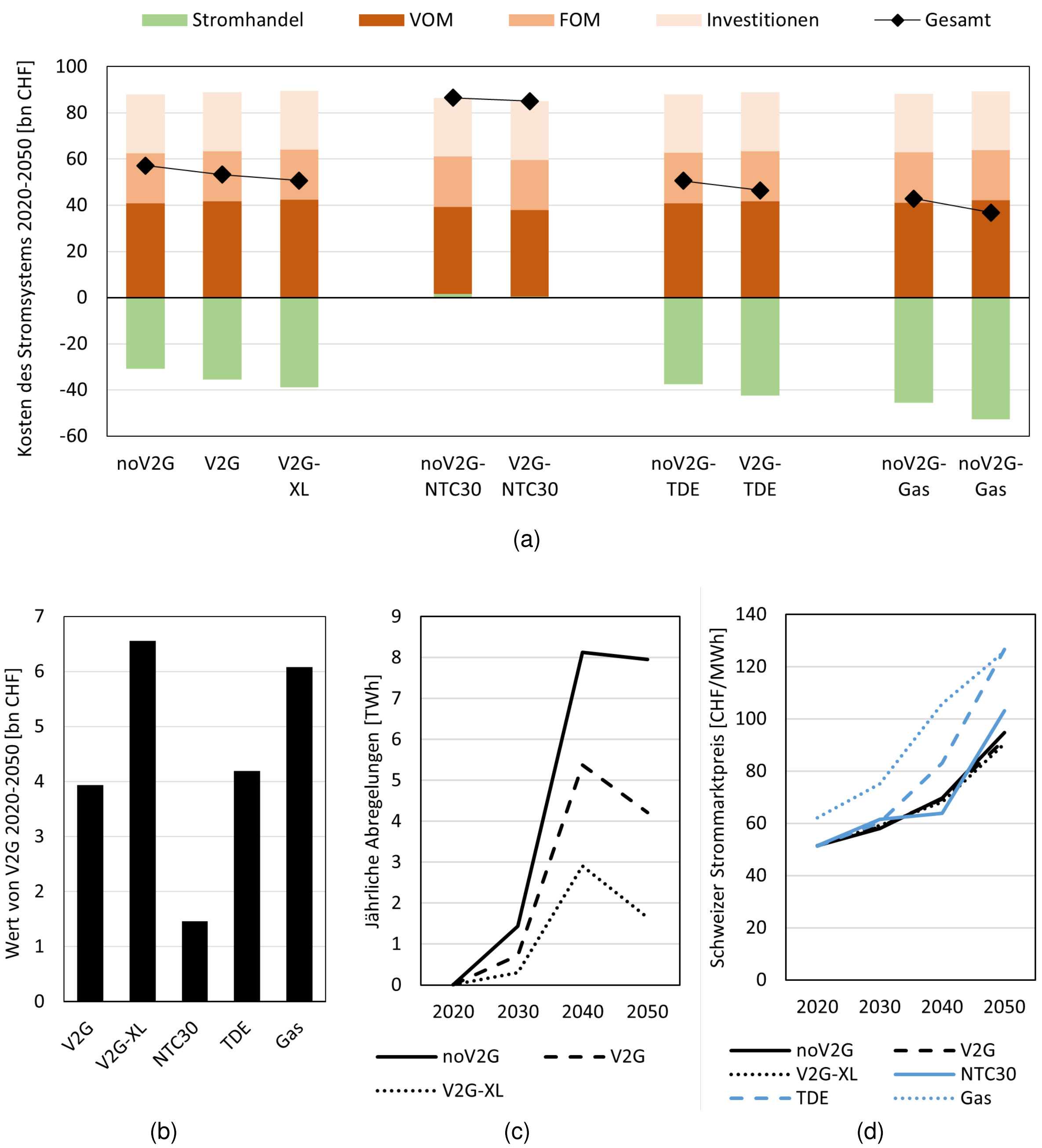

Figure 1: (2a) Kosten des Stromsystems von 2020 bis 2050 für die Referenzszenarien und die vier Sensitivitätsanalysen. VOM steht hier für die variable Betriebs- und Unterhaltskosten, FOM für die fixen Betriebs- und Unterhaltskosten. (2b) Wert von V2G für das Schweizer Stromsystem, (2c) Jährliche Abgregelungen, (2d) Entwicklung Schweizer Strommarktpreise. Da V2G kaum Einfluss auf die Strommarktpreise hat, werden für die Sensitivitätsanalysen nur die Werte für die Szenarien mit V2G angezeigt.

Summary

The electrification of the transport sector will have a substantial impact on the Swiss electricity system. It is expected that the demand for electricity to charge electric vehicles (EVs) will be responsible for the largest increase in Swiss electricity demand. But at the same time EVs provide an enormous amount of batteries connected to the grid. V2G – the bidirectional interaction between electric vehicles and the grid – is one way of leveraging the battery capacity to provide flexibility for the electricity system.

In this study, we make a first estimate of the potential impact of V2G on the Swiss electricity system. To do so, we use Nexus-e, an energy system modeling platform. We hereby assume that V2G is used for balancing supply and demand on a system level. Other use cases such as minimizing the distribution grid extensions or providing ancillary services are neglected. We investigate two reference scenarios, one with and one without V2G, and four sensitivity analyses on restricted electricity trading (NTC30), developments in neighboring countries (TDE), higher gas prices (Gas), and higher levels of V2G available (XL).

Our results indicate that participation of EVs in V2G can lead to lower electricity system costs. In our scenarios and sensitivity analyses, thanks to the smart integration of car batteries into the power system, electricity system costs decrease by 1.7 to 6.6 billion CHF (see Figure 2b). This corresponds to a reduction of 2 to 14 percent. The electricity system costs do not include the costs for required expansions of the transmission and distribution grid.

There are three main drivers for the value of V2G for the electricity system:

1. V2G enhances the exploitation of the installed renewable energy source (RES), by charging the EV batteries during peak electricity generation time (e.g., during noon on a summer day) and discharging them at times with lower RES production (e.g., at night) or high demand. Ultimately, such enhanced exploitation reduces curtailment. Figure 2c depicts the annual curtailments of renewables from 2020 to 2050. It is clear that the more EVs can participate in V2G, the lower the curtailments become. Between 2020 and 2050, a total of 55.3 TWh can be injected additionally into the grid when adding V2G. The value of this additional generation amounts to 1.1 billion CHF (if sold on the electricity market instead).

2. The added flexibility by V2G also allows utilizing market price differences between hours and days. So, for example, with the help of V2G, the system can shift exports from hours of low electricity market prices to hours with higher prices. The same holds true for imports which can be avoided during times of high market prices. In turn, electricity trading becomes more lucrative. Restricting trading mitigates this benefit of V2G and is the main reason for the lowest value of V2G in the NTC30 scenario. Relevant for utilizing temporal differences in market prices is the level and volatility of these prices. Figure 2d shows the annual averages for the Swiss market prices. We see that the scenario with high gas prices also has the highest electricity prices (and is characterized by high price volatility), which increases the value of V2G substantially.

3. V2G can also help to avoid using expensive backup generators based on fossil fuels, for example, in situations in which inland generation based on renewables and imports would be insufficient to supply demand. In the NTC30 sensitivity assessment, adding V2G to the system helps to avoid the dispatch of gas units.

The results of this study should be understood as scenarios and not as forecasts. The modeling of V2G and the Swiss electricity system is subject to many assumptions and simplifications, which can substantially influence the value of V2G for the Swiss electricity system. Especially the plug-in behavior of e-vehicle users and how this will change over time is controversial in academia and practice.

