Vehicle to Grid assisted 100% renewable energy supported electric grid system in Japan.

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ABSTRACT:

Japan emits 1.08 billion Metric Tons of greenhouse gases (GHG) every year, which ranks fifth in the world, with higher emissions per capita than China and India. Through various initiatives, Japan aims to reduce emissions by 46% by 2030 and achieve carbon neutrality by 2050. The phasing out of coal and the production of 100% carbon-free electricity are two of these milestones. This study examines the use of renewable energy (RE) to support 100% of electricity generation in Japan, with EVs as the primary energy storage system. The purpose of this conceptual study is to highlight the significance of vehicle-to-grid (V2G) technology for a nationwide electricity grid system that is supported by RE. We conduct this study in two phases.

Phase 1 of the study estimates the amount of RE installation required to meet 100% of electricity generation from RE sources. Considering 17 million EVs with 65 kWh batteries, 100% V2G acceptance, 80% battery availability, and 22 GW of PHS, the model estimates that 454.8 GW of solar PV and 199.3 GW of wind turbines are necessary to meet electricity demands. Exploring V2G in-depth, phase 2 examines the influence of V2G acceptance and battery availability on energy flow. The results show that the system's self-sufficiency reduces when V2G acceptance and battery availability decrease. The hourly reliability of the system drops from 99% to 80%, and the self-sufficiency of the system falls from 99% to 90% when V2G acceptance is reduced to 50% and battery availability to 40%. With 0% V2G acceptance (scenario when the whole vehicle fleet is electrified, but not used for storage), the system's hourly reliability is 66% and self-sufficiency is 80%. Furthermore, the results indicate that at low V2G acceptance rates, the EVs must go through more charging cycles, while at high V2G acceptance rates, they must go through fewer cycles. The study's overall results indicate that V2G technology will be an effective storage solution for Japan in the future.

KEYWORDS: vehicle-to-grid(V2G), V2G acceptance, battery-to-grid, 100% renewable energy system

1. INTRODUCTION

The Paris Agreement in 2015 is the initial stepping stone towards the 2050 carbon neutrality goals for different countries [1][2]. In 2050, the USA and European Union countries aim to reduce gas emissions and reach carbon neutrality by increasing the renewable energy share and improving energy efficiency [3][4][5]. The continent Asia emits around 50% of global emissions (around 17.7 billion metric tons (BMT)), despite the fact that the continent produces around 80% of the PV and wind turbine parts [6]. Out of this, China release around 60% (10.7 BMT) of emissions, followed by India (2.4 BMT), Russia (1.7 BMT) and Japan (1.08 BMT) [6][7]. In this case study, we focus on Japan because of its high emission of 1.08 BMT of GHG against a population of 125 million people, with 8.64 Ton GHG emission for each person, which is higher compared to China, India, and Russia.

To reach energy goals, countries around the globe are investing money and time into renewable energy sources (RES). RES is considered the driving force for sustainable development in the energy sector [8]. The limitless availability of RES with very less emissions over the lifetime will be enough to meet global energy needs [9]. This potential encourages the exponential growth of RES such as PV and wind installations. In 2012, the total PV installation around the world was 100 GW and it has grown 12-fold by 2022 (1185 GW) [10]. While for wind turbine installations, a growth of 4 times is observed between 2021 with a total installation of 812 GW and 2011 with 220 GW [11].

In 2021, the RES generated around 22.4% of the total electricity generation in Japan [12]. Solar PV contribution is 9.3%, biomass contribution is 4.1%, hydropower contribution is 7.8%, and wind contribution is 0.87%. Even though the total energy generation from RES increased by 12% more than that of 2014, it is lower as compared to the average RES generation around the world [13]. In 2030, Japan aims to reduce its emission by 46% and reach carbon neutrality by 2050 [14]. The studies presented within METI's comprehensive resources and environment study group Basic Policy Committee have shown that it is feasible for Japan to achieve 100% RES-supported electricity generation [15].

