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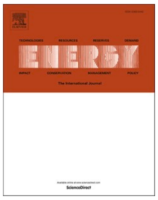

The influence of socio-technical variables on vehicle-to-grid technology

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ABSTRACT

Vehicle-to-grid technology (V2G) is a novel large scale energy storage option to improve the grid integration of renewable energy sources (RES). Using electric vehicle (EV) batteries to store and provide electricity to the grid, the intermittency of RES can be reduced. However, a successful implementation of this technology depends on various social and technological factors. This study analyses the influence of social and technical factors such as V2G acceptance (percentage of EV users that allow V2G energy transfer), EV battery availability for V2G service (percentage of the EV battery), EV adoption level (number of EVs in EV fleet) and the charger power for the energy transfer between the storage system and grid.

Using Germany for the case study, a simulation model is developed and employed for the study. The base simulation results show that Germany needs 190 GW of PV and 170 GW of wind turbine installation to meet 80 % of electricity generation from RES in 2030. Further results show that an increased V2G acceptance and EV battery availability reduces the V2G contribution from individual EVs. A V2G acceptance of only 30 %, using half of the battery capacity dedicated to V2G, can help to reach an hourly reliability of 86.6 %. Having 50 % V2G acceptance, the hourly reliability increases by 5.3 %–91.9 %. The final analysis on charger power and EV adoption level highlights that a normal charger power of 7 kW or 11 kW can successfully accommodate V2G service. The study's overall results indicate that V2G technology will be an effective storage solution for Germany in the future.

Nomenclature

ESS	Energy storage system
EU	The European Union
EV	Electric vehicles
EV cons (t)	EV energy consumption
GW	Gigawatt
GWh	Giga watt-hour
HP	Hydropower system
HR	Hourly reliability
IEA	International energy agency
IRENA	International Renewable Energy Agency
kW	Kilo watt
kWh	Kilowatt-hour
L_B	Load balance
LCOE	Levelised Cost of Energy
m_{share}	EV share of moving vehicles
PHS	Pumped hydro storage system
P_{share}	EV share of parked vehicles
PV	Photovoltaics
RES	Renewable energy source
$S_{ava\text{-}EV}$	The storage capacity available in EV
SOC	State of Charge
SOC_m	*Updated SOC of moving vehicles*
SOC_{max}	Maximum SOC to which EV can store energy through V2G
SOC_{min}	Minimum SOC to which EV can discharge through V2G
SOC_P	*Updated SOC of parked vehicles*
SOC_{total} (t)	State of charge of EV fleet at the time 't'
SOC_{temp}	
Temporary SOC point between time 't' and 't+1'	
SS	Self-sufficiency
TW	Tera watt
TWh	Tera watt-hour
V2G	Vehicle-to-grid technology
VRE	Variable renewable energy sources

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1. Introduction

The development of society is dependent on energy. An absence of sufficient energy generation can affect the supply and demand of various sectors. Around the world, all countries intend to develop clean energy sources to reduce environmental impacts. Using alternate and renewable energy sources (RES) and conserving energy are the two aspects of sustainable development in energy systems. RES is being used instead of non-renewable resources, such as solar power, wind energy, and hydropower, all of which are low-emission and renewable. The European Union is aiming to reduce 40 percent of greenhouse gas emissions in 2030 as compared to 1990 levels [1]. Among other plans, the EU aims to increase the share of energy production from renewable sources by up to 32 percent by improving the efficiency of systems [2]. To achieve these goals, it is necessary to replace fossil energy sources with RES. Additionally, the European Union Commission presented its strategy for a prosperous, competitive, and climate-neutral economy by 2050 [1]. RES are a driving force for sustainable development in the energy sector [3]. As RES can generate energy with very little carbon emissions, RES can meet carbon emission standards. The limitless availability of renewable sources will be more than enough to meet the requirements of the world's needs [4]. Despite this, a lack of infrastructure and the intermittent energy generation are hindering the growth of RES. An important solution to balancing these issues is energy storage. In an energy storage system (ESS), the excess electricity from RES is stored and then used when energy production from RES is low [5].

Since the early 21st century, RES application has increased for electricity generation as an alternative to fossil energy sources. In the energy sector, Solar photovoltaics (PV), wind and other sources have been widely used for the generation of electricity and heat. Since then, several more studies focus on the development of an electricity grid with 100 % electricity generation from RES, supported by ESS. Hrnčić et al. [6] studied the possibility of achieving a 100 % RES in Montenegro. Their results from the EnergyPLAN model indicate a positive response on achieving 100 % RES grid with ESS. The study by Tetteh et al. [7] focuses on cost-effective electro-thermal ESS. The hypothesis focuses on modular electro-thermal energy storage (ETES) with various storage materials (thermal oil, molten salt, and sand) at high capacities and high efficiencies. The results show sand as an efficient storage medium with higher efficiency (85 %), with extremely high-temperature tolerance, increasing the Carnot efficiency of Stirling engines and driving down the cost of ESS six times compared to other technologies. Teki et al. [8] studied residential units with solar and ESS. The results show that the system performs well during daytime conditions, including peak shaving. Al-Ghussain et al. [9] conducted a study on the microgrid in a university campus with 100 % RES. According to the results of the study, the hybrid system guarantees high self-sufficiency, approaching almost 99 %. The study by Giarola et al. [10] analyses the role of ESS combined with RES. The study encompasses a model comparison approach where four models (GENeSYS-MOD, MUSE, NATEM, and urbs-MX) are used to analyse storage uptake in North America. The results show that storage may promote emission reduction at lower costs when renewable mandates are in place whereas, in the presence of carbon taxes, renewables may compete with other low-carbon options.

Despite these studies showing the feasibility of RES integrated with ESS for a 100 % RES-supported grid, the development towards 100 % RES systems in the real world has been slow. One of the reasons for this is that the development of ESS technologies requires additional investment in the form of money and resources. Simultaneously, money and resources are being invested within the transportation sector to electrify large parts of the sector, by replacing fossil cars with electric vehicles (EVs), gasoline stations with EV charging stations and the grid being upgraded to facilitate large-scale EV charging. Replacing fossil-fuelled vehicles with EVs, it is estimated that each vehicle can reduce its emissions by between 25 % and 80 % depending on the electricity source [9]. This electrification process and transition towards EVs provide a great opportunity to develop ESS through Vehicle to Grid (V2G) technology with much less additional investments compared to developing large-scale thermal, mechanical or electro-chemical ESS. In V2G technology, the EV is connected to the grid through a bi-directional charger, which facilitates energy storage and extraction. Considering the only investments in bi-directional chargers instead of uni-directional chargers, the total financial and resource investment would be much lower compared to the development of the new ESS.

In our study, we focus on vehicle-to-grid technology (V2G), which is stored in EV batteries. Through bi-directional chargers, the technology offers a storage capacity of 20 MWh of energy from 200 EVs, considering 100 kWh batteries. The initial study by authors to support Germany with V2G as an ESS indicates that V2G can be a viable ESS [11]. Another study by Sagaria et al. [12] shows that Spain can achieve its 2030 and 2050 renewable energy goals with EV as the primary ESS through V2G, facilitating high penetration of RES into the grid. The study on V2G transfer and applications by Lakshmi et al. [13] points out various applications, such as vehicle-to-home and building energy transfer during peak load periods. Mozafar et al. [14] performed a study on smart grid operations considering large-scale integration of EV to grid through V2G technology. The results showed that an EV is a good ESS for the smart grid, which can virtually eliminate the need to use high-cost generators or other ESS to supply the system in peak hours ergo reducing the hourly cost of the system. Many other studies also support the integration of EVs into the grid to develop virtual ESS [15–18]. Further, Sagaria et al. [19] analyses photovoltaic integrated EVs, where EVs generate energy themselves through onboard PV and can transfer this energy to the grid through V2G. These EVs can be further utilized during peak load periods.

In a recent study by Zhao et al. [20], the environmental impacts of Vehicle-to-Grid (V2G) technology were evaluated within the context of a 2050 United Kingdom system, employing a consequential Life Cycle Assessment (LCA) methodology. The results show that the implementation of V2G has the potential to effectively offset the environmental footprint of electricity generation in high RE scenarios. Ramaiah et al. [21] study on the microgrid using fast charging DC architecture shows that V2G coupled with proper controller provides excellent dynamic performance in terms of dc bus voltage stability, and the charging station design assures low harmonic distortion of grid injected current. The study by Li et al. [22] introduces a scheduling optimization model for an integrated energy system with EV and hydrogen vehicles. Their results show that with V2G mode the total cost of power is reduced by 7.8 %, and the cost of power purchased from the grid decreases by 53.7 %.

Boström et al. [23] analyse a pure PV-EV energy system PV as the only electricity source working solely with EVs to satisfy the nationwide energy requirement in Spain. Their result showed that an hourly reliability of 100 % is possible with 73 m^2 of PV per capita in Spain, solely using EVs for energy storage and balancing. The study by O'Neill et al. [24] assesses the V2G operation in the microgrid to support Variable Renewable Energy (VRE) generation. The simulation results over 1 calendar year shows that V2G reduces the LCOE grid cost by 5.4 % for the solar supported microgrid, 4.6 % for wind supported micro grid and 4.5 % for solar and wind supported microgrids. Schuller et al. [25] developed an optimization model aimed at maximizing the utilization of EVs through V2G and VRE under various power generation and charging infrastructure scenarios. Their findings highlight the potential of coordinated charging, which could more than double VRE utilization, although the effectiveness is constrained by the length of the lookahead period. Nezamoddini and Wang [26] approached the challenge from the perspective of ISOs, incorporating uncertainties in VRE output, load and parking patterns, and transmission line reliability to optimize V2G dispatch. The studies [17,27–30] examine the peak load shaving capacity, techno-economic analysis and grid parameters using V2G technology. The results show that the power demand reduces by up to 6 % with a proper energy management system.

Whereas early studies demonstrated the high technical potential of V2G systems [31], more recent studies have started to focus on social factors of V2G systems that act as a barrier to widescale V2G deployment, such as user willingness to accept new technological developments and V2G acceptance. For example, a study by Esmaili et al. [32] indicates range anxiety as a key barrier to user participation in V2G. Range anxiety is the driver's fear that a vehicle has insufficient energy (battery capacity) to cover the distance needed to reach its intended destination, and would thus strand the vehicle's occupants mid-way. Geske and Schumann [33] analysed the willingness of EV drivers to participate in V2G technology and the different reasons for their decision. Their result shows that range anxiety and minimum range are the most determinant decision factors for V2G participation. Kester et al. [34] study variables promoting V2G in the Nordic region and also point out the lack of infrastructure, battery degradation and consumer awareness as main hurdles for V2G growth. Their study points to user concerns over their battery degradation through V2G purposes. Fast DC chargers over 50 kW, enable charging and discharge of batteries over 1C rate, which can increase chemical and thermal stress in the batteries, which reduces battery life. A study by Noel et al. [35] studied different barriers apart from range anxiety. Their study was based on a survey and results show that reasons for low V2G growth include low EV adoption levels, poor business models, and battery degradation. The diffusion study on PV and EV by Van der Kam et al. [36] shows the adoption of EV and its implication on the transition to smart grid systems. Focusing on the Netherlands, their study shows that EV adoption levels have a high influence on V2G potential.