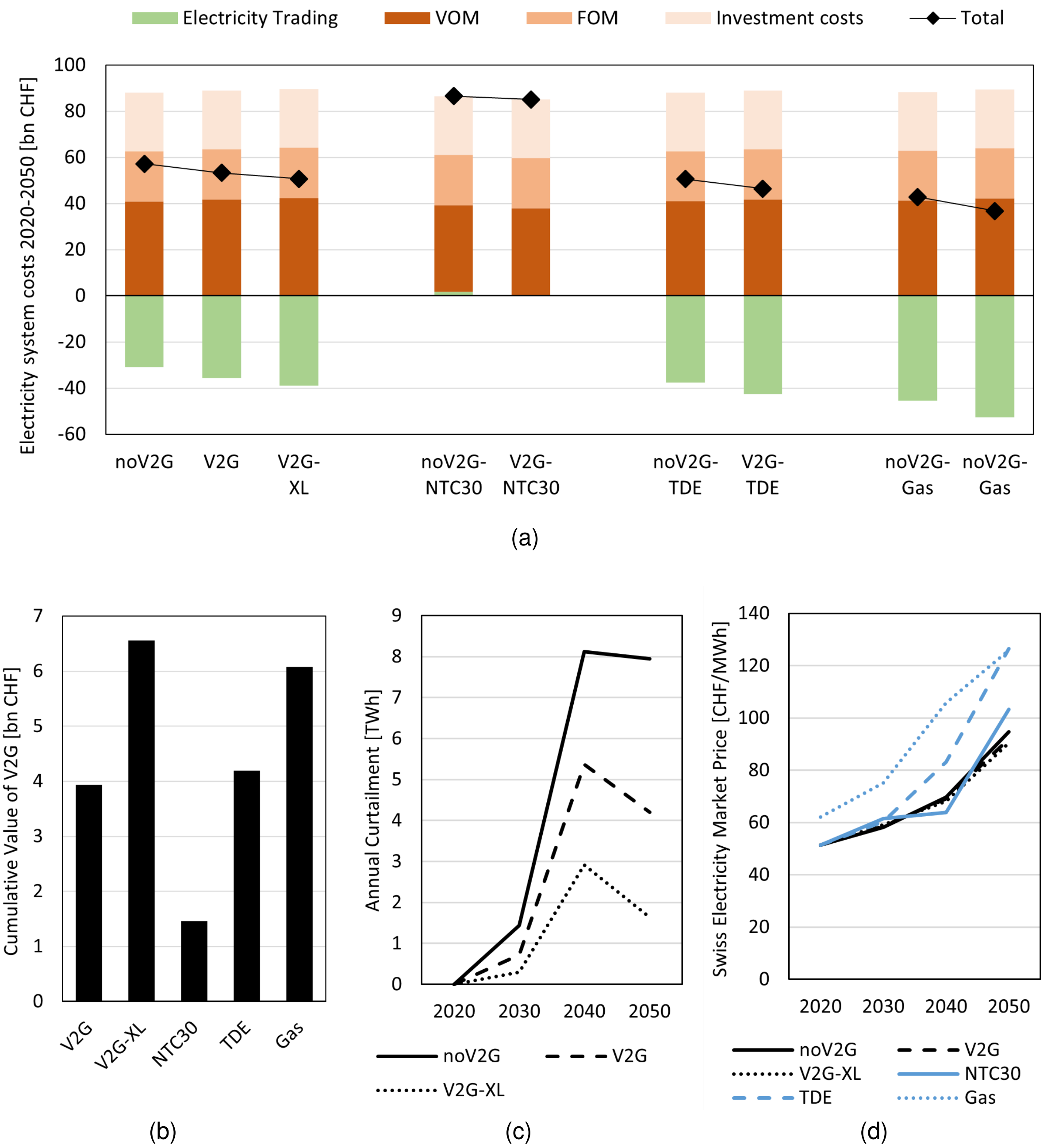

Figure 2: (2a) Electricity system cost from 2020 to 2050 for the reference scenarios and the four sensitivity analyses, VOM: variable operating and maintenance costs, FOM: fixed operation and maintenance costs, (2b) total value of V2G for the Swiss electricity system, (2c) annual curtailment, (2d) development of Swiss electricity market prices. Since V2G has hardly any influence on electricity market prices, only the values for the scenarios with V2G are shown for the sensitivity analyses.

Contents

Abbreviations

CentIv	Centralized Investments Module
EV	electric vehicle
FOM	fixed operation and maintenance
NTC	net transfer capacity
PV	photovoltaic
RES	renewable energy source
RoR	run of river
V2G	Vehicle-to-Grid
VOM	variable operation and maintenance

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1 Introduction

The transition from combustion engines to electric motors and batteries is having a substantial impact on the Swiss electricity system. It is expected that the charging of electric vehicles will be responsible for the largest increase in Swiss electricity demand. These additional loads require new investments in inland electricity generation and electricity grids. However, electric vehicles are not only a burden to the electricity system. In fact, vehicle batteries can make an enormous contribution to ensuring the security of electricity supply in Switzerland and help to integrate renewable energies into the electricity system.

V2G is the interaction between the electricity grid and the electric vehicle, in which the vehicle does not only draw power from the grid but can also feed it back into the grid. Such a “bidirectional” (dis)charging allows electric vehicles, for example, to react to price signals and to sell electricity on the market in times of high market prices. With the increasing proportion of electric vehicles, the importance and potential of V2G will continue to increase.

In this study, we assess the impact of V2G on the Swiss electricity system. In particular, we investigate the following questions:

- How does the use of power generation units (dispatch) change with the availability of V2G – especially that of other flexible units such as pumped storage power plants and power-to-gas plants?
- How does V2G influence electricity trading with neighboring countries?
- How does V2G affect the curtailment (and thus the profitability) of renewables?
- What impact does V2G have on the total cost of the electricity system?

To answer these questions, we use Nexus-e, an energy system modeling platform developed by ETH Zurich. Please note that in this study we do not consider the effects of Vehicle-to-Grid (V2G) on the distribution grid. We also assume that V2G is fully utilized to balance demand and supply on a system level. Other use cases such as minimizing the required distribution grid extensions or providing ancillary services are not taken into account.

2 Method and Data

2.1 Nexus-e

Nexus-e is an energy system modeling platform consisting of multiple modules. For this study, we use the Centralized Investments Module (CentIv). CentIv is a linear optimization problem aimed at identifying the optimal investments into electricity generation capacities and the operations thereof to meet electricity demand, taking a system perspective. As for this study, we use predefined capacities in the reference scenario, CentIv is optimizing only the operations of these units. Detailed information about Nexus-e and CentIv can be found in [1] and [2], respectively.

We simulate the years 2020, 2030, 2040, and 2050. Optimal dispatch is computed for every hour of every second day of these years to reduce runtime and computational complexity. All generation technologies are modeled considering their operation limits and characteristics. We use normalized profiles for renewable energies with hourly and cantonal resolution based on historical power generation. The use of dispatchable power generation units such as gas-to-power plants is optimized in the model, taking into account technical constraints. The Swiss extra-high-voltage grid, corresponding to grid level 1 and 2, is modeled and its grid constraints are taken into account. Neighboring countries are aggregated into a few synthetic nodes, that allow for the representation of all Swiss cross-border lines and synthetic cross-border lines in-between neighboring countries.

2.2 Modeling V2G

We represent V2G as many small-scale batteries that are distributed all over Switzerland proportionally to the electricity demand by electric vehicles and are connected to the transmission grid nodes (as we do not model the distribution grids). We calculate the available storage capacity and available power for V2G of these batteries with the following parameters:

- **Number of EVs**: We base the number of EVs on scenarios from Swiss eMobility until 2035 and on the "Verkehrsperspektiven" published by the Swiss Federal Office of Energy until 2050.
- **Storage capacity**: According to expert interviews, the energy density of car batteries will increase. We assume a stagnation due to a decreasing marginal benefit of larger batteries. Break-throughs in the field of solid-state batteries were not assumed.
- **Share of plugged-in vehicles**: Share of vehicles that are located at a charging station and are plugged in. There is literature on assessing charging behavior on plug-in time and consequentially on the timing of electricity demand (see for example [3, 4, 5]). But exact values for plug-in probabilities are unclear yet.
- **Share of bidirectional charging stations**: The probability that the charging station is bidirectional and allows the car to participate in the market. Values according to expert interviews.
- **Share of accessible capacity for V2G**: Share of EV battery that can be used for V2G.
- **Available power per vehicle/station**: According to expert interviews this is the current standard for power output. It was assumed that bidirectional charging stations will also be able to achieve that value. First products on the market support this assumption.
- **Charging power limitation**: With the increasing amount of EVs, their charging power will need to

be managed to avoid local grid congestion. This factor accounts for overarching load management.

Table 1 lists the values for these parameters that we assume for the reference scenario and the resulting storage capacity and power available for V2G. Appendix A provides the annual values for the number of V2G vehicles, the available capacity and the available power for V2G.

It is important to note that we do not assume investment and operating costs for V2G in this study. Vehicles participating in V2G are considered privately owned, so we assume that from a system perspective, there are no investment costs for electric vehicle (EV). Additionally, due to the lack of literature and business cases on remuneration for the V2G service offered by EV, we assume 0 variable operation and maintenance (VOM) and fixed operation and maintenance (FOM) costs for V2G. By comparing the total system costs of the scenarios with and without V2G, we can identify a monetary value that the compensation and the costs for the technical implementation of V2G (e.g., charging station, IT, management) would not be allowed to exceed. If compensation and technical implementation costs are higher than such value, then V2G is financially unattractive from a system's perspective.

Table 1: Overview of assumptions to calculate available storage capacity and power for V2G

	2020	2030	2040	2050
Number of EVs [# MM]	0.08	1.7	3.5	4.5
Storage capacity [kWh/vehicle]	60	100	100	100
Share of plugged-in vehicles	40%	40%	40%	40%
Share of bidirectional charging stations	0%	60%	73%	80%
Share of accessible capacity for V2G	25%	25%	25%	25%
Available storage capacity for V2G [GWh].	**0.0**	**10.5**	**25.3**	**36.4**
Available power per vehicle/station [kW]	11	11	11	11
Charging power limitation	90%	71%	61%	50%
Available power for V2G [GW].	**0.0**	**3.5**	**6.8**	**8.0**

2.3 Input Data

For the reference scenarios, electricity demand and installed generation capacities are predefined for this project (see section 2.4) and not a result of optimization. All other input data and assumptions required to run Nexus-e can be found in [6]

To make use of the predefined scenario data in Nexus-e, we have to process it as followed: First, since the predefined values do not provide information on where in Switzerland the addition of new power generation units will take place, we need to define this in Nexus-e. This is important as Nexus-e represents the transmission grid in detail. Loads and generation units have thus to be assigned to a respective grid node so emerging load flows can be calculated. We allocate distributed technologies (e.g., photovoltaic (PV), wind, stationary batteries, and EV batteries) to the grid nodes proportionally to the node's annual demand. For the other power generation units, we manually allocate the capacities. In general, the allocation is done in a way that does not overburden the power grid.