The Research Institute of Innovation and Technology for the Earth (RITE) presented that it is possible to fulfil Japan's 1100 TWh electricity requirement in 2050 through 100% RES, 3980 GWh battery and 570 GW system enhancement technologies [15][16]. The results from Renewable Energy Institute (REI) in Japan showed that in 2050, Japan's electricity demand would be 1470 TWh and can be supplied with 100% RES, with 524 GW solar and 158 GW wind installations including onshore and offshore; with energy storage systems (ESS) [15][16]. While results from Deloitte show a similar electricity demand of 1450 TWh and show that this requirement can be met with 95% RES and 5% non-fossil energy sources (including nuclear fuel) with carbon capture systems. They also consider energy storage systems to improve system reliability [15][16]. Both REI and Deloitte considered vehicle-to-grid (V2G) technology as an energy storage option [15] [16]. Even though more RES increases energy generation, the intermittent nature of RES disrupts the continuous and constant energy supply. A possible solution to energy balancing issues resulting from this intermittent nature are energy storage systems (ESS)[17]. Furubayashi [18] [19] analyses the potential 100% RES-supported Akita prefecture in Japan. The result details that with 3 times more wind energy potential than demand, batteries are required to store excess energy generation during peak times to avoid curtailment. This research strongly indicates that ESS are essential to develop RES-based electricity systems to replace fossil-powered electricity production.

In addition to the mentioned studies focusing on Japan, several studies focus on the development of an electricity grid with 100% RES, supported by ESS around the world. Hrnčić et al [20] investigate the possibility of having 100% energy from RES in Montenegro. Using the ENERGYPLAN software, the results from their study show that with ESS, it is possible to support the load demand with 100% RES. Tetteh et al [21] identify different cost-effective thermal energy storage options to support RES. Their article provides valuable insights on using sand as an effective storage medium, and the results show it will reduce the cost of the system by six times compared to other considered technologies. The study by Al-Ghussain et al [22] implies that it is possible to have 100% RES-supported micro-grids with ESS. Focusing on the Cyprus university campus, the results demonstrate 99% self-sufficiency from the hybrid system. Despite the positive results from the development in the real world is slow. Currently, Japan has only 4 ESS plants with a storage capacity of above 30 MW. To support energy storage in Terra watt hours (TWh), a huge amount of investment is required. At the same time, the national investments in green transition (replacing fossil cars with EVs, gasoline stations with EV charging stations, upgrading the grid to facilitate uncontrolled EV charging process) provide a great opportunity to develop a virtual ESS, with huge energy storage potential through V2G technology.

In our study, we focus primarily on V2G, which stores energy in EV batteries, unlike the other studies based in Japan [15][16] [18] [19]. It is because compared to other ESS including stationary battery and run-off hydro storage systems, V2G technology requires relatively low investment costs assuming the electrification of the transportation sector progresses as planned. The only additional investments are in bi-directional chargers instead of uni-directional chargers and in V2G software and platforms. Various studies consider V2G technology to support 100% RES. The study on V2G transfer and applications by Lakshmi et al [23] points out various applications, such as vehicle-to-home and building energy transfer during peak load periods. Sagaria et al [24] examine the possibility of V2G on a RES-supported grid in Germany. The result from the nationwide study shows that V2G technology can meet the ESS requirements in the future, with any new hydro, electro-chemical, or mechanical ESS installations. The smart grid operation study with large-scale EV integration through V2G by Mozafar et al [25] shows that EV is an acceptable ESS for the smart grid, which effectively eliminates the requirement of the high-cost power plant and pristine ESS. The integration of EVs into the grid to develop virtual ESS has also been supported in many other studies [26]–[29][30]. Sagaria et al [31] also examine photovoltaic integrated EVs, in which EVs can generate energy through onboard PV and convert it into grid energy through V2G conversion.