From the former studies, we identify range anxiety, battery life anxiety, V2G acceptance and EV adoption level as key variables. Noel et al. [35] show that 28 % of the EV users who attended the interviews prefer other energy balancing technologies than V2G and 17 % show resistance due to the unwillingness to accept a third party to access their battery or the concept of V2G was too complex. While 12 % of the participants worry about battery degradation due to V2G and 10 % of the participants indicate V2G is not practical because of the lack of a large EV adoption level. A study by Meelen et al. [37] also mentions that user preference, technology and infrastructure all have a high impact on upscaling of V2G technology. Kester et al. [34] study variables promoting V2G in the Nordic region and also point out the main challenges for the faster development of the technology as battery degradation and consumer awareness. In this study, we aim to understand the potential impact of these variables through simulating scenarios with different V2G acceptance rates, battery capacity, charger power and EV adoption levels.

Even though past technical research, analyses the possibility of EV as ESS through V2G, they failed to demonstrate how the change in social behaviour affects the results. On the other hand, social behaviour studies demonstrate the influence of social variables in V2G technology without technical details. Our paper aims to combine both technical and social factors to generate insightful results. Multiple RES (Wind, PV, and hydropower systems) and ESS [EV and pumped hydro system (PHS)] are included in the model which helps to simulate real-life scenarios. We consider EV as the primary ESS and PHS as the secondary ESS to give more focus on the V2G energy flow. As secondary ESS, instead of PHS, we can include other ESS such as thermal and electrochemical ESS or multiple storage systems. Through this conceptual study, we look forward to delivering meaningful insights by analysing primarily four variables, 1) V2G acceptance rate – which illustrates how many EV users allow energy transfer between EV and grid through the centralized control system. 2) EV battery availability – what percentage of the battery can be used for V2G purposes and avoid range anxiety between users. 3) Charger power – to study whether fast chargers are necessary or not for successful V2G execution, and finally, 4) EV adoption level - to study how the change in the number of EVs influences the total outcome of the technology.

For better insights, the study focuses on Germany. We choose Germany due to its diverse electricity generation portfolio [38]. In the latest update in Erneuerbare Energien Gesetz (EEG - The Renewable Energy Act), Germany aims to generate 80 % of their electricity from RES in 2030 and increase the share of wind and PV to 115 GW and 230 GW respectively [39]. Considering Germany's 80 % electricity generation milestone in 2030, it is vital for a RE-supported grid system to have ESS. Building new ESS requires more resources and infrastructure. Considering the estimates of 15 million EVs in 2030 [40], this provides a platform to test the influence of V2G technology in the grid system, where we can save more resources and emissions from those infrastructures by using EVs as ESS. Our model does presently not include electricity imports and exports. Germany is a country with many neighbours and, electricity exchange with them is obvious and generates better energy security. Electricity imports and exports will be added in later versions of our model.

The research paper is structured as follows, Section 2 details the development of the simulation model. Section 3 explains the operation condition of the model and the initial setting. Section 4 gives the results from the simulation model under different operation scenarios. Section 5 discusses the results and outcomes in detail and section 6 presents the conclusion of the study.

2. Model development

To study the influence of social variables in V2G, a simulation model is developed in MATLAB/Simulink software. Previous studies in the field focus solely on one RES or ESS technology or a combination, and its influence on the grid. In the real world, multiple RES is integrated with ESS to satisfy energy needs. This underestimates the flexibility within the energy systems. Our study aims to fill this void through a model that considers multiple energy sources and storage systems for the analysis and includes the variables to perform this study.

The primary goal of the study is to perform an analysis of the influence of socio-economic variables on V2G technology. In the model, we consider a top-down analysis approach to study the influence of variables on V2G electricity flow. Since V2G technology is still in the development phase and with little research on the V2G acceptance rate and average expected EV battery availability, it requires further large-scale pilot experiments and surveys. Additionally, there are presently not enough EV volumes and chargers for V2G purposes (considering 1:1 bi-directional chargers). Because of these reasons, our study took a top-down approach, where we analyse scenarios with different V2G acceptance rates, EV battery availability, charger power and EV adoption levels.

In this study, PV, wind, and hydropower (HP) are considered as RES, and PHS and EV are considered ESS. The inputs are given in the load profile subsystem, EV subsystem and Operation subsystem. The load profile determines the hourly load requirement from yearly consumption. Based on the electricity consumption profile from TSO/DSO, the yearly consumption is segregated into hourly load profiles. This gives the electricity consumption from the household and the industry each hour in a year. Also, the subsystem estimates the electricity generation from RES. The estimations are based on the yearly electricity generation profile from Germany, obtained through the Agora Energiewende GmbH database [21]. The vehicle subsystem estimates the EV battery capacity from the EV for the V2G service. The EV fleet characteristics like usage profile for each day, number of EVs, and battery capacity are input to this subsystem. The operation subsystem derives the electricity flow between RES and ESS to give the required outputs. Fig. 1 shows the model developed in Simulink software.

Germany's annual average electricity consumption is approximately 520 TWh, consumed for transport, trade and service, household, and industrial applications [41]. Based on the user profiles of the household and industrial section from Stromnetz Berlin [42], the hourly load profile is generated. For RES, since solar and wind installations are growing rapidly, the simulation uses annual electricity generation data

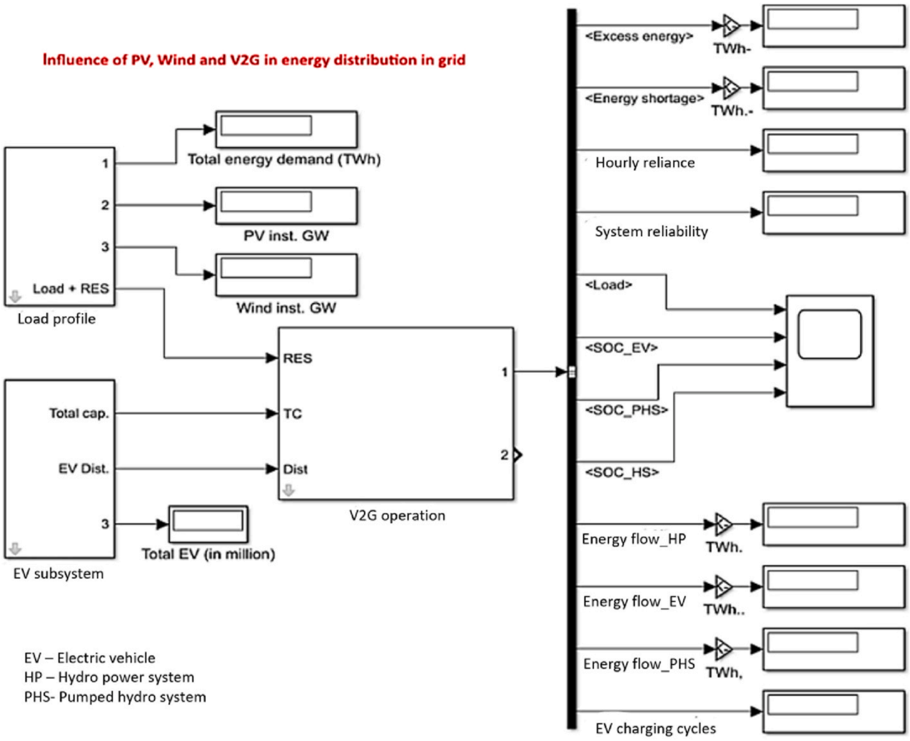

Fig. 1. Model A structure in Simulink.

from 2020. At the end of 2020, Germany had a PV installed capacity of 54 GW and 62.67 GW of wind energy combining both onshore and offshore installation. In 2020, a combined 181 TWh of electricity was produced from both PV and wind (50.7 TWh from PV and 130.32 TWh from wind). From this, the hourly generation for 1 MWh is calculated for a year. This is further used. For Hydroelectric power, the electricity generation profile from 2020 is given as the input. In 2020, 18.3 TWh of electricity was produced through hydropower in Germany [21].

The model considers a total load of 520 TWh/year for Germany. We assume the electricity requirements will be the same even in 2030. The past electricity consumption data from 2000 to 2021 [41], shows the change in electricity consumption as ±40 TWh from the average of 500 TWh. From 2010 to 2021, the yearly electricity consumption is decreasing at a rate of 7 %. In our analysis, we consider EVs and they can increase the electricity requirement in the future. However, the model calculates EV energy requirements separately in addition to the electricity load. This assumes that the electricity requirement in 2030 is valid, nevertheless, extrapolating historic consumption data results in a reduction of total electricity consumption in 2030 as compared to the assumption.

In this study, we investigate the maximum potential of V2G for grid balancing. Therefore, the model considers the EV battery as the primary ESS and PHS as the secondary ESS. For the simulation, the average driving distance per day is 49 km, with an average energy consumption of 200 Wh/km [23,43]. For the V2G process, the round-trip efficiency of the V2G technology is 87 % with 93.5 % efficiency for charging and discharging respectively [23]. In the base case study, the maximum and minimum state of charge (SOC) of the EV fleet is confined between 90 % and 10 % to avoid extra energy losses, battery degradation and improved battery life [44]. The EV driving distribution represents the

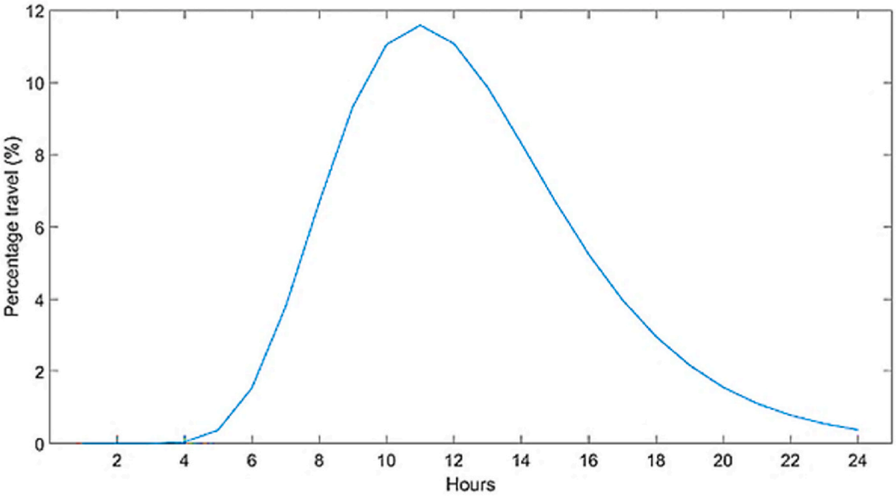

Fig. 2. EV driving distribution.

vehicle moving pattern each hour for a day. The EV driving distribution is generated through a log-normal function, showing the percentage of vehicles moving each hour [23]. Fig. 2 shows the moving distribution of EVs for a day. We assume the same pattern will be followed all day around the year. The energy consumed by the EV is calculated individually using (1).

$$\text{EV cons }(\mathrm{t}) = \text{Average energy cons./km} \times \text{distance travelled} \times \text{total EV} \times \tag{1}$$

percentage of EVs driving at timestep t.

The model considers PHS as the secondary storage system, to focus more on energy flow through EVs through V2G technology. Germany currently has a PHS capacity of 5355 MW [45]. For this study, 5355 MW capacity is considered with 85 % round trip efficiency, assuming the state-of-the-art technologies employed. Fig. 3 represents the logical flow diagram of the model. The minimum and maximum SOC for EV and PHS, initial SOC and energy profiles were given as inputs for the model.