Second, the scenarios include geothermal generation as part of the future electricity mix. Nexus-e, however, has no detailed representation of geothermal technologies yet. We, therefore, model the technology as a renewable energy source (RES) with constant power output. Values for investment and VOM costs are taken from [7]. We set FOM costs to 0 EUR/MW due to a lack of information available. The installed geothermal power plant is geographically allocated to the Mühleberg node to which the dismantled nuclear site was connected until 2019. The node thus has some free transmission capacity.

Third, the increase of biomass generation is implemented by increasing the installed capacity of existent biomass power plants proportionally to their current installed capacity. The construction of biomass power plants in new locations is therefore not considered. Additionally, the distinction between biomass power plants with and without CCS/CCU technology is not taken into account, due to a lack of information on investment and operational costs.

Fourth, to account for the variations in the installed capacity for fossil-fueled power plants, we adjust the installed capacities of all currently available fossil-fueled power plants. The CCS technology and its costs are considered. The only gas-to-power technology we consider is hydrogen. In previous studies, possible locations for new gas power plants were identified.[1] These grid nodes are used for the H2-fired power plants.

Fifth, for all types of hydropower plants (i.e. run of river, storage hydro and pumped storage hydro), detailed information from previous studies with Nexus-e is used. The original information on installed capacity is kept unchanged for all scenarios. Investment cost values for new hydropower plants are taken from [7]. However, there is a large variability in values. This is due to the dependence on the power plant type and its size, location, and reservoirs. For these simulations, an average value of 7500 EUR/kW is considered for run-of-river and storage hydropower plants. For pumped storage plants, however, a value of 2300 EUR/kW is considered, which is equal to the investment costs of the most recent Swiss hydropower plant of Nant De Drance [8].

Sixth, whereas the annual, Swiss-wide demand is predefined, we have to make assumptions on its spatial and temporal distribution. The scenarios split the annual demand data into the four categories e-mobility, heat pumps, hydrogen production, and conventional demand. For each category, we use typical hourly load curves and then scale them according to the annual demand. Summing the load curves for all demand categories gives us the hourly Swiss-wide demand curve. We then allocate this curve to the grid nodes proportionally to the population in the region of the grid node.

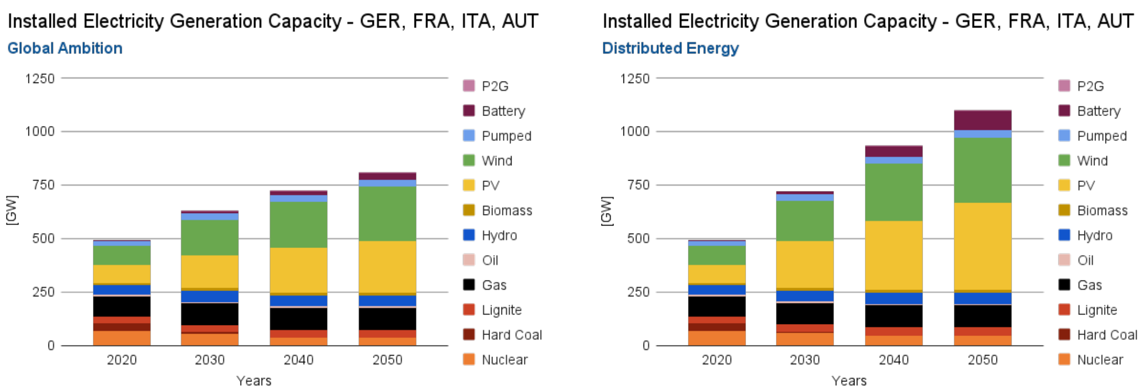
[1] see "Konzept Spitzenlast-Gaskraftwerke zur Sicherstellung der Netzsicherheit in ausserordentlichen Notsituationen - Bericht zuhanden Bundesrat"

2.4 Reference Scenarios and Sensitivities

The two reference scenarios, one with and one without V2G, build upon the same assumptions for electricity demand and supply in Switzerland. The development of the installed capacities in Switzerland is visualized in Appendix A. The reference scenarios build upon the target values for renewables set forth recently by the parliament in the "Energie-Manelerlass".[2] The target for renewables except hydropower is set to 45 TWh of electricity generation per year.

In addition to the reference scenarios, we conduct four sensitivity assessments. First, we test the impact of the developments in the neighboring countries on the feasibility of the two scenarios ("TDE" sensitivity scenario). While in the reference scenarios, we base the installed generation capacity and the demand in the neighboring countries on the ENTSO-E "Global Ambition" scenario, here we test the impact of using the ENTSO-E "Distributed Energy" scenario [9] instead (see Figure 3). The "Global Ambition" scenario is based on an energy transition where the power supply is mainly based on centralized production facilities such as offshore wind. The "Distributed Energy" scenario, on the other hand, is based on a decentralized energy transition in which consumers play a more important role. The scenario is thus characterized by higher electrification of transport and heating as well as a stronger focus on renewables, especially PV.

That is, they actively participate in the energy market as "prosumers" by investing in solutions such as PV with local battery storage and exploiting price peaks for expensive imports.



(a) (b)

Figure 3: Installed generation capacities in ENTSO-E scenarios (3a) "Global Ambition" and (3b) "Distributed energy"

Second, we want to test the impact of electricity trading limitations on the feasibility of the three scenarios ("NTC30" sensitivity scenario). The EU Clean Energy Package, which came into force in 2020, sets the rules for electricity trading and technical grid operation. It requires that by the end of 2025, all European transmission system operators make at least 70 percent of relevant electricity network capacity available for cross-border trading. However, it has not yet been regulated how third countries such as Switzerland are to be included in the 70 percent criterion. In an extreme case, this could limit cross-border capacities towards Switzerland and thus also electricity trading. Here we reduce the net transfer capacity (NTC) to 30 percent of the values in the reference scenarios to illustrate such an extreme case.

Third, we want to observe the impact of higher gas prices ("Gas" sensitivity scenario). We use the values from the IEA 2021 report [10] for the European gas prices. Table 2 lists the values for the

[2]parlament.ch

development of assumed gas prices in the reference scenarios (Reference) and the sensitivity on higher gas prices (High).

Table 2: Development of gas prices [CHF/MWhth]

	2020	2030	2040	2050
Reference	33.4	33.4	32.7	33.7
High	38.0	38.0	54.7	55.6

Fourth, we test the impact of even higher EV capacity and power available for V2G ("XL" sensitivity scenario). We do so by adjusting the parameters required for the calculation of the capacity and power provided by EVs participating in V2G.

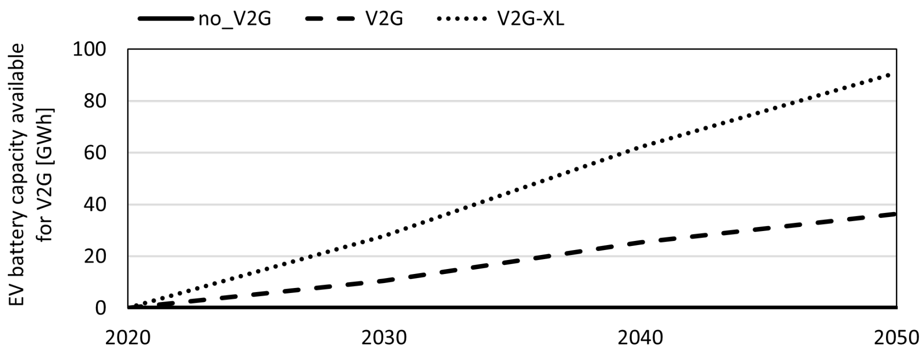


Figure 4: Development of EV capacity available for V2G

3 Results

3.1 Overview

The results of the simulated scenarios are analyzed with respect to their hourly dispatch of power generation units, curtailment of RES, and total costs of electricity supply. Results are visible on the Nexus-e webviewer at the following web address: `https://nexus-e.org/results_v2/v2g`.[3] The different scenarios can be selected from a drop-down menu and compared to each other:

Reference scenarios

- No V2G: *eg_nov2g*
- V2G: *eg_v2g*

Sensitivity on restricting electricity trading:

- No V2G with reduced NTC: *eg_nov2g_30ntc*
- V2G with reduced NTC: *eg_v2g_30ntc*

Sensitivity on developments in the neighboring countries:

- No V2G with Distribute Energy: *eg_nov2g_de*
- V2G with the Distribute Energy: *eg_v2g_de*

Sensitivity on high gas prices:

- No V2G with high gas prices:*eg_nov2g_gas*
- V2G with high gas prices: *eg_v2g_gas*

Sensitivity on V2G penetration:

- V2G with higher penetration: *eg_v2g_xl*

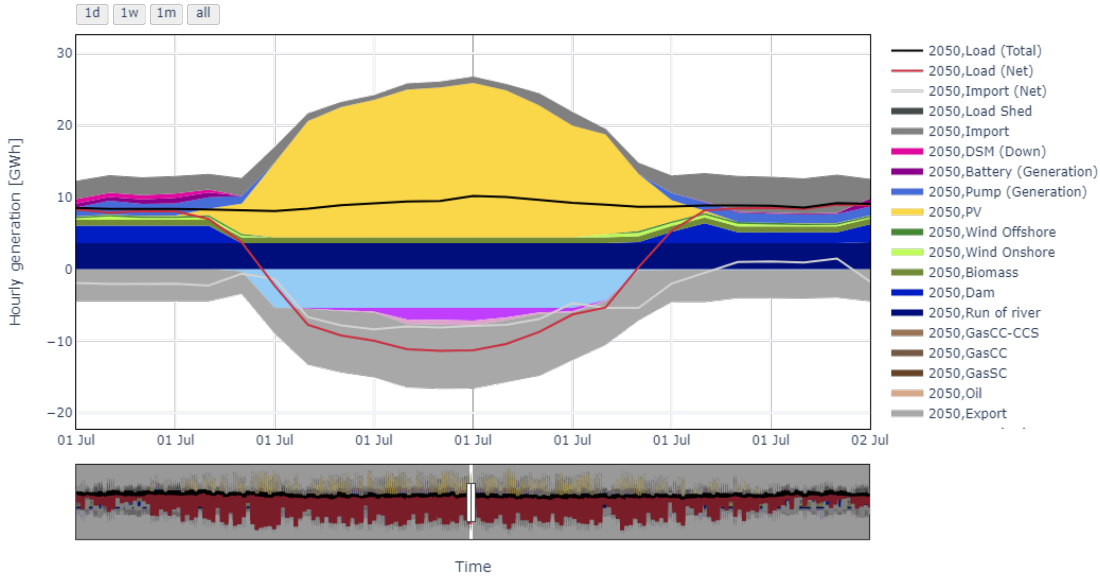
In the following, we present the results for the reference scenarios with and without V2G (section 3.2). We then highlight the most important insights from the sensitivities on the developments in neighboring countries (section 3.4), electricity trading (section 3.3), higher gas prices (section 3.5), and larger V2G penetration (section 3.5).

3.2 Reference Scenario - The Impact of V2G

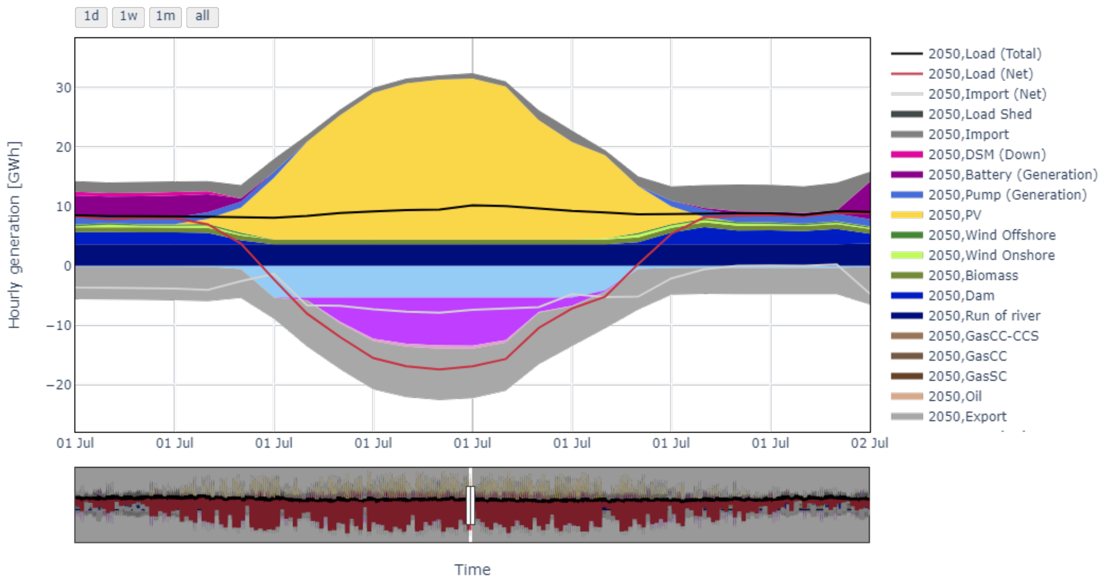
3.2.1 Electricity Generation

In our results, the integration of V2G (and thus the addition of storage capacity connected to the electricity grid) leads to better exploitation of the installed RES, by charging the batteries during peak production time and discharging them at times with lower RES production. The batteries' charging and discharging patterns of a representative summer day are visualized in Figure 5. We see that during the day electricity production by far exceeds the demand, mostly due to PV and run of river (RoR) electricity generation. Curtailment of this excess generation is avoided through three measures: filling up pump reservoirs, charging electric vehicle batteries, and exporting electricity to neighboring countries.

[3] Please note that the technology "geothermal" is listed as "wind offshore" due to the current limitations of the webviewer.



(a) Without V2G integration



(b) With V2G integration

Figure 5: Representative summer day without and with V2G integration. Please note that the technology "geothermal" is here shown as "wind offshore".

We also observe that due to the highly efficient and low-cost flexibility available due to V2G, other flexibility options are utilized slightly less. For example, pumped hydro storage units generate 8 TWh of electricity in 2050 without V2G but only 6.8 TWh with V2G.

The scenario includes investments in gas-to-power based on synthetic fuels (GasCC-Syn) and fossil fuels with carbon capture and storage. However, these generation technologies are not economically competitive enough to be activated on an average year under baseline developments (see section 3.3 for a situation in which the backup capacities are used)

3.2.2 Curtailment

The better exploitation of renewables with V2G helps to reduce curtailment. Figure 6 shows the development of the annual curtailed electricity for the simulated years. We see that V2G curtailment is going up due to the increase in installed RES capacity until 2040, and then – even in the noV2G scenario – decreases slightly. This is because other flexibility options such as stationary storage are added to the electricity system faster than new RES capacity. When adding V2G, between 2020 and 2050, a total of 55.3 TWh can be injected into the grid additionally. The value of this additional RES generation amounts to 1.1 billion EUR (if sold on the electricity market instead) by 2050. It translates into an average annual value of 941 EUR per MW of RES installed capacity.

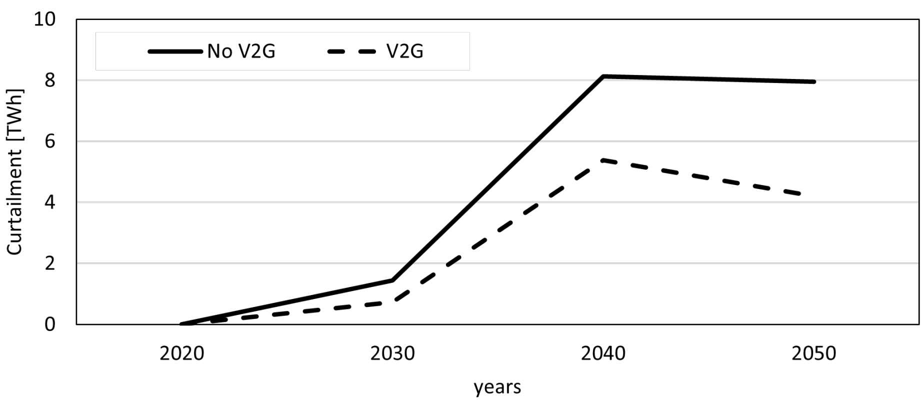


Figure 6: Annual curtailment in the reference scenarios with and without V2G

3.2.3 Costs

Implementing V2G reduces the total costs for the Swiss electricity system. First, as already indicated, it enables better exploitation of renewables. The additional injected electricity has a value to the system of 1.1 bn EUR by 2050. Second, the added flexibility by implementing V2G can be used beyond integrating inland renewables. It also allows the system to shift exports from hours of low electricity market prices to hours with high prices. The same logic holds true for avoided imports during times of high market prices. In turn, more profit can be made from favorable imports and exports from/to the neighboring countries. Third, V2G can also help to overcome extreme situations in which inland generation based on renewables and imports would be insufficient to supply demand and expensive fossil fuels would be used for electricity generation. Here, for example, the use of gas units is completely avoided in the V2G scenario.

Figure 7 depicts the electricity system costs from 2020 to 2050 for the scenarios with and without V2G. We see that during that time system costs are reduced by 8 percent, saving 3.9 billion EUR. This value of V2G for the electricity system can be expressed also in terms of revenues per vehicle or per available storage capacity and amounts to average annual values of 63 EUR/vehicle and 7 EUR/kWh, respectively. System costs include VOM, FOM, investment costs, and costs/revenues related to the import/export of electricity from/to neighboring countries. The main change in costs we observe is in the profits from electricity trading, with an increase of 4.8 bn EUR. In fact, Switzerland is not only able to export more (due to lower curtailment), but it is also able to plan the exports for more profitable hours. The total cost reduction through V2G, however, is mitigated by the higher VOM costs (from 40.8 to 41.7 bn EUR). This is because the V2G scenario has lower curtailment and therefore a higher electricity generation. Curtailment has no costs in our model. If we would assume a cost for curtailment, for example, because injected PV generation has to be compensated by the electric utility even in case it gets curtailed, the value of avoided curtailments and thus also V2G would be even higher.