Aside from these technical studies, it is also critical to understand V2G's social dimensions. Range anxiety is cited as a major barrier to V2G in a study by Esmaili et al [32]. Range anxiety is the driver's fear that a vehicle does not have enough energy to cover the distance needed to reach its intended destination and would thus strand the vehicle's occupants midway. According to Geske and Schumann [33], some EV drivers were unwilling to participate in V2G technology for a variety of reasons. Among many, the most concerning reasons were range anxiety and minimum range. Variables that promote V2G in the Nordic region have been studied by Kester et al [34]. The study highlights that the main obstacles to V2G growth include infrastructure issues, battery degradation, and consumer unawareness. Noel et al [35] also found that range anxiety is not the only barrier to V2G participation. low adoption rates of electric vehicles, poor business models, battery degradation and consumer resistance to accept new technology are other barriers to V2G.

In this study, we will be focusing to include social and technical parameters and analyse how we can achieve 100% RES-supported electricity generation in Japan to reduce the influence of non-fossil fuels in electricity generation. In addition to this, we will bridge the gap between technical and social variables by combining both the technical and social factors to generate insightful results. Through this conceptual study, we:

- Estimate PV and Wind installations required to meet electricity demand.
- Analyse the influence of variables - V2G acceptance and battery availability for V2G to understand the energy flow between EV and the grid.

For the study, we develop a model in Simulink. Section 2 explains the model development in detail. Multiple RES (Wind, PV, and hydropower (HP) 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 V2G energy flow. For secondary ESS, instead of PHS, we can include any other ESS such as thermal and electrochemical ESS or multiple storage systems.

2. MODEL DEVELOPMENT

This study aims to analyse the influence of V2G technology on the 100% RES-supported electricity grid in Japan. A simulation model is developed in MATLAB/Simulink platform for the study. 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. This improves the flexibility of our model to study targeted variables within the energy systems.

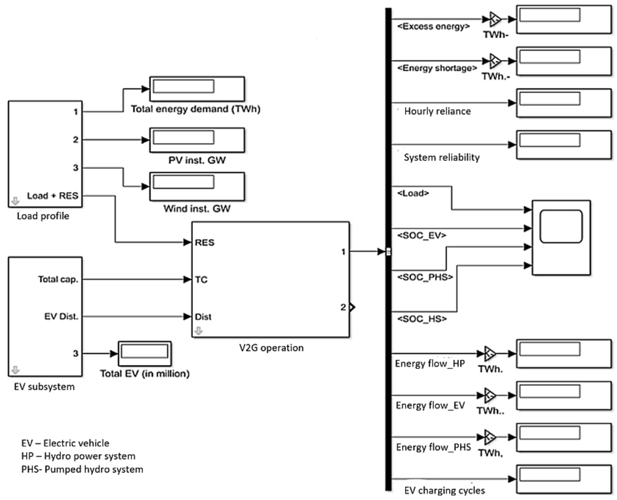

Figure 1: Simulation model developed in Simulink.

Figure 1 shows the model developed in Simulink software. The inputs are given in the load profile subsystem, EV subsystem and Operation subsystem. Based on the electricity consumption, the electricity generation profile for PV, Wind and hydropower is retrieved from the Institute for Sustainable Energy Policies (ISEP), Japan [36]. 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 energy flow between RES and ESS in the operations subsystem to give the required outputs.

For the simulation, we use hourly data from June 1st 2021 to May 31st of 2022 as the reference. Japan's annual average electricity consumption is approximately 870 TWh, consumed for transport, trade and service, household, and industrial applications [36][37]. The model also considers a yearly load demand of 870 TWh. From the past electricity consumption data from 1991 to 2001, we can observe that the load requirement is decreasing since 2010. Over the last decade, the load demand was reduced by an average of 0.8 %/year [37][38]. In our study, the model calculates EV energy requirements separately in addition to the electricity load, which supports the electricity requirement for EVs. Considering all the above factors, we claim our assumption of stable non-EV electricity demand up to 2030 is reasonable. The hourly energy demand profile is then generated from the input [36].