At the start of the simulation, the model calculates the load balance in the system, through equation (2). The load balance is the difference between the load requirements and the electricity provided by PV and wind installations. The load balance can be positive, zero or negative. A zero-load balance indicates energy generation from RES equal to the load demand. The positive load balance represents higher electricity consumption than electricity generation from RES, and the negative load balance represents less electricity consumption than electricity generation from RES.

$$\text{Load balance } (L_B)(\mathrm{t}) = (\text{load cons.}(\mathrm{t}) + \text{EV cons.}(\mathrm{t})) - (\text{Wind energy } (\mathrm{t}) + \mathrm{PV}(\mathrm{t})) \tag{2}$$

Electricity generation from RES is insufficient to meet the load demand during a positive load balance. Electricity from external sources is necessary to balance the requirements. In this model, the external source is ESS. The model analyses the SOC of both ESSs. If electricity from the EV battery is enough to satisfy the additional requirement, the electricity is extracted from the EV. If more electricity is needed, the rest will be taken from PHS after the EV batteries successfully discharge to the minimum SOC. The hydropower system activates when the PHS electricity supply is insufficient to meet the load demand. If there is still an electricity demand, it is considered an energy shortage point where the required electricity must be supplied by external sources.

A negative load balance represents excess electricity generation from RES over the electricity demand for that hour. The SOC of the EV fleet is checked at the beginning. If the SOC is less than the maximum SOC, electricity is stored in the EV batteries until the SOC reaches the maximum. If more electricity is still available, it is stored in the PHS system. If electricity is available even after storage, it is considered excess energy. This energy is wasted or discarded without being used on the grid.

The SOC of the EV fleet during each period is calculated as the sum of the SOC of the parked vehicles (SOC_p) and moving vehicles (SOC_m), as in equation (3). At the beginning of each time step, the model assumes the same SOC for all the vehicles. The SOC_m of EV includes the energy required to drive during the hour, thus capturing the dynamic nature of the EV fleet. Based on the driving distribution a fraction of vehicles will not be able to connect to the grid. This proportion of vehicles uses their battery only for transportation purposes, which is the reason for estimating the SOC of moving vehicles separately. While it gets parked, the vehicle is connected to the grid and only the allowed battery limits for parked vehicles can be used for V2G purposes, not the whole vehicle

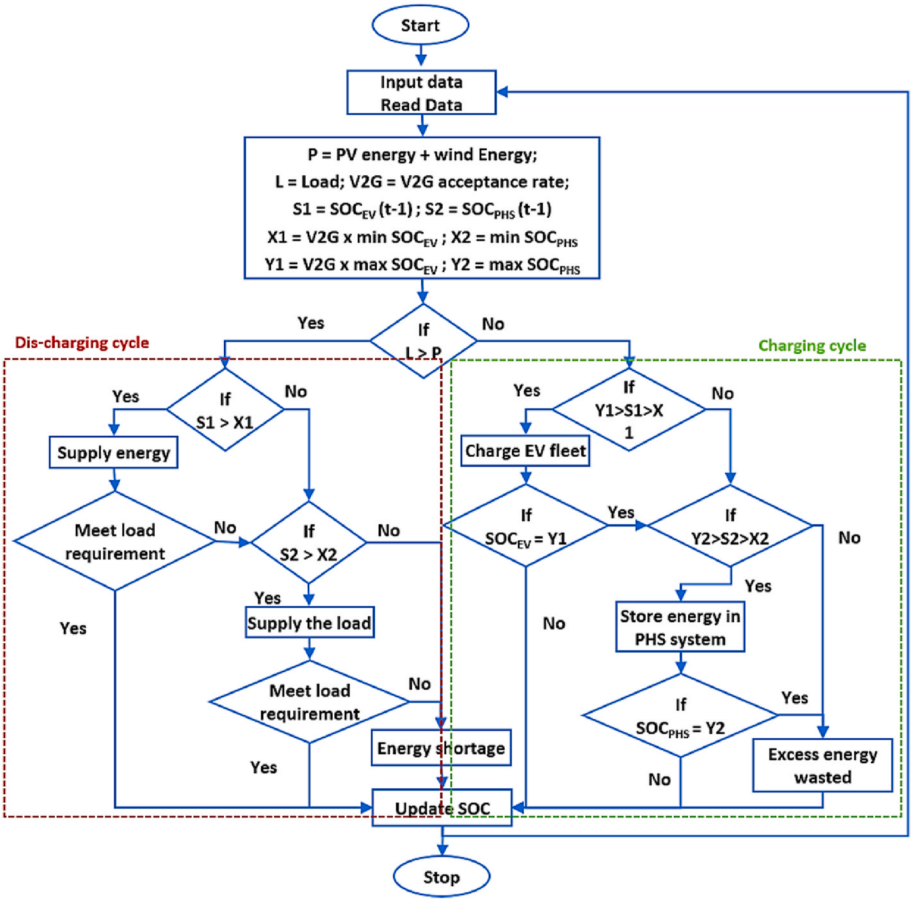

Fig. 3. Flow-diagram of the simulation model.

fleet. The SOC of the parked vehicles and moving vehicles is estimated individually using equations (4) and (5).

$$SOC_{total}(t) = p_{share}(t) \times SOC_p(t) + m_{share}(t) \times SOC_m(t) \qquad \text{Equation 3}$$

$$SOC_p(t) = \begin{cases} a)\ \text{if } SOC_{temp}(t) > p_{share}(t) \times SOC_{max}\ ; p_{share}(t) \times SOC_{max} \\ b)\ \text{if } SOC_{temp}(t) < p_{share}(t) \times SOC_{min}\ ; p_{share}(t) \times SOC_{min} \\ c)\ \text{if } SOC_{temp}(t) < p_{share}(t) \times SOC_{max}\ \delta\ SOC_{temp}(t) > p_{share}(t) \times SOC_{min} ; SOC_{temp}\ (t) \end{cases} \tag{4}$$

$$SOC_m(t) = SOC_m(t) - \ EV\ cons\ (t) / _{total\ EV\ fleet\ capacity} \qquad \text{Equation 5}$$

Where p_{share} is the share of SOC of the parked vehicle and m_{share} is the share of SOC of the moving vehicles at the time step *'t', SOC_{temp}* is the temporary SOC of the EV fleets used for calculation purposes, SOC_{max} is the maximum SOC attainable by the EV fleet and SOC_{min} is the minimum SOC attainable by the EV. SOC_p calculation considers 3 operational cases. Case a) represents when there is excess energy generation. In this case, the EV recharges the battery to SOC_{max}. Case b) represents when an EV does not have enough electricity to meet the required loads. In this case, the EV discharges until EV reaches the SOC_{min} state. Case c) represents when EV can accommodate the whole excess energy generation from RES.

SOC_{temp} is a variable used to calculate the intermediate SOC of the moving and stationary EV. When we have excess electricity from RES or insufficient electricity from RES, the energy flow happens between the parked EV vehicles. Due to this, the SOC estimation of the parked vehicle must consider 3 different cases, positive load balance with enough electricity to meet additional requirements (case c), positive load balance with not enough electricity to meet the requirements (case b) and negative load balance (case a). Equation (6) shows the calculation of $SOC_{temp,}$

$$SOC_{temp}(t) = \begin{cases} a)\ \text{if } L_B\ (t) < 0; p_{share}(t) \times SOC_p(t) + L_B(t) \times charging\ eff \\ b)\ \text{if } L_B(t) > 0\ \ \delta\ p_{share}(t) \times SOC_p(t) > L_B(t); p_{share}(t) \times SOC_p(t) + \dfrac{load\ balance(t)}{charging\ eff} \\ c)\ \text{if } L_B(t) > 0\ \delta\ p_{share}(t) \times SOC_p(t) < L_B(t); p_{share}(t) \times SOC_p(t) \times charging\ eff \end{cases} \tag{6}$$

The SOC_{temp} calculation varies according to the load balance. During the negative load balance, the electricity is stored in the EV, as shown in case (a). The inflow of electricity to EV revises SOC_{temp} updated with a positive number. During positive load balance, the model checks the capability of the EV to satisfy the additional load requirements. Case (b) represents when EVs can meet the requirements through energy discharge from the EV fleet. Case (c) represents a scenario in which the EV cannot meet the total additional load requirement. energy discharge from the EV fleet, where EVs cannot meet the additional electricity requirement. Equation (7) and 8 show the equation to calculate p_{share} and $m_{share,}$ respectively.

$$p_{share}(t) = (1 - EV\ driving\ distribution(t)) \times total\ EV\ fleet\ capacity \qquad \text{Equation 7}$$

$$m_{share}(t) = EV\ driving\ distribution(t) \times total\ EV\ fleet\ capacity \tag{8}$$

The SOC of PHS is also estimated each period through equation (9). Similar to the EV fleet, the SOC estimation depends upon factors such as the load balance and energy flow with the EV. SOC_{temp} is used as the intermediate point to determine the electricity flow in PHS. Case (a) represents additional electricity availability after charging the EV fleet to SOC_{max}. The excess electricity is stored in the PHS system and SOC_{PHS} is updated. Even after electricity is available after PHS reaches PHS-max_{SOC}, the available electricity is discarded. Case (b) and (c) represent positive load balance points. When EV cannot fulfil the excess load requirements, energy from PHS is extracted, represented by the case (b) and If PHS cannot fulfil the additional requirement, the time period is marked as an energy shortage point. case (c) shows when EV stores the energy excess electricity from RES.

$$E\ bal._{PHS} = \begin{cases} a) SOC_{temp} > \ SOC_{max}\ ; SOC_{temp} - SOC_{max} \\ b)\ SOC_{temp} < \ SOC_{min}\ ; SOC_{temp} - SOC_{min} \\ c)\ SOC_{temp} < \ SOC_{max}\ \delta\ SOC_{temp,n} > \ SOC_{min}\ ; 0 \end{cases} \qquad \text{Equation 9}$$

Finally, the system's self-sufficiency (SS) and hourly reliability (HR) of the system are calculated. Hourly reliability indicates whether the RES and ESS system can satisfy the electricity requirement for each hour without external support. At the same time, system SS indicates the amount of electricity provided to meet the requirements over a year of RES and ESS systems. Equations (10) and (11) represent the calculation of HR and system SS.

$$HR = \sum_{1}^{8760} \left\{ \begin{array}{c} E\ bal._{PHS} + E_{HP} < 0; 0 \\ E\ bal._{PHS} + E_{HP} \geq 0; 1 \end{array} \right\} / 8760 \tag{10}$$

$$\text{SS} = \frac{Total\ energy\ supplied\ by\ RES\ \&\ ESS}{Total\ energy\ required} \times 100 \qquad \text{Equation 11}$$

3. Application of the model

The goal of the model is to facilitate a study to analyse the influence of social parameters such as V2G acceptance, charger power, EV adoption and EV battery availability on V2G service. Before the analysis, the initial step is to determine the base state. Base state refers to the results of simulations of a particular scenario. In this study, we establish the base state based on the 2030 energy goals of Germany. In 2030, Germany is aiming to have 80 % of its electricity from RES, primarily solar and wind sources [46]. In addition, Germany estimates that there are 15 million EVs on the road [40]. Considering these statistics and assuming instant energy transfer from EV to the grid and 100 % V2G acceptance,