The difference in total system costs between the scenarios with and without V2G can also be understood as the max value of V2G for the system as we have set its investments, operating, and maintenance costs to 0. If the cost for its technical implementation (such as changes in the charging infrastructure, IT, and overhead) and the required compensation for EV owners participating to V2G exceed such maximum value, V2G would become uneconomical. This means that implementation costs plus revenues should not exceed 63 EUR/vehicle.

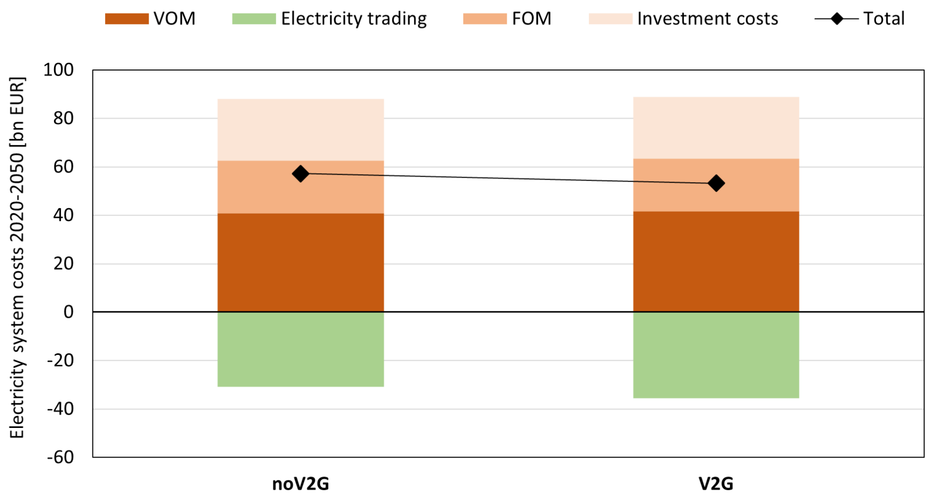
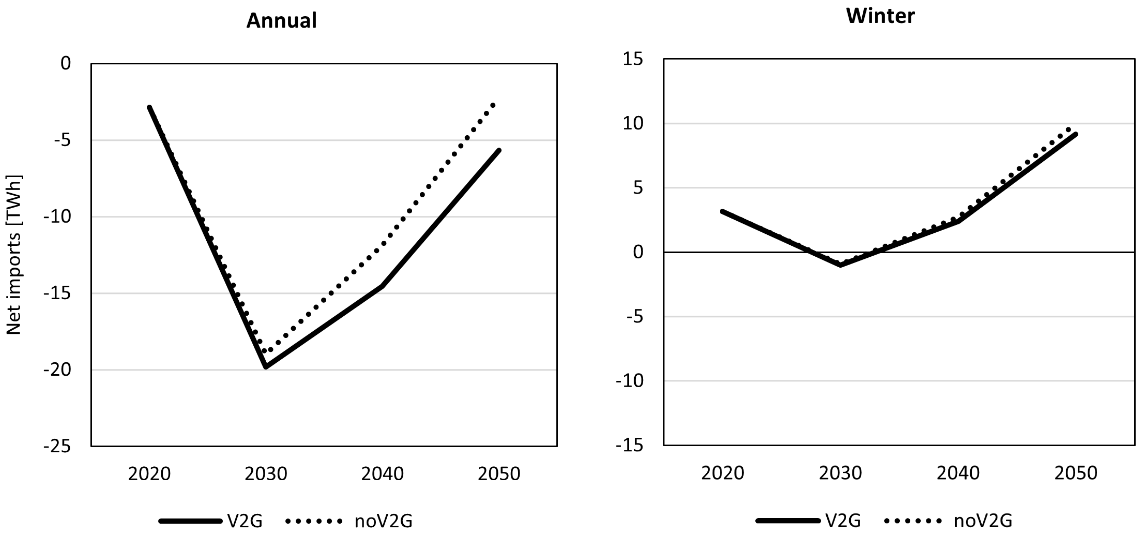


Figure 7: Cumulative electricity system costs in the reference scenarios for the time span 2020-2050

3.2.4 Dependence on Electricity Imports

Both scenarios, with and without V2G, build upon substantial electricity trading between Switzerland and its neighboring countries. Figure 8 depicts the annual and winter net imports for both scenarios.

Due to the higher exploitation of renewables in the V2G scenario, also the annual net exports are higher (visualized as negative net imports). As this higher exploitation is mostly in the summer months, the net imports in winter are mostly unaffected by the implementation of V2G. This is also expected as V2G provides flexibility mostly for hours or days but is not suitable to address seasonal energy imbalances. Thus, despite having a positive electricity balance over the year, imports in winter are required in both scenarios in all years except 2030. It is, however, important to note that the net import values provide no direct insight for the level of security of supply in the scenarios. In our model, Switzerland imports if it is the economically better solution instead of generating electricity itself. For example, in the V2G scenario, the gas-to-power units are not utilized as their operation is more costly than importing electricity from the neighboring countries – even in winter.



(a) (b)

Figure 8: (8a) Annual and (8b) winter net imports for the reference scenarios with and without V2G

3.2.5 Grid impact

In this study, we do not consider the restrictions of the distribution grid and local load management. However, to better understand the potential impact of V2G on the low-voltage distribution grid (Level 7), we assessed the simulated behind-the-meter loads on an hourly basis (i) without PV, (ii) with PV, and (iii) with PV and V2G. We thus assume for this grid impact assessment that all electricity demand is supplied via the low-voltage distribution grid, that all PV electricity is also injected into the low-voltage distribution grid, and that EVs are charging solely at the low-voltage distribution grid (no fast charger). All other technologies such as hydropower are assumed to be connected on higher grid levels.

The box plots in Figure 9 visualizes the distribution of historical hourly loads for 2022 and simulated hourly loads for 2030-50, all on a national Swiss level. We see that the electricity load in 2022 was around 7 GW.[4] The simulated load in 2030 without additional PV installations is slightly higher as new loads from EV and heat pumps slowly begin to increase demands. When calculating the net of load and PV injection, we see that the average load is decreasing but the volatility of the load substantially increasing. Load plus PV injections reach net values from -10 to +10 GW. We observe that when adding V2G such volatility is mitigated as negative extremes (corresponding to high peaks of PV injection) can be avoided. This picture remains the same for 2030-50, with a more pronounced effect of PV and V2G on load volatility. In 2050, for example, there are some hours in the year that result in twice the PV grid injection than the average demand. Without any measures to address such high power peaks, it is reasonable to expect overloads and voltage violations in the distribution grid. Considering this, the V2G becomes increasingly important with higher installed PV capacities. While the visualized results are only on an aggregated level, we see similar trends when assessing the loads at each line and transformer of the transmission grid.

However, this assessment can provide only initial insights into how V2G affects low-voltage distribution grids. Especially on a very local level, it can be expected that grid congestion becomes more challenging as PV and EVs are not always co-located and evenly distributed in distribution grids. Bal-

[4] See Swiss Energy-Charts

ancing demand and supply with V2G could then cause higher EV charging demand at one grid location while PV is actually injecting at another location. To account for increasing levels of local grid congestion with more EVs participating in V2G by limiting the max power each EV can contribute to V2G (see parameter "Charging power limitation" in section 2.2).

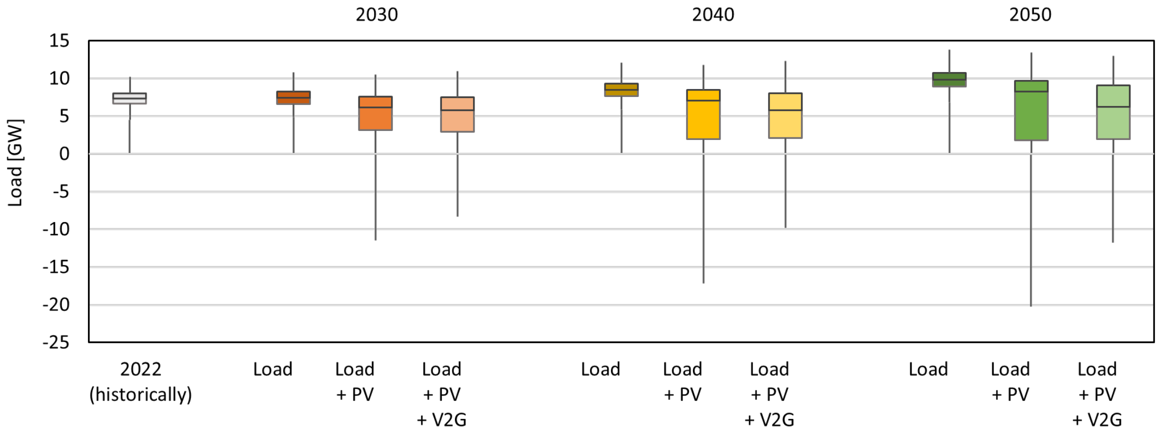


Figure 9: Distribution of hourly demand, demand minus PV generation, and demand minus PV generation and minus net generation of battery storage (generation - demand) in 2050

3.3 The Influence of Reduced NTCs

In this sensitivity, we test the impact of electricity trading limitations on the value of V2G. To do so, we reduce the net transfer capacities (NTCs) to 30 percent of the values in the reference scenario.