Since solar and wind installations are growing rapidly, the simulation uses annual energy generation data from 2020-2021. In 2021, Japan have a total PV installation of 74.1 GW, the third largest PV capacity in the world, and 4.4 GW of wind installations [39][40]. From June 2020 to June 2021, PV and wind generate around 83.3 TWh (74.2 TWh from PV and 9.1 TWh from wind). From this, the hourly generation for 1 GW installation for PV and wind is calculated for a year. This is further used. For hydroelectric power, the energy generation profile from 2020-2021 is given as the input. In 2020, 70.2 TWh of energy is produced through hydropower in Japan [36]. In the study, we predominantly focus on the growth in PV and wind. However, Japan generated around 13.4 TWh from biomass and 2.5 TWh from geothermal which is assumed to grow slowly in the future; while 38 TWh from nuclear energy will be swapped by with wind/PV in future and to generate 85% of total electricity demand from PV and wind sources alone.

In the 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. The model only considers EVs owned for personal purposes. Public vehicles and heavy-duty vehicles operate continuously and it will reduce the flexibility as compared to privately owned vehicles. It is estimated that a private vehicle owner travels around 6800 km/year in Japan [41]. This corresponds to the profile of users who use the vehicle for the one-way commute to work or school of around 30 minutes [42]. From the data, we consider an average travel of 20 km/day, with an average energy consumption of 185 Wh/km [43][44]. Currently, Japan has 1.7% EV in their total vehicle fleet of 62 million cars [45]. In 2030, they aim to improve this to 27% (17 million) including battery and plug-in EVs [38]. For the V2G process, the round-trip efficiency of the V2G technology is 87% with 93.5% efficiency for charging and discharging respectively. 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 [46]. The EV distribution represents the 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 [30]. We assume the same pattern will be followed all day around the year. The total energy consumed by the electric vehicle each hour is calculated individually using (1).

$$EV\ cons\ (t) = Average\ energy\ cons./km \times distance\ travelled \times total\ EV \times EV\ driving\ distribution \quad \text{Equation 1}$$

The model considers PHS as the secondary storage system, to focus more on energy flow through EVs through V2G technology. Japan currently has a PHS capacity of 21,890 MW which is considered for the study with 85 % round trip efficiency [47]. *Figure 2* represents the logical flow diagram of the developed model. The minimum and maximum SOC for EV and PHS, initial SOC and energy profiles were given as inputs for the model.

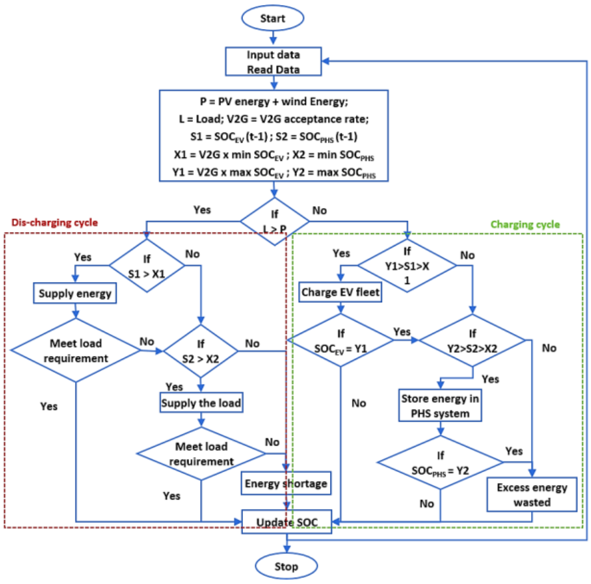

Figure 2: Flow diagram of the developed model

The initial step of the simulation is to calculate the load balance. Load balance is the difference between the electricity demand and the electricity generation by PV and wind installations, as shown in equation 2. The load balance can be positive, zero or negative. A load balance of zero occurs when the load requirements are exactly equal to the electricity generated by renewable sources. The positive load balance represents higher energy consumption than energy generation from RES, and the negative load balance represents less energy consumption than energy generation from RES.

$$Load\ balance\ (Lb)\ (t) = (load\ cons.(t) + EV\ cons.(t)) - (Wind\ energy\ (t) + PV(t)) \quad \text{Equation 2}$$