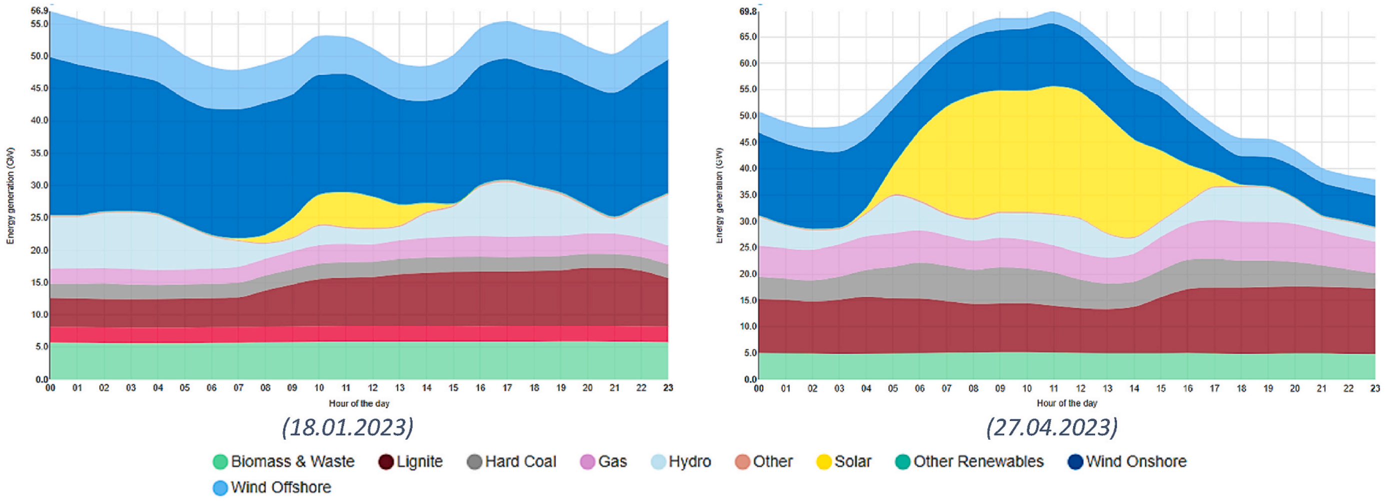

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Fig. 4. Hourly electricity mix of Germany for 2 different days.

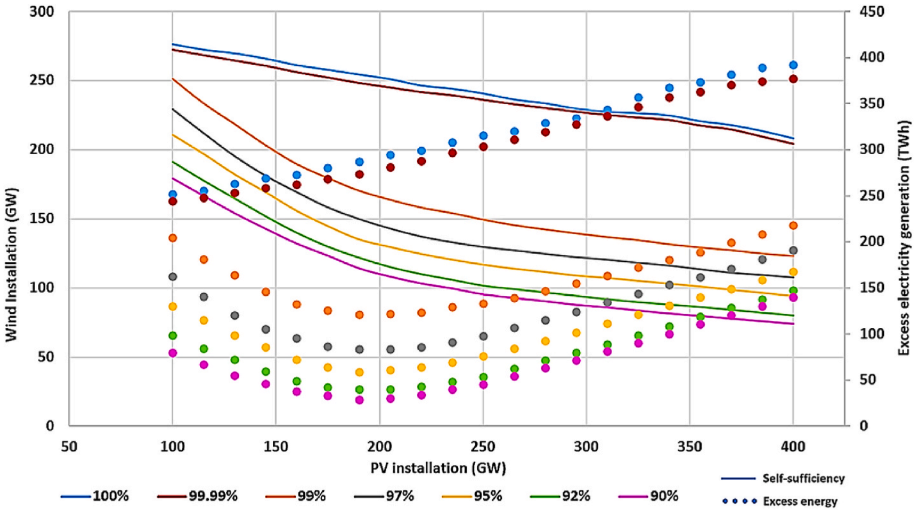


Fig. 5. RE installation and excess electricity generation for different self-sufficiency points.

an initial simulation will give the base results for further studies.

Using the developed model, estimating the amount of RES installations needed to reach 2030 requires multiple simulations. During each simulation for RES installations, the model predicts excess energy, energy shortages, system SS, HR and SOC of different ESS. Using the model, we will estimate PV and wind installations for the operation condition with different systems SS and HR. Analysing different SS levels through the model helps to identify trade-offs between PV-wind installations and other sources. A system with 100 % SS must meet all electricity needs at any particular time, but this can result in excess electricity generation. By reducing SS, it is possible to decrease the amount of RES installation required and the amount of excess electricity generated. However, other sources should be used to compensate for this decreased capacity of PV-wind installations. Based on the current energy mix and future forecasts, biomass might be an attractive option. This is further discussed in *Section 4.1* (Fig. 5 shows the RES installation requirements for different SS). In 2030, the goal of Germany is to generate 80 % of its electricity from RES. In the simulation, we only consider PV, wind, and hydropower. Nevertheless, we can see from the electricity mix chart of Germany (Fig. 4) that it has other RES such as biomass and other RES contributions [47].

Currently, biomass generates around 10 % of the total electricity from RES in a day. The study by the International Renewable Energy Agency estimates that 90 % of total electricity generation in Germany for 2030 will be from PV, wind and hydro and the rest from biomass [48]. Considering the biomass contribution, PV and wind contribution are estimated to be 72 % (90 % of 80 %) of the total electricity mix in 2030. Along with this, the final 20 % of the electricity is assumed to be delivered from other non-RES. Based on the electricity mix profile of Germany, illustrated in Fig. 4 (note that the solar and wind resources change from day to day and with the season) we can observe that non-renewable electricity forms the base load. Base load represents the constant output from the source over the period. Even though the fact that gas power plants offer flexibility, in this study we treat all non-renewable sources as non-flexible to primarily study the influence and contribution of V2G on the grid. Hence, we assume that 20 % of electricity generated by non-RES sources is the base load.

After defining the base case, the simulation model is used for the analysis of social and technical variables. The parametric study includes i) an Analysis of V2G acceptance vs EV battery availability and ii) an Analysis of Charger power vs EV adoption level. Considering the top-down approach, where we analyse scenarios with different V2G acceptance rates from 100 % to 0 %, EV battery availability from 80 % to 20 %, charger power from slow AC charger (2.3 kW) to fast DC chargers (100 kW) and EV adoption level (from 1.8 million to 35 million EV in 2030) to get insights over various development stages. The variables in the study offer 6 different options to combine for the analysis. Here we present the results from the analysis of V2G acceptance vs EV battery availability and charger power vs EV adoption level. The appendix section presents additional results, which are i) analysis of V2G acceptance vs charger power, ii) analysis of V2G acceptance vs EV adoption level, iii) analysis of EV battery availability vs charger power and iv) analysis of EV battery availability vs EV adoption level. Finally, a sensitive analysis analyses how the change in assumed SS affects the results.

4. Simulation and results

Through a top-down analysis approach, the study progresses through 4 steps using the simulation model in a MATLAB/Simulink interface. Sections 4.1 to 4.4 provide the results and details of the simulation. In addition to this, from the simulation. In addition to this, Appendix Fig. 1 - Appendix Fig. 4 shows further results from the cross-analysis of all four variables.

4.1. Renewable energy installation analysis to satisfy the 2030 energy goals (base case study)

We estimate the requirements of the RES system to meet the 2030 goals by running multiple simulations. As mentioned in Section 3, it would be difficult to determine the required installation directly with a single simulation. Consequently, multiple simulations are done with the model for a different combination of RES. At the end of 2020, Germany had an installed PV capacity of 53.8 GW and 62.7 GW of wind energy, combining both onshore and offshore installations [49,50]. Using the present installation as a reference state, we can estimate the HR for different combinations of PV and wind installations. For SS between 90 % and 100 %, the initial simulation assumed a PV installation between 100 and 400 GW and the simulation model then determines the required wind installation to meet the electricity demands. Fig. 5 shows the results obtained from the simulations.

From Fig. 5 we can observe that to meet 100 % SS compared to an SS of 99 %, an additional 90 GW of wind energy installation is needed with 190 GW of PV installation. It is due that in winter, the specific hourly demand can be very high, compared to the average hourly demand. Installing more RES can satisfy the demand, but this higher installation generates more electricity in the summer time than the demand which increases the excess energy generation as shown in Fig. 5. By relaxing the SS target, the required RES installation and the resulting excess electricity are decreased. Due to the intermittent nature of wind and solar energy, there is a trade-off between increasing their installed capacity to reach SS goals and reducing excess electricity. Increasing other RES, such as biomass, reduces energy system intermittency, allowing to achieve higher SS without increasing excess energy. We explore this trade-off below and argue for a 99 % SS target as a reasonable mid-point in this trade-off.

For a 100 % SS system with 190 GW of PV, 255 GW of wind installations and 288 TWh excess energy generation, PV-Wind contribution is 72 % of the total electricity, while other RES, mainly biomass contributes 8 % and non-RES contributes the rest of the 20 %. Reducing the SS target to 99 % reduces the required wind installation to 170 GW with 190 GW PV, generation of 121 TWh excess energy. Reducing SS further to 95 % and 90 % reduces wind installations further down to 135 GW and 114 GW respectively with excess energy generation of 59 TWh and 30 TWh. However, decreasing installed wind and solar capacity needs to be compensated by increased use of other sources.

Here, we focus on biomass as a replacement energy source, which is planned to contribute 10 % of renewable electricity in 2030 in Germany [48]. For a 99 % SS target based on wind and solar energy, the electricity contribution from PV and wind reduces by 0.72 % and reduces the final contribution from 72 % to 71.28 %. Using bioenergy to cover this small fraction increases the bioenergy share from 8 % to 8.72 % in annual electricity generation, which requires an additional land area of 9 %. While for SS targets of 95 % and 90 %, the share from biomass increases from 8 % to 11.6 % and 15.2 %, respectively. Also, this demands an additional land area of 45 % and 90 % for 95 % SS and 90 % SS respectively from bioenergy which seems unreasonably high compared to the current plans. Considering the reduction of wind installation from 255 GW (100 % SS) to 170 GW (99 % SS), 135 GW (95 % SS) and 114 GW (90 % SS) against the increase of land area by 9 %, 45 % and 90 %, we argue that 99 % SS point is a good compromise between reducing the wind and solar capacity target and increasing land-use for biomass. To explore the impact of setting other SS targets, we perform sensitivity analysis is performed for different SS targets (Section 4.4). Appendix Table 1 shows the complete results of the simulation.

From the 99 % SS scenario, we choose 190 GW of PV installation and 170 GW of wind installation, which results in the least excess energy generation of 128 TWh. For the initial simulation, we assume the most favourable condition towards V2G technology with 100 % V2G acceptance, an 11-kW AC charger for 15 million EVs with 80 % EV battery availability [44]. The PHS capacity is kept constant throughout the studies at 5.35 GW and the maximum available energy through the HP system is 18.38 TWh. Table 1 shows simulation results with 190 GW of PV and 170 GW of wind installations.

The simulation results in Table 1 show that to meet 71.28 % of the total electricity demand from RES, we require the installation of 190 GW of solar and 170 GW of wind. Additionally, we can observe that HR and system SS are both 99 %. This is because the simulation focuses on satisfying 99 % of the requirements instead of 100 %, as explained earlier. The results also show excess energy generation of 121 TWh. This excess energy is considered a waste because the ESS is at its maximum storage capacity. This can be reduced by increasing the ESS capacity or by exporting the energy to neighbouring countries. Increasing the ESS capacity also helps to reduce the installation required. This is further discussed in sessions 4.3 and 5.

Table 1
Simulation results from 190 GW of PV and 170 GW of wind energy installations.