Reducing the NTCs has a huge impact on system costs, with and without V2G implementation. The cumulative costs from 2020 to 2050 increase from 57.2 bn EUR to 86.5 bn EUR in the noV2G scenario and from 53.3 bn EUR to 85.1 bn EUR in the V2G scenario. Figure 10a depicts these cumulative system costs. The added value of V2G integration is reduced to 1.5 bn EUR when restricting electricity trading.

The general increase in electricity system costs can be attributed mainly to the substantially higher curtailment when reducing NTCs (see black lines in Figure 10b). In 2050 and without V2G, annual curtailed electricity increases by 6.8 TWh to 14.7 TWh. Curtailments are more pronounced as lower NTCs restrict the electricity that can be exported every hour. This also limits the effect V2G has on curtailments. While, in the reference scenarios, adding V2G reduced curtailments by 55.2 TWh, in the NTC30 scenarios, the effect of V2G is reduced to 49.2 TWh. Additionally, the restricted imports and export capacities also limit the value of flexibility and make trading less lucrative.

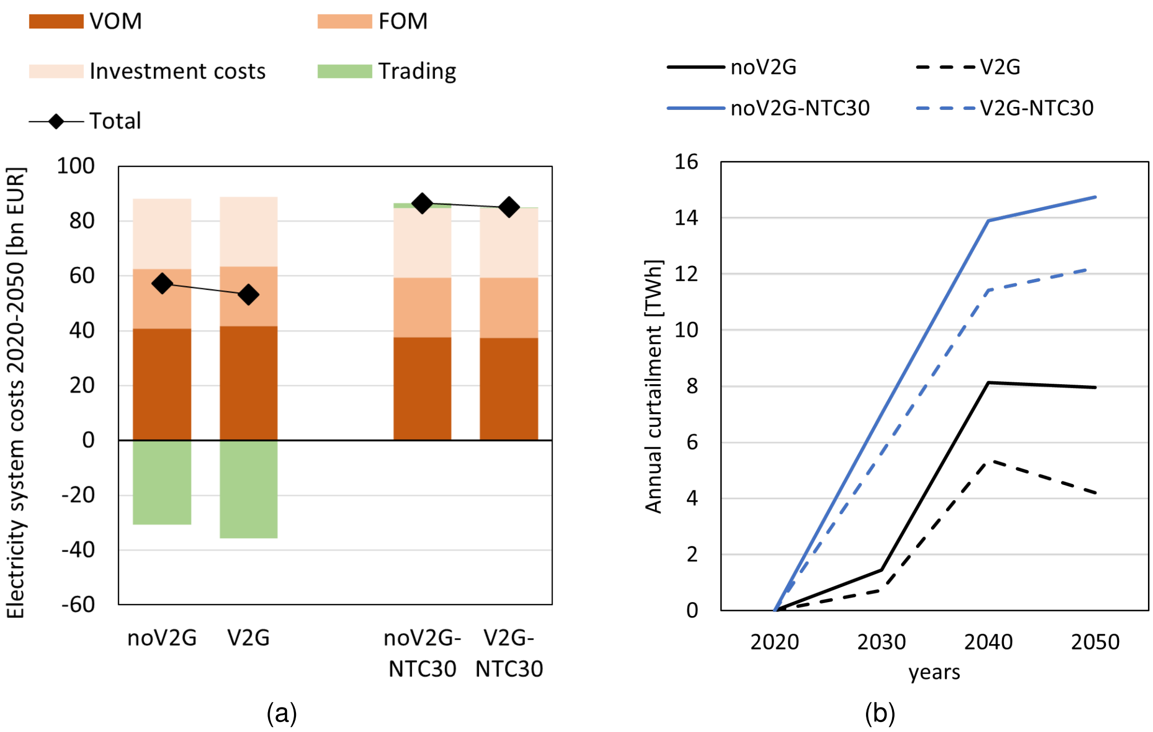


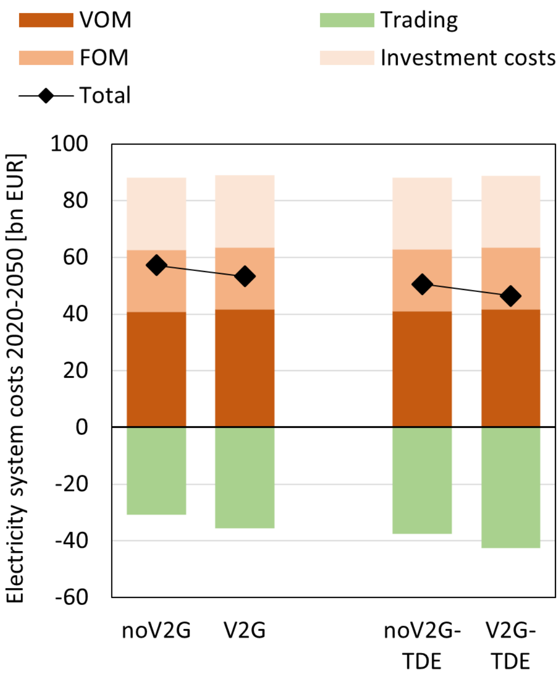
Figure 10: (10a) Cumulative electricity system costs and (10b) annual curtailment from 2020-50

3.4 The Influence of Developments in the Neighboring Countries

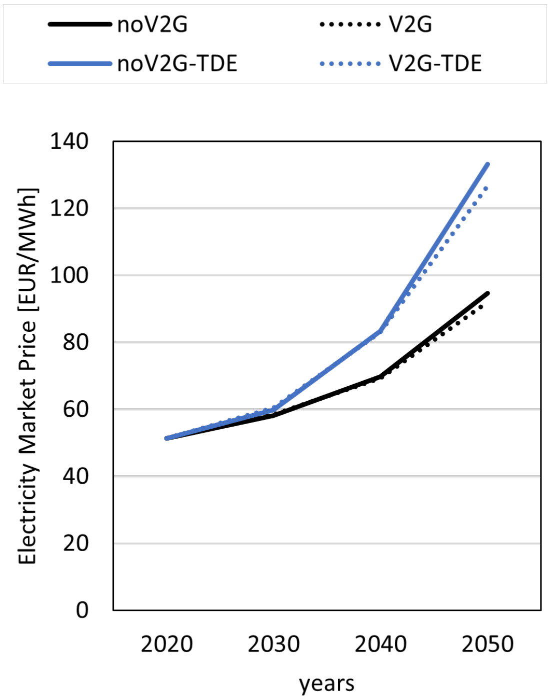
In this sensitivity, we test the impact of the developments in the neighboring countries on the value of V2G for the Swiss electricity system. In particular, we evaluate what impact larger penetrations of distributed energy resources (especially PV) abroad have on the Swiss electricity system and on the integration of RES.

Adjusting the developments in the neighboring countries results in a decrease in the cumulative system costs. The 2020-50 cumulative costs decrease from 57.2 bn EUR to 50.6 bn EUR in the no-V2G scenario and from 53.3 bn EUR to 46.4 EUR in the V2G scenario. The system costs are depicted in Figure 11a. Although we see higher levels of curtailments and decreasing exports, more profit is made from electricity trading with neighboring countries. The main reason for this is higher electricity prices in the neighboring countries that then also affect Swiss prices (see Figure 11b). In fact, the electricity prices in 2050 in Germany and Austria are 1.8 times the values we see in the reference scenario. This and the higher volatility of market prices lead to more profitable opportunities for electricity export in this scenario, in both cases, with and without V2G.

The implementation of V2G in the Swiss electricity system leads to cost reductions of 4.2 bn EUR from 2020 to 2050. Compared to the reference scenarios, the value of V2G increases by 0.3 bn EUR. The system cost reduction by V2G is mainly attributed to more profitable electricity trading which is possible due to the provided flexibility by V2G. The higher volatility of electricity market prices in Switzerland and the neighboring countries makes this flexibility even more valuable than in the reference scenarios.