During positive load balance, RES energy generation is not enough to meet the demands, and energy from external sources is necessary to balance the demand. In the model, the external source is ESS and energy is supplied to the grid if there's enough energy in EV. If EV cannot meet the extra requirements, the rest will be taken from PHS after the batteries successfully discharge to the minimum SOC. The hydropower system activates when the PHS energy supply is insufficient to meet the load demand. If there is still an energy requirement, it is considered an energy shortage point. Excess energy generation from RES than hourly demand represents a negative load balance. With excess energy, EV batteries are prioritised over other ESS and are charged back to the maximum SOC. If more energy is still available, it is stored in the PHS system. If energy is available even after, it is considered excess energy. In real life, this energy is considered curtailed.

The SOC of the EV fleet during each hour is calculated as the sum of the SOC of the parked vehicles (*SOCp*) and moving vehicles (*SOCm*), as in equation 3. The *SOCm* of EV includes the energy required to drive during the hour, thus capturing the dynamic nature of the EV fleet. 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 battery pack. So, the SOC of the parked vehicle is estimated. The SOC of the parked vehicles and moving vehicles is estimated individually using equations 4 and 5.

$$SOC_{total}(t) = P_{share}(t) \times SOC_p(t) + M_{share}(t) \times SOC_m(t)$$

Equation 3

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

Equation 4

$$SOC_m(t) = M_{share}(t) \times SOC_m(t) - EV\ cons\ (t) \Big/ total\ EV\ fleet\ capacity$$

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', SOCtemp 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 the excess energy generation is more than what EV can take in. In this case, EV recharges the battery to SOC_{max}. Case b) represents when EV doesn't have enough energy 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 energy from RES or insufficient energy from RES, the energy flow happens between the parked EV vehicles. Due to this, the SOC estimation of the parked vehicle has to consider 3 different cases, positive load balance with enough energy to meet additional requirements (case c), positive load balance with not enough energy to meet the requirements (case b) and negative load balance (case a). Equation 6 shows the calculation of SOC_{temp},

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

Equation 6

The SOC_{temp} calculation varies according to the load balance. During the negative load balance, the energy is stored in the EV, as shown in case (a). The inflow of energy to EV revise 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 energy requirement. Equations 7 and 8 show the calculation of P_{share} and M_{share} respectively.

$$P_{share}\ (t) = (1 - EV\ driving\ distribution) \times total\ EV\ fleet\ capacity$$

Equation 7

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

Equation 8

The SOC of PHS is also estimated each time 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 energy flow in PHS. Case (a) represents additional energy availability after charging the EV fleet to SOC_{max}. The excess energy is stored in the PHS system and SOC_{PHS} is updated. Even after energy is available after PHS reaches *PHS*-SOC_{max}, the available energy is discarded. Case (b) and (c) represents positive load balance points. When EV cannot fulfil the excess load requirements, energy from PHS is extracted, represented by case (b) and If PHS can't fulfil the additional requirement, the time period is marked as an energy shortage point. case (c) shows when EV fulfils the energy excess energy requirement.

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

Equation 9

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

$$Hourly\ reliability = \sum_1^{8760} \begin{Bmatrix} E\ bal._{PHS} + E_{HP} < 0; 0 \\ E\ bal._{PHS} + E_{HP} \geq 0; 1 \end{Bmatrix} \Big/ 8760$$

Equation 10

$$System\ Self\text{-}sufficiency = \frac{Total\ energy\ supplied\ by\ RES\ \&\ ESS}{Total\ energy\ required} \times 100$$

Equation 11

The study is performed in 2 phases where in the initial phase we will estimate the RES installation required to meet the load demand. As explained, we will consider a yearly electricity demand of 870 TWh. Currently Biomass and Geothermal are generating around 15 TWh of energy and in the future, we estimate it will increase by a factor of 5, resulting in a total generation of 75 TWh. The rest is to be supplied by PV, wind, and hydro. We assume no more installation of Hydro power plants, which results in PV and wind to satisfy the electricity requirement of 750 TWh, which is around 85%. In Phase 1, we will estimate the PV and wind installation to meet 85% of the electricity demand in Japan. In Phase, the study analyses the impact of variables in the results from phase 1. This will help to evaluate how the change in variables such as V2G acceptance rate and battery availability influence the energy flow and system reliability.