PV installation (GW)	Wind energy installation (GW)	Hourly reliability	System self-sufficiency	Excess energy (TWh)	Energy shortage (TWh)
190	170	98.87	99	121.2	3.7

4.2. Influence of V2G acceptance and EV battery availability on the grid

The potential of V2G technology highly depends on social factors, mostly on the user acceptance of the V2G technology. V2G acceptance refers to the willingness of EV users to participate in V2G services. According to previous studies [31,33–35], several hurdles need to be overcome in order for V2G to become more widely accepted. According to previous research, such as Esmaili et al. [32], and Noel et al. [35], range anxiety is one other main barrier to V2G. Essentially, range anxiety is the fear that a vehicle does not have enough energy (battery capacity) to travel the distance required to reach its destination, leaving its occupants stranded. This range anxiety arises because of not limiting the battery available for the V2G service. With this analysis, we combine and study the two variables V2G acceptance and EV battery availability to understand how they influence the hourly dependence and energy flow through EV and RES-supported grids.

In the study, we simulated different V2G acceptance rates, from 0 to 100 %, for different battery capacities reserved for V2G purposes. For the simulation, we assume a 190 GW PV installation and 170 GW wind energy installation with 15 million EVs connected to the grid through an 11-kW bi-directional charger. Fig. 6 shows the results of the simulation. To show the change in HR for different scenarios more clearly, we plot HR results from 65 % (on the Y axis).

From the results in Fig. 6a, we can observe that the HR on the RES-supported grid is declining as the V2G acceptance rate and EV battery

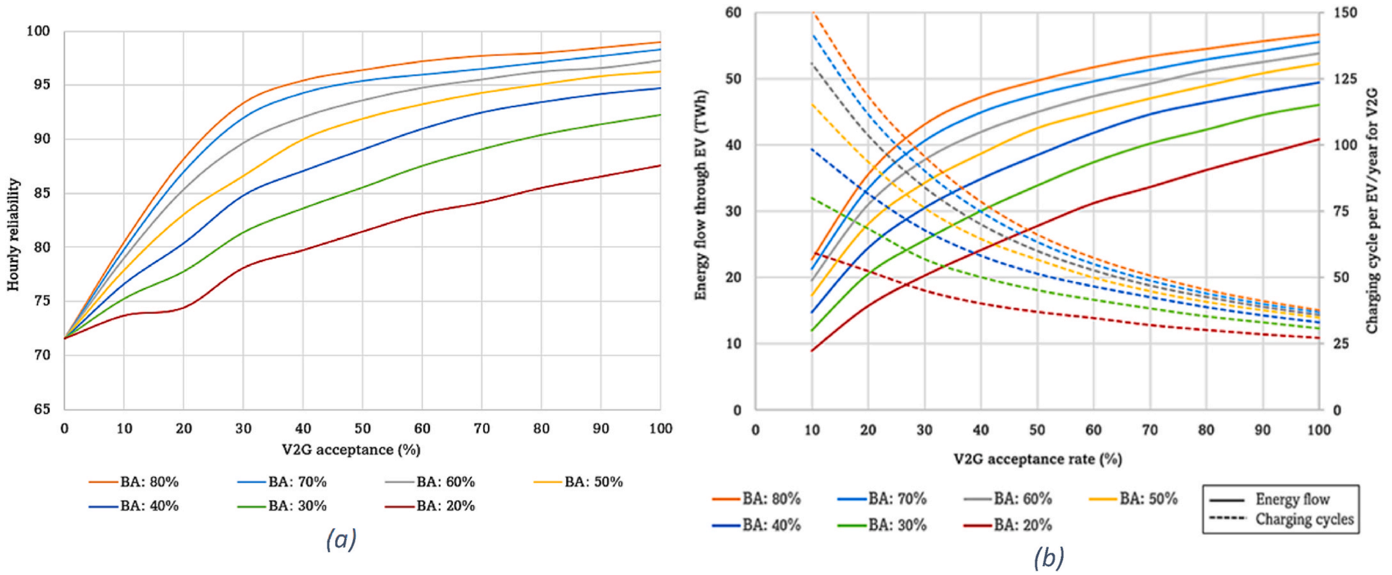


Fig. 6. Influence of V2G acceptance and EV battery availability on hourly reliability and EV energy flow.
Note: BA – EV battery availability; For 0 % V2G acceptance, the EV energy flow and charging cycle for V2G is 0.

availability drop. With a lower V2G acceptance rate, fewer EVs are connected to the grid for energy transfer. As a result of the reduction of EVs connected for V2G service, the total ESS capacity available through V2G is lowered. This will reduce the storage potential of energy. During periods with high-RES excess energy generation, total stored energy reduces and will decrease energy discharge during high-load periods. This reduces the SS and the HR of the system. While for the same V2G acceptance rate, a decrease in available battery capacity for V2G service also reduces the storage capacity through V2G service. Similar to the former scenarios, lowering EV EV battery availability will result in the reduction of SS and HR in the system. From Fig. 6a, it can be seen how the V2G acceptance rate and the EV battery availability finally affect the total energy storage potential through V2G.

Fig. 6b shows the change in energy flow through EVs and the number of charging dedicated for V2G purposes for different operational scenarios. From the results, we can observe that as V2G acceptance or EV EV battery availability reduces, the energy flow through EVs is also reduced. It is because of the reason mentioned before, the change in total energy storage capacity. This will then reduce the maximum possible storage/extraction, thus the energy flow. However, looking into the number of charging cycles each vehicle must go through, for different V2G acceptance rates and EV EV battery availability, we can observe that a low V2G acceptance rate puts more pressure on each vehicle. With 10 % V2G acceptance and 50 % EV EV battery availability, each EV has to go through 128 full charging cycles as compared to 76 and 58 charging cycles with 30 % and 50 % V2G acceptance.

From the results, we can observe that with 50 % V2G acceptance and 50 % EV battery availability, we lose approximately 7 % HR (to 91.9 %) as compared to the scenario with 100 % V2G acceptance and 80 % EV battery availability (from 99.02 %). The results also show a 30 % V2G acceptance rate with 50 % EV battery availability helps to achieve 86.6 % HR with 92.4 % system SS. Subsequently, the study indicates that V2G services using EV batteries can reduce RES intermittency issues, also if only less than half of the owners are willing to be part of the V2G service. Appendix Fig. 1 - Appendix Fig. 4 shows further results from the cross-analysis of the V2G acceptance rate and EV battery availability with

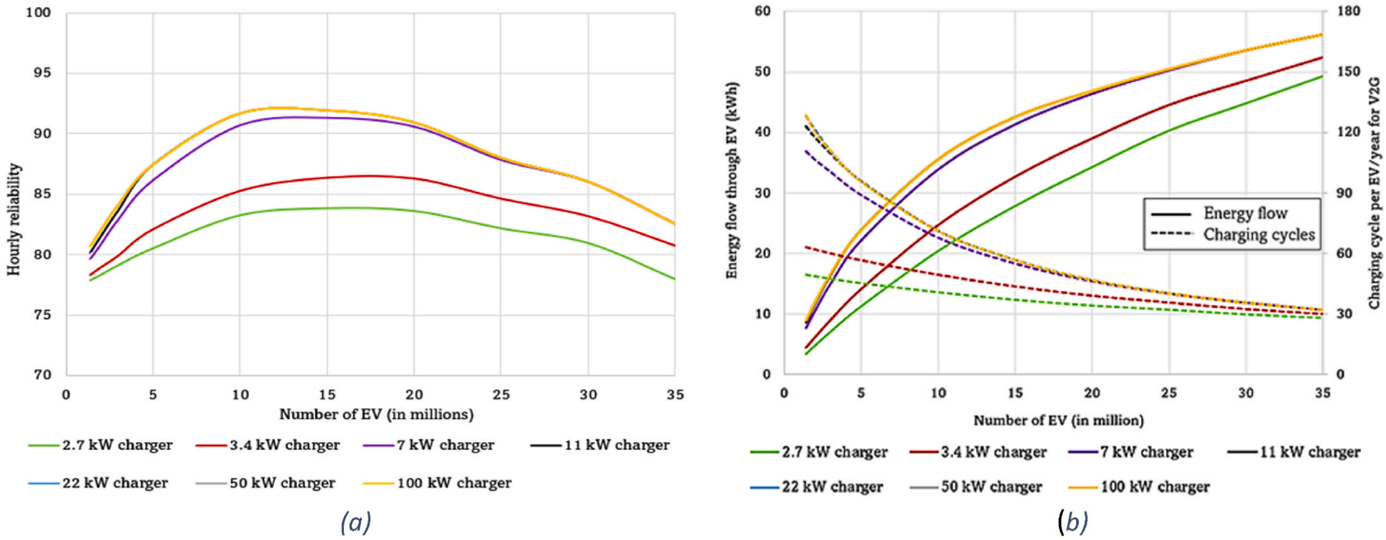


Fig. 7. Influence of V2G acceptance and EV battery availability on hourly reliability and EV energy flow.
(Note: The results from 11 kW, 22 kW, 50 kW and 100 kW chargers are the same and overlap each other).

other variables.

4.3. *Influence of charger power and EV adoption level on the grid*

As the transportation sector electrifies rapidly, more EVs are being sold each year. By 2030, Germany aims to have 15 million EVs on the roads. As the number of EVs increases, it can have a positive impact on the energy storage potential. However, the expectation for the number of EVs can change. Our study assumes 15 million EVs to analyse different scenarios. Along with this, the EV charger power has a significant impact on its energy transfer to the grid. High-power DC chargers can transfer up to 350 kW, while regular home or work AC chargers normally peak at 11 kW. However, charging especially high-power charging can reduce battery life due to the thermal stress induced inside the battery, which is one of the concerns with V2G technology. In this analysis, we investigate the energy storage impact of the V2G technology on changes in the EV adoption level and charger power. To examine the energy flow and HR in the study, simulations were performed with different charger powers and EV fleet volumes. The study analyses the V2G technology using EVs from 1.4 million (current EV German fleet) to 35 million EVs (230 % of projection in 2030) and charger powers from 2.3 kW up to 100 kW. In this simulation, we consider 50 % EV battery availability for the V2G service, 50 % V2G acceptance rates, 190 GW of PV and 170 GW of wind turbine installations. Fig. 7 shows the results of the simulations.