(a)



(b)

Figure 11: (11a) Cumulative electricity system costs and (11b) annual electricity market prices from 2020-50

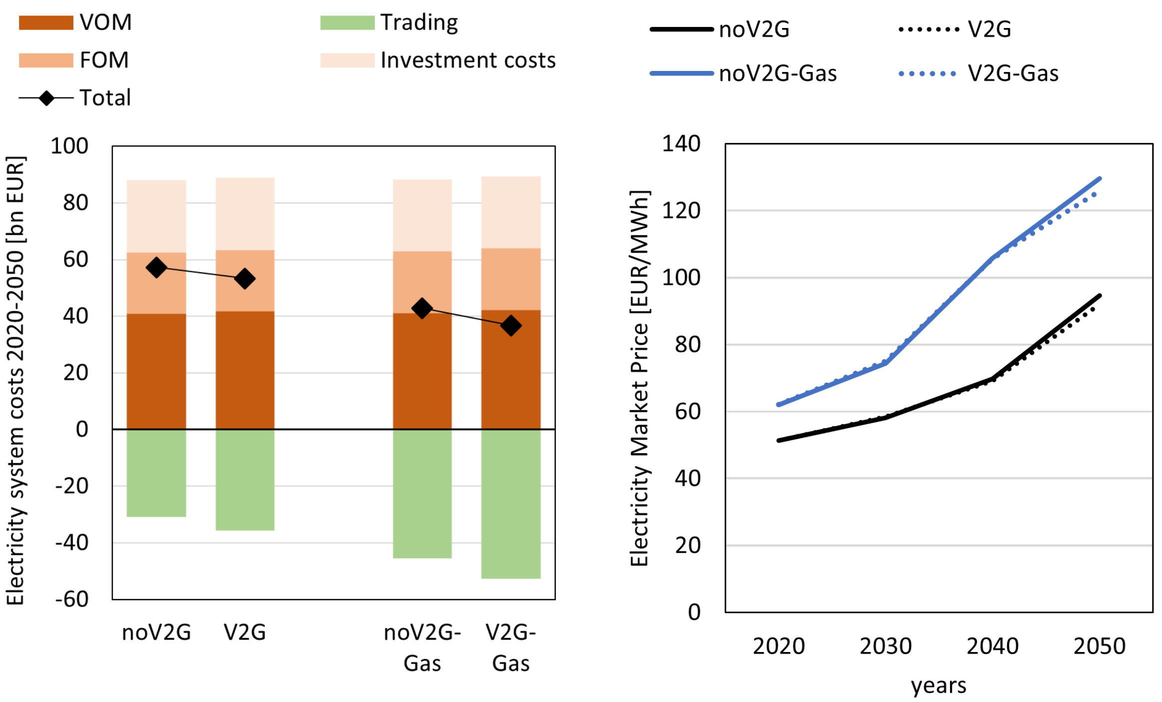
3.5 The Influence of Higher Gas Prices

In this sensitivity, we test the impact of higher gas prices to reflect the current uncertainties regarding the future availability and prices of natural gas. Generally, gas prices have a negligible direct effect on the cost of electricity generation in Switzerland as there is only a small number of backup gas units installed in Switzerland. The neighboring countries, however, have higher shares of gas in their electricity mixes.

Their cost of electricity generation is thus more sensitive to changes in gas prices. We use the European gas prices from the IEA 2021 report [10].

Higher gas prices result in a heavy decrease in cumulative system costs. The 2020-50 cumulative costs decrease from 57.2 bn EUR to 42.9.6 bn EUR in the no-V2G scenario and from 53.3 bn EUR to 36.8 EUR in the V2G scenario. The system costs are depicted in Figure 12a. The main reason for this is similar to what we have observed in the sensitivity on developments in the neighboring countries. High electricity market prices make electricity trading more lucrative as Switzerland is a net exporter in all years 12b) and the cost of electricity generation remains the same. However, compared to the sensitivity on developments in neighboring countries, electricity prices are at a much higher level and curtailments are much lower. This leads to low electricity system costs and high value of V2G.

Due to the higher electricity prices also the value of V2G increases substantially. Total system costs are reduced by 6.1 bn EUR between 2020 and 2050. This translates into a yearly cost reduction of 97 EUR per EV, and 11 EUR per kWh of offered storage capacity. Exports become especially valuable if they can displace the use of even more expensive gas units in the neighboring countries.



(a) (b)

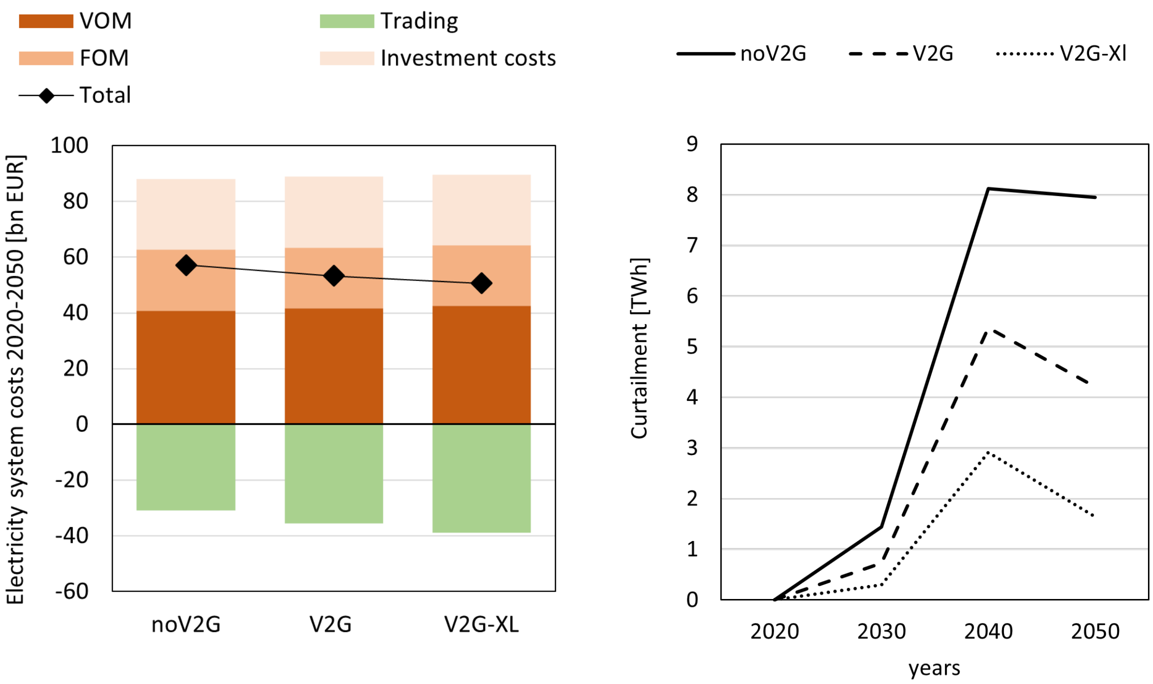
Figure 12: (12a) Cumulative electricity system costs and (12b) annual electricity market prices from 2020-50

3.6 The Influence of Available EV Battery Capacity and Power for V2G

In this sensitivity, we assess the value of V2G for the Swiss electricity system when we assume (i) that more EVs participate in V2G and (ii) that participating EVs can provide a higher capacity and more power for bidirectional charging.

Compared to the reference scenarios, the only difference for the electricity system is the higher storage capacity [TWh] and power [GW] available for V2G. Therefore, we observe the same effects of V2G on the electricity system (higher exploitation of renewables, less curtailment, higher annual exports, lower annual net imports, lower system costs, and unaffected winter imports) but on a higher scale. Total system costs (Figure 13a) are reduced by 6.6 bn EUR. So the value of V2G is 2.7 bn EUR higher when increasing the level of V2G. As before, the cost reduction is to be attributed mainly to even lower curtailments and using flexibility to optimize profits from electricity trading. If the cost savings derived from V2G integration are put into perspective to the number of vehicles and the offered storage capacity, the annual benefit of V2G integration is expressed as 92 EUR per vehicle and 5 EUR per kWh of offered storage capacity.

When adding such high levels of V2G, cumulated curtailments are reduced from 138 TWh to 40 TWh and, alone in 2050, from 8 TWh to 1.6 TWh (see Figure 13b). This means that 98.1 TWh of electricity can be injected additionally into the grid and lowering the curtailment to 4.4 percent of the total electricity generation by PV and wind. The value of these additional injections amounts to 2.1 bn EUR (if sold on the electricity market) from 2020 to 2050 and 1903 EUR per year and per MW installed capacity of PV or wind power.



(a) (b)

Figure 13: (13a) Cumulative electricity system costs and (13b) annual curtailment from 2020-50

4 References

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Appendices

A Development of Available Capacity and Power for V2G

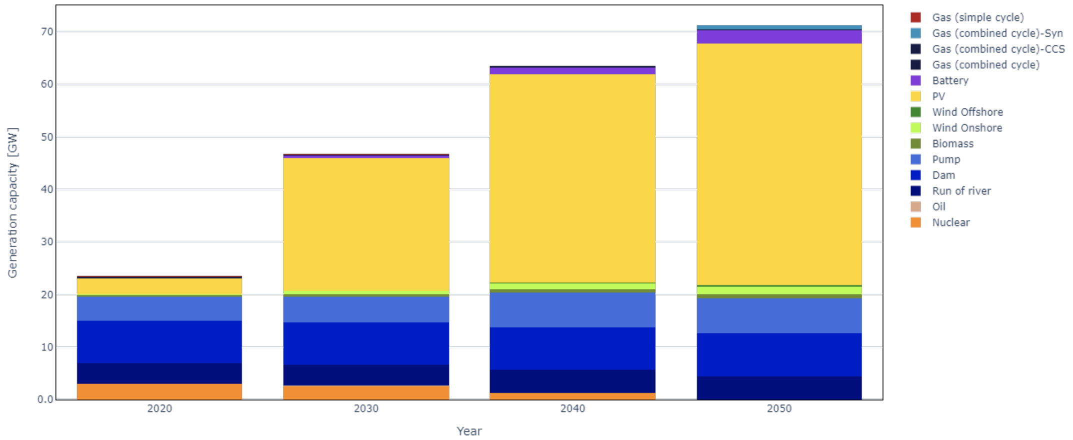
Table 3: V2G data for the V2G scenario.