3. SIMULATION RESULTS

This study analyses a potential 100% RES-supported electricity grid system in Japan. The simulation is done in two phases. In phase 1, the amount of RES installation from PV and the wind is estimated. It is explained in detail in section 3.1. Phase two study includes an analysis of V2G variables such as V2G acceptance and battery availability. The influence of these variables on V2G technology is explained in section 3.2.

3.1 Phase 1: Analysis of PV and Wind installations

We estimate the RES installation required to meet 100% of electricity demand through multiple simulations. Various studies consider different yearly load requirements [15][16]. But past data shows a decrease in yearly electricity demand and our study considers a yearly load of 870 TWh [37][38]. The simulation estimates PV and wind installation to satisfy 85% of the electricity demands with 99% hourly reliability. To meet 100% hourly reliability, the system must meet all the electricity requirements at any hour. In the winter, electricity demand is higher than average requirements and the hourly demand varies according to the time of day. The peak demand only retains for a couple of hours each day. During a year, there is 8760 hours total, of which the peaks only account for 1% of the time. Increasing RES installation to reach 100% hourly reliability also generate more excess energy during low-demand periods. With 99% hourly reliability, we aim to flatten the peak energy demand points. Furthermore, a difference of 1 Wh can decrease hourly reliability, so the model needs to increase the installation even more. To avoid this excess curtailment and RES installations, the simulation is performed for 99% hourly reliability and system self-sufficiency. *Figure 3* shows the results of the simulation.

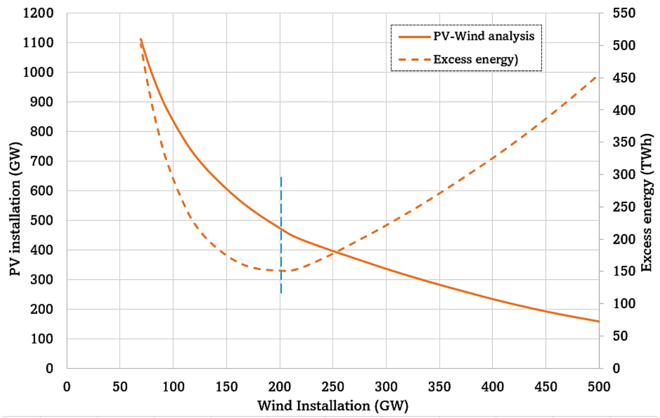

Figure 3: Simulation results to estimate RES installations.

Figure 3 shows the simulation results from multiple simulations. The result shows a different combination of PV and wind installation and the excess energy generated from each combination. For phase 2 studies, we choose 454.8 GW of PV and 199.3 GW of Wind turbine installation, with an excess energy generation of 152 TWh (Blue line). Compared with the current installation, to reach 100% RES-supported electricity generation, Japan needs to increase PV and wind installation by 6 and 40 times respectively. Considering the installation projection in 2030; to increase total PV installation to 108 GW and wind turbines to 10 GW, we can observe more resource investment reserved for PV installations [38]. Such a portfolio of RES installations can significantly reduce excess energy generation. From June 2021 to June 2022, Japan curtailed a total of 560 GW of energy from RES [36].

3.2 Phase 2: Assessment of the influence of V2G acceptance, and battery availability on V2G technology.

The potential of V2G technology highly depends on social factors such as V2G acceptance and battery availability. From previous studies by Esmaili et al [32], Noel et al [35] and other researchers [33]–[35], [48], the former variables play a vital role. Through this analysis, we aim to get a deeper insight into how the change in these variables influences the potential of EV as an ESS.

In the initial analysis, we combine V2G acceptance and battery availability and seek to understand how changes in the variables influence the hourly reliability and energy flow through EV and RES-supported grids. We simulate different V2G acceptance rates, from 100% to 0% for different battery capacities reserved for V2G purposes. For the simulation, we assume a 454.8 GW PV installation and 199.3 GW wind energy installation with 17 million EVs (27% of total cars in Japan). *Figure 4* and *Figure 5* show the results of the simulation.