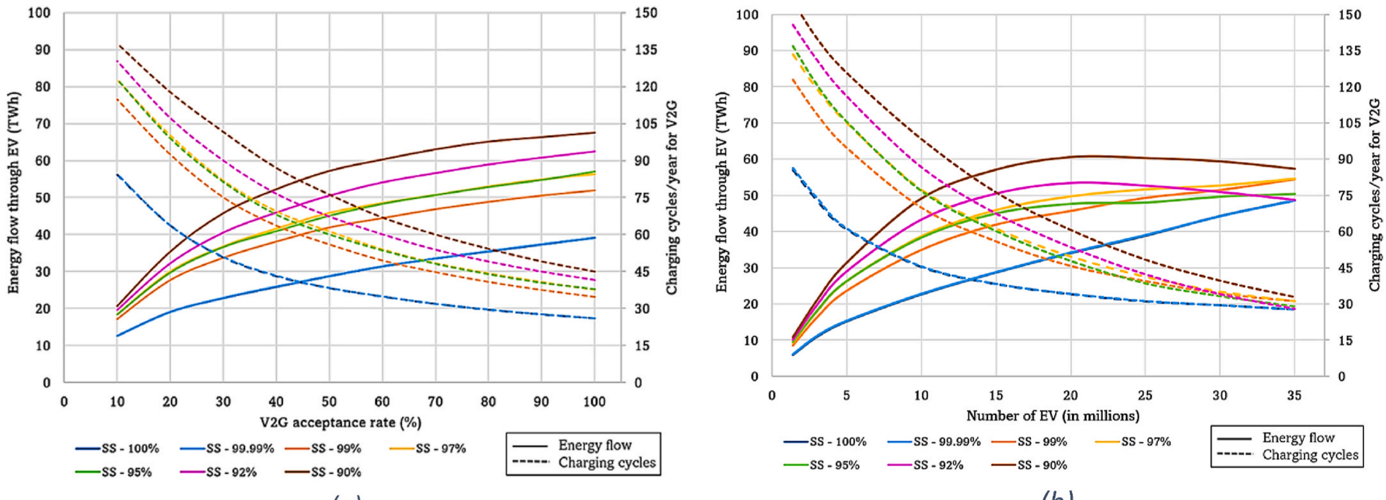
In Fig. 7a and b, we can observe that the HR varies based on the EV adoption level and charger power. The results show that charger power with a maximum charging rate higher than 11 kW does not further increase the V2G potential. In Fig. 7a, we can observe that the HR increases as the number of vehicles increases up to 10 million EVs and reduces for higher EV adoption. This is because as the number of EVs increases, the electric energy required for the transportation sector and thus the total electricity demand increases. At the same time, an increasing amount of EVs increase the capacity to store excess electricity, which otherwise would have been wasted. The increased storage improves the HR and SS, during high-load periods. However, when the EV adoption level increases beyond 10 million, the extra storage capacity cannot be optimally utilized, because the RES output is constant. An EV fleet of more than 10 million leads to higher energy demand, reducing the HR and SS.

Fig. 7b shows the energy flow through the EVs and the estimated charging cycles from each EV. From the results, we can observe that as the EV adoption level increases, the energy flow through the EVs is also increasing. More EVs offer more space for excess energy storage and increased usage of stored EV battery energy, during low RES-energy generation periods. Considering the results in Fig. 7b with a charger power of 11 kWh, we can observe that when increasing the EVs from 1.4 million to 15 million, the EV energy flow increases from 8.8 TWh to 43.6 TWh, which is about 5 times. While increasing EVs from 15 to 35 million EVs, the increased energy flow is only 11 TWh, up to 55 TWh. This reduced increase in energy flow reflects the reduction of HR. Also from Fig. 7b, we can observe that as the number of EVs increases, the number of charging cycles each vehicle has to go through is reduced. It is because as a greater number of EVs are available for V2G service, the energy flow is distributed between more vehicles. This reduces the number of charging cycles each vehicle must go through in a year.

While examining the influence of charger power, from the results in Fig. 7a and b, we can observe that increasing the bidirectional AC-charger power from 2.7 kW to 11 kW helps to improve the HR of the system, along with the EV energy flow. As the charger power increases, the ability of EVs to push energy to the grid increases. Assuming that the grid has a specific energy requirement (e.g., 1 MWh), the maximum energy contribution from each EV is limited by the ratio of total energy required to the total number of EVs participating in V2G. For instance, with 100 EVs participating in V2G, each EV would need to deliver an energy amount of 10 kWh. Chargers with lower power can only discharge up to their respective maximum power output (e.g., a 2.3 kW and 7 kW charger can only discharge at 2.3 kW and 7 kW, respectively), whereas chargers with higher capacities, such as 11 kW, 22 kW, or 50 kW, will only discharge the required 10 kW from each EV. In addition to this, the charger power also restricts the maximum energy flow from the grid to the battery which limits the total energy stored in the battery. Considering 1-year simulation, the results suggest that there is no need to have any DC high-power bidirectional charger, as there is no improvement in HR. Even the results for 7-kW chargers are almost on par with the 11-kW case. Consequently, a 7–11 kW charger would be sufficient to deliver the required energy back to the grid during the energy shortage period, for the considered scenario. This also implies that high-power DC chargers are not required to perform V2G services. Appendix Fig. 1 - Appendix Fig. 4 shows further results from the cross-analysis of the V2G acceptance rate and EV battery availability with other variables.

4.4. *Sensitivity analysis on self-sufficiency vs V2G acceptance and EV adoption level*

For the former analysis, we have assume that the SS of the system is 99 %. Replacing fossil sources with RE sources to generate 80 % of electricity in 2030, 72 % of total electricity generation is expected to



(a)

(b)

Fig. 8. Sensitivity Analysis on Self-sufficiency vs V2G Acceptance and EV adoption level.

deliver by PV and wind [48]. With 99 % SS, the total generation would be 71.3 % instead of 72 % and the reduction is covered by other RE sources such as biomass to meet 80 % SS. However, in this section, we analyse the impact of SS on the system.

For SS ranging between 100 % and 90 %, the corresponding RE installation changes, as shown in Fig. 5. The RE combination with the least excess electricity generation points is chosen for further study. Considering EV battery availability of 50 % for V2G service and 11 kWh charger power, the study examines the change in HR for different V2G acceptance rates and EV adoption levels. Fig. 8 shows the result of the simulation.

As we can see from the results, the SS of the system has a noticeable impact on the simulation results. As SS decreases from 100 % to 99 % for 50 % V2G acceptance, EV energy flow and charging cycles increase by 40 % (Fig. 8a). This is because lowering SS reduces the installation of RE. A reduction in RE installation reduces electricity generation over hourly demand. At the 100 % SS point, the additional RE installation supplies more electricity, while the ESS contributes a small proportion to reach 100 % HR. While at 99 % SS, the EVs provide more electricity via V2G, to meet the hourly electricity requirements. Because EVs contribute comparably little in the 100 % case, only a small portion of additional electricity gets stored, and the rest goes unused (excess energy generation). With 100 % SS, RE sources generate 252 TWh of excess electricity, while 99 % SS generates less than half of that,121 TWh. The sensitivity analysis on EV adoption level also shows a similar behaviour, where reducing the SS increases the electricity flow through EVs and charging cycles/EVs for a year (Fig. 8b).

5. Discussion

This research article presents a conceptual study which analyses the social and technical parameters of V2G technology. The study focuses on analysing the influence of variables such as V2G acceptance, EV battery availability, charger power and EV adoption level on V2G service and energy flow. Giving more attention to V2G services, the results from this study help to further understand V2G and its importance in large-scale RES integrated grid systems. The case study is based on Germany and the analysis is done to meet 2030 energy goals, to generate 80 % of the electricity from RES.

The results from the study are presented in three sections. In section one, we focused on the base case, which helped to identify the RES system required to meet the goals with best-case scenarios. Assuming the most favourable scenario for the base case with 100 % V2G acceptance rate, 11 kWh bi-directional chargers, 15 million EVs and 80 % EV battery availability for the V2G service. But this is practically impossible as V2G acceptance and EV battery availability for V2G service highly depend on EV owners and their approach towards the technology [31, 35,51,52]. To what extent EV drivers will participate in V2G in the future is highly uncertain. Next to consumer behaviour, EV policies and technological developments will influence further other relevant factors such as EV diffusion and charger power. The result of this study presents how these variables and their uncertainty influence the HR and SS of the grid and the energy flow between the grid and the EVs. A very important parameter that determines the EV user participation level is the economic incentive the car owner gets. This must be investigated using a questionnaire and will be performed in the coming research.

The initial results show that with favourable conditions, we can achieve the 2030 goals with 190 GW of PV and 170 GW of wind turbines, coupled with V2G for energy storage in EVs. This is approximately 3.7 times PV and 2.7 times wind turbines as compared to 2020 installations. These proposed installations for PV are less than Germany's PV estimation in 2030 by 40 GW, while wind turbines are lacking by 25 GW [53]. Considering the 2030 goal of Germany to have 230 GW of PV and 115 GW of wind, the simulation shows that Germany can reach SS between 92 % and 95 % (Fig. 5). With 230 GW of PV and 115 GW of wind installation, the total RE share in the 2030 electricity mix would be 75 %, including the 10 % contribution from biomass. However, it can be different in the real world, as Germany plans to diversify and improve its energy storage capacity to support the announced RES installation. While the simulation only considers the existing PHS system with EV. From the sensitivity analysis, we find that the trend followed is the same for different SS points. With 100 % or 90 % SS, the trend characteristics would be the same as those of 99 %, which is considered for variable analysis. However, between 100 % SS and 99 % SS, there is a 40%–50 % difference in energy flow, whereas from 99 % SS to 95 % the difference is 10 %. This is because high RE installations reduce EV energy contribution during higher SS points. Nevertheless, the projected 230 GW installation of PV in 2030 in addition to other supplementary RES would be sufficient to deliver the electricity. Having more RE installations improves the system's SS but also increases the excess energy generation and severely increases the use of material resources. In reality, the excess energy/electricity could be used for cross-border energy trading or in other innovative technologies such as hydrogen production.

In section two of the results, we present the impact of V2G acceptance and EV battery availability on V2G energy flow and grid HR. The results in Section 4.2 show that a reduction in V2G acceptance and EV battery availability has a negative influence on the grid. The HR decreases when one of the two variables declines. Despite this, the results show that even with only 30 % of V2G acceptance, 15 million EV providers and 50 % battery dedicated to V2G service, the EVs can provide an energy flow of 34.3 TWh. To be compared to only 0.31 TWh from 5.35 GW of PHS, which currently is present in Germany. Another important benefit of balancing intermittent energy using EVs and V2G is that the service is assumed to be homogeneously spread over the entire country.

While with 50 % V2G acceptance and 50 % EV battery availability, the model shows an HR of 91.9 % with an EV energy flow of 42.6 TWh. These results reflect that V2G can offer significant storage for grid balancing purposes, even without full V2G participation and EV battery availability. Dedicating 50 % of the battery, the users of modern EVs still have at least 150 km of range. In this scenario, EV users must go through the equivalent of 58 full charging cycles annually for the V2G service. If an EV covers 49 km/day at 200 Wh/km, the annual energy consumption is 3577 kWh, which corresponds to 45 charging cycles. With Germany's average vehicle lifespan of 10 years [54], the total charge and discharge cycles combining V2G service and driving would be 1030 cycles. With a total battery life of 3000 charging cycles, 1030 cycles are less than 40 % of its lifetime [55]. As EV batteries have a warranty of 8–10 years and a lifespan of 10 years, the above estimation indicates that V2G will not reduce EV battery life to less than ten years. This implies that an EV user will never have to replace its battery during the entire EV life cycle because of V2G participation. Nevertheless, monetary compensation is likely necessary to achieve high V2G participation from EV users. From the sensitivity analysis, for 100 % SS points, more RES installation puts less stress on EV energy flow and reduces the charging cycles to 29 cycles per year instead of 58 cycles with 99 % SS. This reduces the total charging cycles over the life from 1030 to 740 cycles. While reducing SS shows an inverse effect, where reducing to 95 % and 90 % SS points increases the charging cycles to 64 and 80 cycles.