Year	Number of V2G vehicles	Available capacity [MWh]	Available power [MW]
2021	0	0	0
2022	0	0	0
2023	2278.6	15.9502	8.714769
2024	10785.6	80.892	40.52067
2025	66228.75	529.83	244.3331
2026	161805.6	1359.167	585.9852
2027	305316.9	2686.789	1085.049
2028	500966.7	4608.894	1746.447
2029	749026.1	7190.651	2560.517
2030	1046058	10460.58	3505.099
2031	1224134	12241.34	4018.925
2032	1403238	14032.38	4511.951
2033	1582598	15825.98	4981.533
2034	1761687	17616.87	5425.997
2035	1940140	19401.4	5844.299
2036	2053171	20531.71	6045.798
2037	2169112	21691.12	6240.369
2038	2287964	22879.64	6427.42
2039	2409728	24097.28	6606.361
2040	2534402	25344.02	6776.601
2041	2661987	26619.87	6937.548
2042	2792483	27924.83	7088.611
2043	2925890	29258.9	7229.199
2044	3062208	30622.08	7358.72
2045	3201436	32014.36	7476.585
2046	3343576	33435.76	7582.201
2047	3488626	34886.26	7674.978
2048	3636588	36365.88	7754.324
2049	3787460	37874.6	7819.648
2050	3638070	36380.7	8003.755

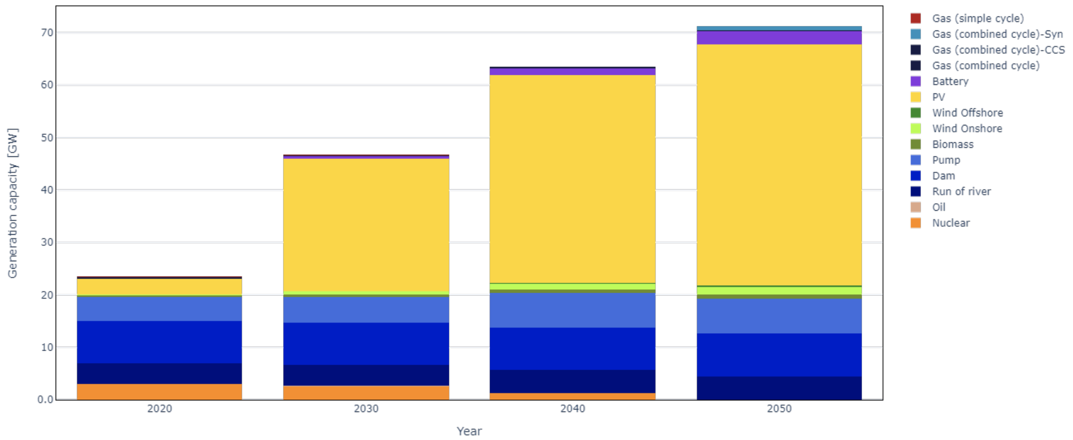
Table 4: V2G data for the V2G-XL scenario.

Year	Number of V2G vehicles	Available capacity [MWh]	Available power [MW]
2021	0	0	0
2022	0	0	0
2023	2278.6	31.9004	11.08627
2024	10785.6	161.784	52.01978
2025	83889.75	1342.236	401.0575
2026	210837.6	3542.072	999.0459
2027	402242.9	7079.475	1888.995
2028	663882.7	12215.44	3089.608
2029	996229.4	19127.61	4594.15
2030	1394744	27894.88	6372.907
2031	1616655	32333.09	7318.471
2032	1836152	36723.04	8234.436
2033	2052432	41048.65	9117.536
2034	2265026	45300.53	9966.116
2035	2473679	49473.57	10779.53
2036	2596657	51933.14	11205.57
2037	2721819	54436.37	11630.54
2038	2849163	56983.27	12054.15
2039	2978691	59573.83	12476.13
2040	3110402	62208.05	12896.21
2041	3244297	64885.93	13314.09
2042	3380374	67607.48	13729.52
2043	3518635	70372.7	14142.21
2044	3659079	73181.57	14551.87
2045	3801706	76034.11	14958.25
2046	3946516	78930.31	15361.05
2047	4093509	81870.18	15760.01
2048	4242685	84853.71	16154.84
2049	4394045	87880.9	16545.27
2050	4547588	90951.76	17508.21

B Development of Installed Generation Capacities in the Reference Scenarios



(a)



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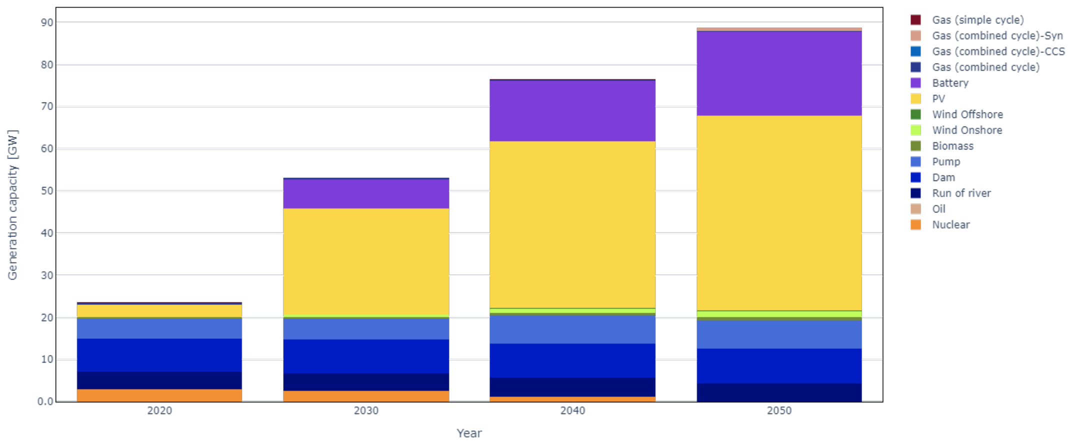

(c)

Figure 14: Development of installed capacities in the reference scenarios with 14a and without V2G 14b and the V2G-XL scenario 14c

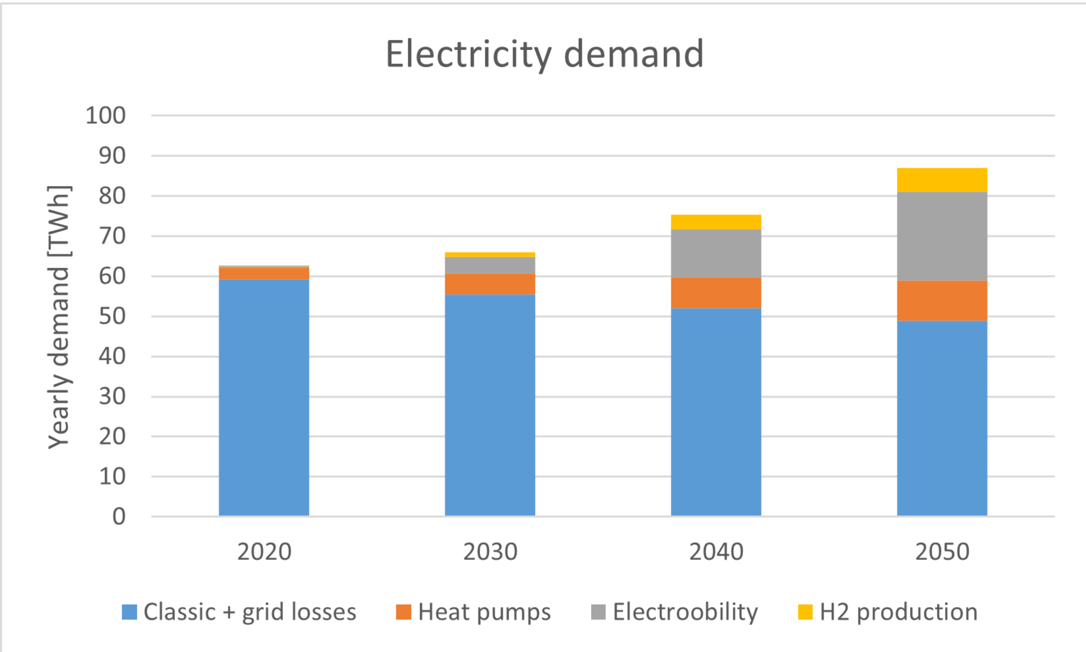

Figure 15: Development of annual electricity demand in the reference scenarios. Demand categorizes as conventional, heat pump, EV, and H_2 production demand.