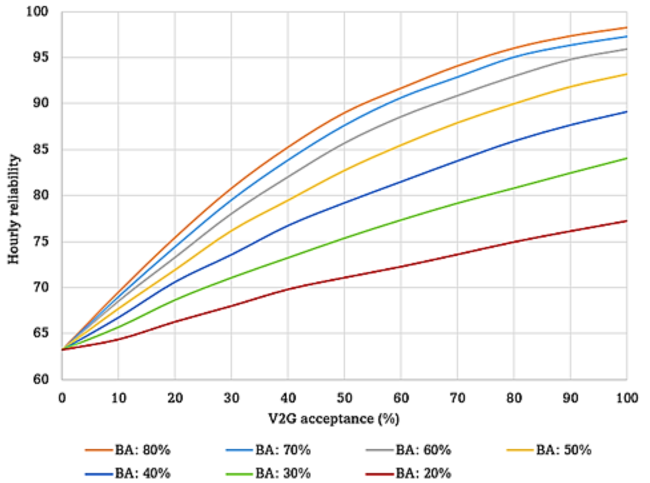

Figure 4: Influence of V2G acceptance rate and battery availability on hourly reliance

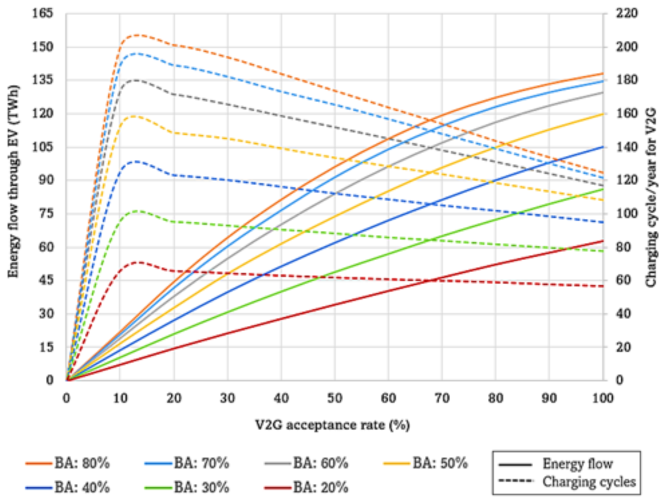

Figure 5: Influence of V2G acceptance rate and battery availability on energy flow through EV and EV charging cycles

From the results in *Figure 4*, we can observe that the hourly reliability on the RES-supported grid is declining as the V2G acceptance rate and battery availability gets lower. With a lower V2G acceptance rate, fewer EVs are connected to the grid for bi-directional energy transfer. As a result of the reduction of EVs connected for V2G service, the total ESS capacity available through V2G is lowered which reduces the total energy flow and reduces the self-sufficiency and the hourly reliability 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. This will result in the reduction of self-sufficiency and hourly reliability of the system.

Figure 5 show the change in energy flow through EVs and the number of charges dedicated for V2G purposes. From the results, we can observe that as V2G acceptance or battery availability reduces, the energy flow through EVs is also reduced. It is because of the reason mentioned before, with battery capacity. This will then reduce the maximum possible storage/extraction of energy, thus the energy flow. However, looking into the number of charging cycles each vehicle must go through, it can be observed that a low V2G acceptance rate would, more rapidly, decrease battery life among the participating vehicles.

Combining both results, we can observe that even with a lower V2G acceptance rate of 50% and battery availability of 40%, we can improve the hourly reliability to 80% from 63% (0% V2G acceptance rate) and self-sufficiency of the system to 90% from 80% (0% V2G acceptance rate). Subsequently, the study indicates that the energy storage and extraction of EV batteries can significantly contribute to balancing intermittent energy production even if less than half of the owners of 17 million EVs in Japan, are willing to be part of the V2G service.