In section three of the results, we present the impact of EV chargers and the EV adoption level in the fleet on V2G energy flow and grid HR. This study focuses on co-relating charging power with battery life. Considering battery chemical topology, charging batteries at high C-rates can reduce their life, due to higher induced battery stress with more chemical and thermal reactions. From the results in Section 4.3, we can observe that fast DC chargers are not required for V2G purposes. The results show that an 11 kW AC charger gives the same HR, energy flow through EV and the number of charging cycles as a 100 kW DC charger. Using an 11-kW charger for a 50-kWh battery pack, the charging occurs at less than 0.5 C. This suggests that an 11-kW charger would be enough to provide the V2G service, without compromising the battery life. Studies show that slow charging with 0.5 C, actually can have a positive influence on battery life [56]. This certainly provides positive confidence for EV users to actively participate in V2G service. For 100 % SS, the EV energy flow decreases compared to other SS points along with the number of charging cycles. This is because at 100 % SS, high RE installation supplies more electricity while the EV contributes a small proportion each hour. Smaller contributions from EV batteries leave space for smaller energy storage during high electricity generation periods, which leads to lower electricity flow between EVs and the grid. With reduced SS EVs provide more electricity via V2G, leaving space for more energy to be stored. This increases the electricity flow and the charging cycles at lower SS points.

While comparison with different EV adoption levels shows that more EVs will not necessarily be an advantage for the V2G purpose and not to the electricity grid. More EVs demand more electric energy, which reduces HR. Even though the system SS goes down, however, having more EVs can reduce the need for fossil-fuel vehicles and thus gasoline use and associated greenhouse gas emissions. Having more EVs instead of gasoline vehicles has environmental and social benefits, which are not considered in this study. Even though this conceptual case study is performed based on German data, the V2G technology could be a good solution for many countries around the world. The required RES installation and thus the potential contribution of V2G to grid balancing changes based on geographical location and RES generation potential. V2G could make a significant contribution in any country with large EV fleets and high RES installed capacity. Nevertheless, the outcome cannot just be extrapolated for certain countries with different geographies and climates. For example, in countries with a cold climate, the EV range and capacity drastically reduce by 25%–40 % during winter times [57]. This will reduce the HR and system SS of the grid. Such operational conditions need to be assessed separately.

5.1. Model limitations

Comparing the model from the study with the real world, our model assumes a centralised V2G system that controls the energy transfers. In the real world, a centralised system has not yet been implemented. Instead, uncontrolled EV charging is still in practice. Uncontrolled energy transfer can result in voltage and frequency fluctuation in the grid which can further lead to breakouts on a large scale [58,59]. Through a centralised control system, it would be possible to assess the SOC of EV batteries and perform energy transfer simultaneously. We can also avoid vehicles with SOC less than minimum SOC during energy extraction and vehicles with SOC higher than maximum SOC during the charging process. Even though at the current stage this can be considered a model limitation, a centralised control system for EVs is essential in the future. Further, the model has a few more simplifying assumptions.

1. Choosing V2G as the primary ESS
2. Having the same EV moving distribution throughout the year
3. Considering the SOC of EVs together as a big battery pack
4. Whenever an EV is parked, it is connected to a bidirectional charger
5. Considering Germany as an Island grid

In our study, the EVs act as the primary ESS whereas in real life other storage options, e.g., PHES, may be more economical in certain instances. Our model does not take that into account but rather shows the maximum potential of V2G technology. If the model would simulate each individual EV and battery pack, the simulation would become computationally too demanding. To overcome this, future work will address these assumptions with further micro-modelling and clustering which consider vehicles with multiple user profiles and charging patterns. Through clustering, we can consider different vehicle clusters based on SOC and moving patterns, as in the study by Sagaria et al. [43]. Considering the assumption that EVs are always connected to a bidirectional charger, whenever parked, the model assumes a 1:1 charger to EVs ratio. This assumption is very optimistic with current developments. However, sustainable development in the transportation sector shows exponential growth in charging stations and with proper infrastructure planning could pave the way for more efficient and scalable charging solutions. Furthermore, advancements in the field of wireless charging are expected to simplify the challenges associated with connectivity. This study also explores the impact of low charger-to-EV ratios by modelling different vehicle-to-grid (V2G) acceptance rates, which can be interpreted as reflecting varying availability rates of bidirectional chargers in-directly. This analysis helps in understanding the practical implications of V2G systems under different infrastructure scenarios, enhancing the model's relevance and applicability in real-world settings. Finally, the study considers Germany as an Island grid. Being a net positive energy exporter of electricity in 2020 and 2021 [60], the generated excess energy can be used for energy exchange between other countries. The influence of energy import and export also helps to reduce RE installations.

Furthermore, the current model does not consider the degradation of batteries participating in V2G and its economic implications. Participating in V2G increases the number of cycles EV goes through a year by a factor of 2 or 3, which reduces the battery life. A study by Thingvad et al. [61] shows a battery degradation of 10 % and 17.8 % for a period of 2 years and 5 years with a 23 kWh battery delivering primary frequency regulation for 15 h per day with a daily energy throughput of 50.6 kWh respectively. Analysing different battery charging strategies for EVs by Bui et al. [62], the study reports a battery degradation of 0.0165 % with V2G against 0.0140 % for a week of EV usage. The additional degradation of 0.0025 %/week of capacity fade is experienced by the battery due to V2G technology, which is 17 % higher than normal battery degradation. These study shows that V2G surely increase the battery degradation process, which adversely affects the V2G acceptance rate. However, offering compensation may help to offset this negative effect of V2G service. In future studies, the authors aim to overcome the simplistic assumptions and limitations, which are further discussed in section 5.2.

5.2. Future studies

Through future studies, the authors intend to address and discuss the limitations of the current model and improve the model with suitable measures. We aim to refine the results from the model by concentrating on EV clusters with similar usage profiles and charging behaviours through micro-modelling and clustering techniques instead of the whole EV fleet. Specifically, clustering based on average vehicle movement patterns for regular weekdays, weekends, and seasonal variations will enable detailed examining different EV movement distributions that impact the V2G energy flow throughout the year. Future work will also focus to over the assumption of Germany as an isolated grid. Future work will include the possibilities of energy import and export during energy excess and shortage points to limit renewable energy installations. Furthermore, we intend to include flexibilities to energy sources and energy pricing for energy generation options. Considering that all nations pursue cheaper energy, the price of electricity from different sources in the electricity market plays a pivotal role in the acceptance of V2G technology. On top of that, future studies will explore the role of V2G in supporting the grid with lower geographical resolution, representing multiple states and zones in a country. Each node/state includes energy generation and consumption units and the simulation will show the energy flow between the EV and grid at a microscopic level (within the zones and states) and a macroscopic level (between zones and states). Finally, the authors aim to develop a battery degradation model to examine the degradation in EVs caused by V2G at a national and individual level. The estimation of battery degradation helps to determine the loss of opportunity for EV owners in terms of range which leads to the estimation of V2G compensation cost for EV owners.

6. Conclusion

This study examines the social and technical variables that influence the adoption of V2G technology in a RES-supported grid system. The model developed simulates annual energy demand and supply scenarios with the 1-h resolution, considering PV, wind, and hydropower as RES, and EV and PHS as ESS. This study comprehensively examines the influence of V2G acceptance rate, EV EV battery availability, EV charger power and EV volume in a grid supported by V2G technology and RES.

The primary simulations predict that in Germany, by 2030, 71 % of electricity could be generated by PV and wind, with 190 GW of PV and 170 GW of wind turbine installations combined with V2G for storage purposes, providing 99 % self-sufficiency (SS). For a 100 % SS, an additional 90 GW of wind power is required compared to 99 % SS to meet the peak demand points. Simulation results also show that low V2G acceptance and EV battery availability have positive outcomes. With a 30 % V2G acceptance and dedicating half of the EV battery capacity to V2G, the hourly reliability (HR) can reach 86.6 %, significantly higher than the 72 % achieved with zero V2G acceptance and no dedicated EV battery capacity for V2G. Increasing V2G acceptance to 50 % enhances the HR further by 5.3 %–91.9 %. Analysis of the required charger power and the level of EV adoption suggests that an AC charger capacity of 7 kW or 11 kW is sufficient to support V2G services and high-power bidirectionalDC chargers are not essential. The results for 2030 indicate that 15 million EVs could provide substantial energy storage opportunities, facilitating higher penetration of RES without the need for additional ESS.

The results indicate that with 10 million EVs, over 90 % HR is achievable with 50 % V2G acceptance and dedicating 50 % of the EV battery capacity for V2G, using a 7-kW charger. This scenario demonstrates that not all EV owners need to engage in V2G services to significantly balance intermittent energy generation and distribution in the grid. Allocating 50 % of the battery for V2G would also create 250 GWh of energy storage capacity. In conclusion, this paper endorses V2G technology as a viable ESS for future large-scale renewable electricity systems, suggesting that V2G can conserve financial and material resources for other sustainable development initiatives in society.

CRediT authorship contribution statement

Shemin Sagaria: Conceptualization, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. **Mart van der Kam:** Conceptualization, Methodology, Supervision, Visualization, Writing – review & editing. **Tobias Boström:** Conceptualization, Methodology, Supervision, Visualization, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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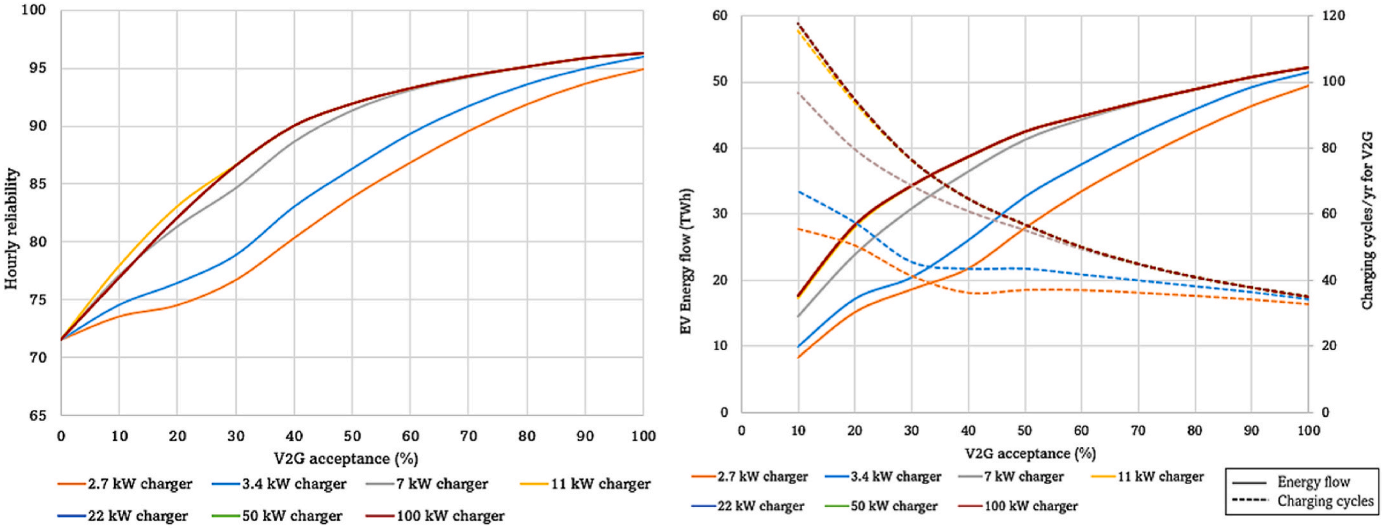
APPENDIX

Appendix 1 (A1): Simulation results from PV analysis.

Appendix Table 1
Simulation results from PV analysis

Self-sufficiency: 100 %			Self-sufficiency: 99 %			Self-sufficiency: 97 %			Self-sufficiency: 95 %			Self-sufficiency: 92 %			Self-sufficiency: 90 %		
PV (GW)	Wind (GW)	Excess energy (TWh)	PV (GW)	Wind (GW)	Excess energy (TWh)	PV (GW)	Wind (GW)	Excess energy (TWh)	PV (GW)	Wind (GW)	Excess energy (TWh)	PV (GW)	Wind (GW)	Excess energy (TWh)	PV (GW)	Wind (GW)	Excess energy (TWh)
100	266.3	232.8	100	251.3	204.3	100	229.0	162.8	100	210.5	130.2	100	191.4	99.0	100	179.1	80.1
115	262.0	236.2	115	233.5	181.1	115	211.7	140.8	115	196.7	115.0	115	177.7	84.7	115	166.4	67.5
130	256.5	237.3	130	218.5	163.9	130	195.1	120.6	130	181.9	98.8	130	164.9	72.2	130	153.9	55.3
145	252.1	241.4	145	203.2	145.7	145	180.9	105.7	145	169.0	86.0	145	151.9	59.7	145	142.7	45.9
160	248.2	246.7	160	189.6	132.5	160	169.2	95.6	160	155.5	72.6	160	140.0	49.4	160	132.0	38.1
175	244.7	253.1	175	179.5	125.9	175	158.2	87.0	175	144.5	64.2	175	130.0	42.7	175	123.3	33.6
190	241.7	260.6	190	170.3	121.2	190	149.8	83.9	190	134.9	59.1	190	122.1	39.8	190	114.1	29.1
205	239.0	268.6	205	163.8	121.7	205	143.0	83.8	205	129.4	61.4	205	115.3	40.1	205	108.1	30.7
220	236.6	277.2	220	158.1	123.7	220	137.2	85.9	220	124.4	64.3	220	110.2	43.2	220	103.2	34.5
235	234.1	285.8	235	154.1	129.2	235	133.1	91.4	235	120.3	69.6	235	106.1	48.2	235	99.6	40.4
250	231.6	294.5	250	149.4	133.3	250	129.7	98.3	250	116.6	76.3	250	101.8	53.9	250	95.3	45.7
265	229.6	304.2	265	145.4	139.1	265	127.3	107.0	265	113.7	84.1	265	99.3	62.6	265	92.7	54.1
280	227.8	314.5	280	142.3	146.7	280	124.7	115.4	280	111.3	92.8	280	96.9	71.5	280	90.4	63.1
295	226.1	321.9	295	139.4	154.7	295	122.3	124.4	295	108.7	101.5	295	94.5	80.2	295	87.7	71.9
310	220.3	329.1	310	136.8	163.1	310	120.5	134.4	310	107.0	111.6	310	92.0	89.0	310	85.9	81.6
325	215.6	331.3	325	134.5	172.5	325	118.2	143.5	325	104.9	121.0	325	89.9	98.7	325	83.6	90.8
340	212.5	338.6	340	131.5	180.3	340	116.3	153.4	340	102.8	130.7	340	88.1	108.7	340	81.5	100.3
355	210.4	348.2	355	129.2	189.1	355	113.6	161.9	355	100.8	140.2	355	86.4	119.0	355	79.7	110.4
370	206.5	354.1	370	127.3	199.1	370	111.0	170.5	370	98.4	149.2	370	84.4	128.5	370	77.7	120.1
385	203.6	362.1	385	124.8	208.1	385	109.5	181.0	385	96.3	158.6	385	82.3	138.0	385	75.8	129.9
400	199.6	367.8	400	123.1	218.5	400	107.7	191.0	400	93.9	167.8	400	80.3	147.6	400	74.0	139.9

Appendix 2. (A2): Simulation results of V2G acceptance vs Charger power

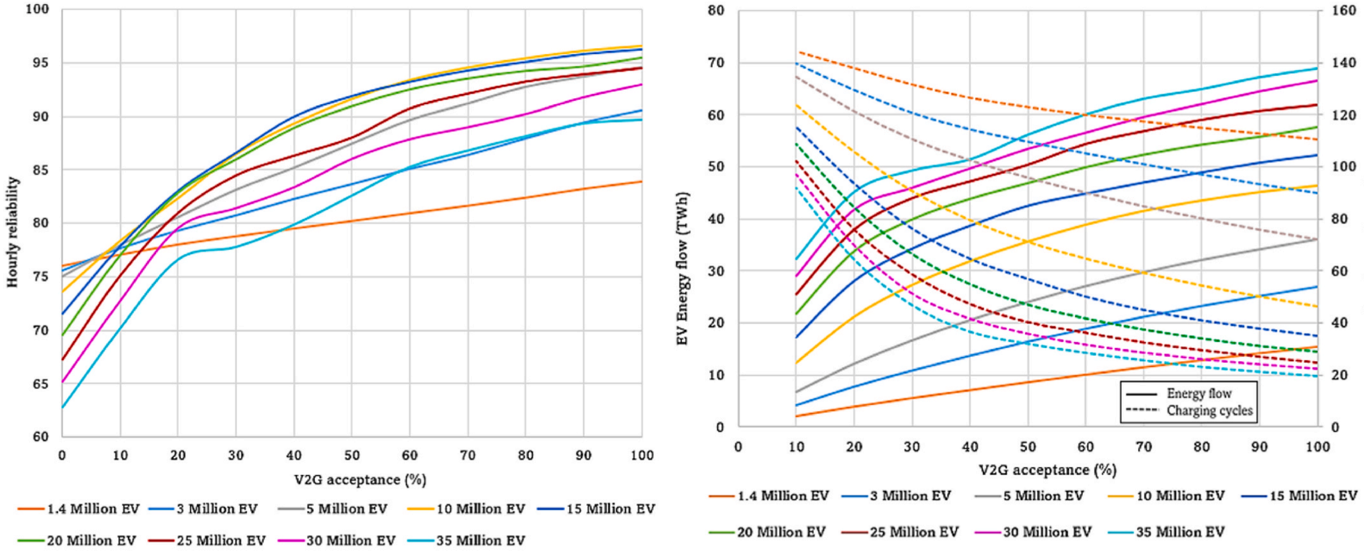


(a)

(b)

Appendix Fig. 1. Simulation results of V2G acceptance vs Charger power.

Appendix 3. (A3): Simulation results of V2G acceptance vs. EV penetration Level

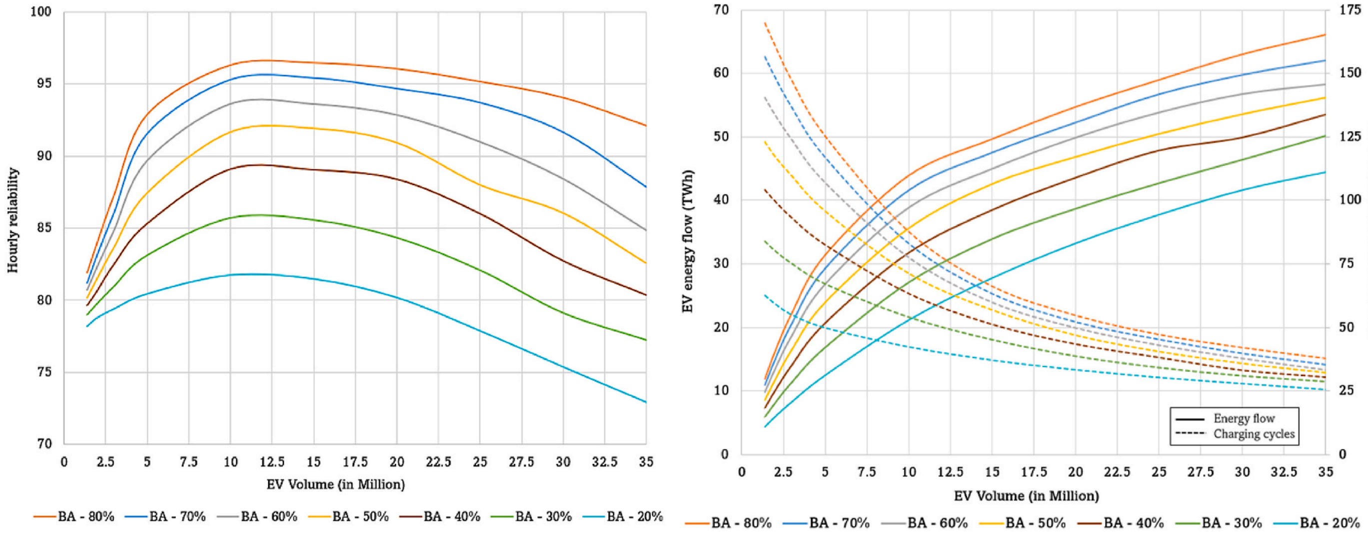


(a)

(b)

Appendix Fig. 2. Simulation results of V2G acceptance vs. EV penetration Level

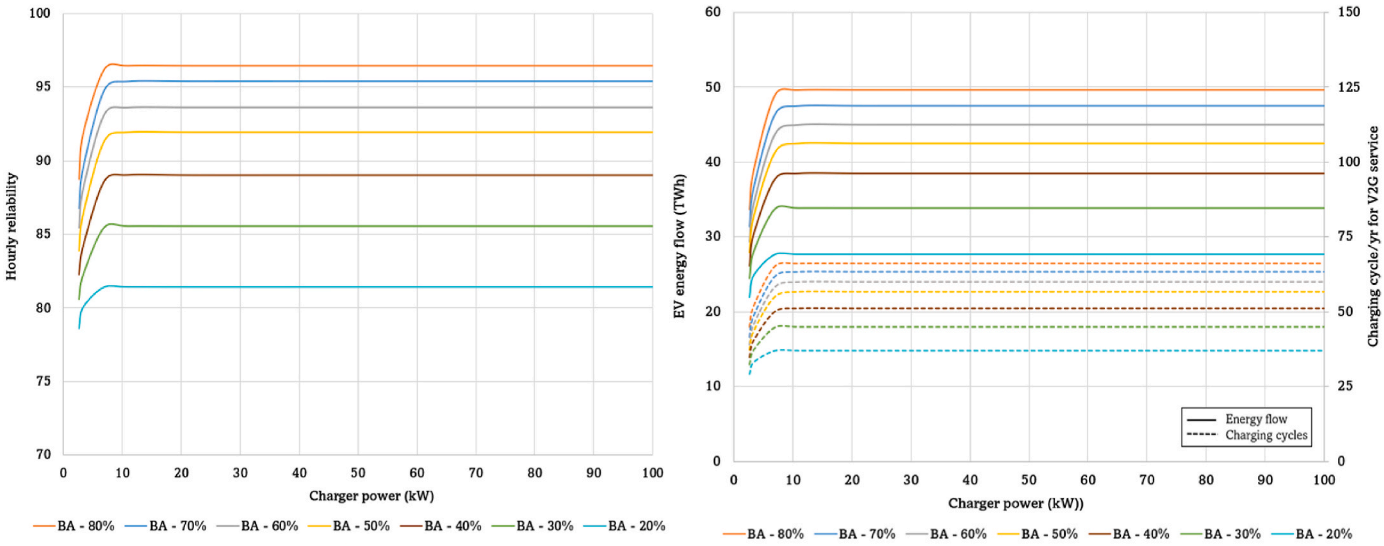
Appendix 4. (A4): Simulation result of EV battery availability vs EV penetration level



(a) (b)

Appendix Fig. 3. Simulation result of EV battery availability vs EV penetration level.

Appendix 5. (A5): Simulation results of EV battery availability vs Charger power



(a) (b)

Appendix Fig. 4. Simulation results of EV battery availability vs Charger power.

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