4. DISCUSSION

This conceptual study examines the possibility of using EVs to support 100% RES-supported electricity grids in the future. The case study is based on Japan's high emission per capita. By focusing on V2G, the study estimates how much RES is needed to meet electricity demand and analyses V2G-related variables such as battery availability and V2G acceptance. The study is conducted in 2 phases, as explained in sections 3.1 and 3.2. During phase 1, we estimate the amount of renewable energy required to meet electricity demand. Our simulation model developed in Simulink estimates 454.8 GW of PV and 199.3 GW of wind turbine installation to meet these requirements.

In 2030, Japan plans to phase out coal use and increase renewable energy generation to 50% by 2030 to reduce total emissions by 46% [49]. It is estimated that by 2030, PV installations will total 108 GW and wind installations will total 10 GW [38]. Results from the 100% renewable energy scenario are comparable to Japan's carbon neutrality goal by 2050 [50]. The Japanese government aims to reach carbon neutrality by 2050, but not solely through RES. With RES at 50%, hydrogen and ammonia at 10%, and nuclear and thermal sources with carbon capture will generate the rest of Japan's total energy needs [50]. Considering these values, i.e., 50% from RES and 40% from gas and nuclear sources, to replace the latter 40% with RES, a doubling of the RES installation is required as compared to what they will have in 2050. REI's 100% RES-supported Japan study indicates 524 GW of PV installations and 152 GW of wind turbine installations (onshore and offshore), with 8% imported energy. Even though the phase 1 study supports the above-mentioned installation combination, the excess energy generated would be higher. REI's study also includes 643 GWh of battery storage through V2G, utility and stationary sources. Considering only V2G services (as in our study), 20 million EVs can provide this capacity, with a 65 kWh battery and 50% of the battery dedicated to V2G services [15][16].

In Phase 2, we examine how V2G acceptance and battery availability affect energy flow and grid self-sufficiency. The inference from the results is that both V2G acceptance rate and battery availability influence the final storage capacity provided by EV. The results indicate that V2G acceptance by EV owners is more crucial than battery availability. Although the operational scenario with 50% battery availability and 20% V2G acceptance offers the same storage capacity as the operational scenario with 20% battery availability and 50% V2G acceptance, the latter scenario undergoes fewer charging cycles for each vehicle. The studies [34], [35], [48], [51] also mention the importance of V2G acceptance, also called consumer acceptance, as a key factor to its success. Users of electric vehicles must better understand technology and operation to improve their acceptance of V2G. In addition to range anxiety, EV users are concerned about EV batteries reaching End of Life (EOL) sooner. As a result of this study, it is evident that having a battery with a capacity of 30-50% definitely improves grid self-sufficiency, as it means the users don't have to dedicate the whole battery to V2G services. Even after dedicating 40% of the battery to the V2G service, an average EV can still drive over 200 km (considering EVs with a maximum range of 400 km). Having high V2G acceptance rates will result in fewer charging cycles, however, there is a relatively small difference between 30% V2G acceptance and 70%. Reduced charging cycles help to extend the battery's life by reducing stress. Even so, EV owners must be compensated for the extra wear on their batteries.

5. CONCLUSION

This conceptual study examines 100% RES-supported electricity with EV as ESS through V2G technology. The simulation model in Simulink simulates the yearly electricity demand-supply scenario. We consider PV, wind and hydropower as RES and EV as future energy storage options along with the existing PHS system.

The results show the different PV-Wind installation combinations to generate electricity to meet the electricity demands. In our study, we estimate 454.8 GW of PV, and 199.3 GW of wind turbine installation are required to fulfil the electricity demands with 100% RES. We considered 17 million EVs with 65 kWh battery packs, our analysis identified the influence of the grid's hourly reliance and self-sufficiency. The result shows that the system's self-sufficiency reduces when V2G acceptance and battery availability decrease. The results also indicate that higher V2G acceptance (more than 30%) is more vital than battery availability. The overall results show that V2G technology has a positive influence on the grid and has the potential to be an effective storage solution in the future even when its full potential is not used due to low V2G acceptance.

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