Exploring Electric Vehicle Participation in the Icelandic Balancing Market as Virtual Power Plant

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***Abstract*— The electrification of the transport sector is one of the key measures to mitigate global CO_2 emissions. With increased roll-out of EVs, further opportunities for generating additional benefit for various parties can be explored. For example, the provision of balancing energy through vehicle-to-grid (V2G) technology has been identified as a market with large potential for EV owners and fleets, enabling them to potentially accumulate profits from participation. This research presents a case study of V2G in Iceland and sets out to analyze the competitiveness of a fleet of EVs in the Iceland balancing market. The fleet is managed and modelled as a virtual power plant (VPP) to secure the minimum bid size for participation in the balancing market and ensure the availability of the bid capacity throughout a balancing period.**

An agent-based simulation determined the viability of an EV-VPP in an Icelandic setting. The results show that a VPP of EV batteries can participate successfully in the balancing market. Both participating vehicle owners and the VPP operator can accumulate minor profits. Vehicle owners profit most through the provision of free charging, while the VPP operator benefits primarily from market participation payments and cheaper battery packs. The performance of a VPP in the Icelandic balancing market is most sensitive to battery pack costs, minimum bid size for market participation, and the electricity retail price.

Keywords: electric vehicles, agent-based simulation, vehicle-to-grid, balancing market, Icelandic energy system, virtual power plant

I. INTRODUCTION

Increased use of electric vehicles (EV) has often been named as one in a set of recommended measures to achieve an effective reduction of CO_2 emissions [1]. Many national, regional, and local governments have therefore either considered the adoption of, or already developed a strategy and subsequent policies on, how to facilitate the increased deployment of electric vehicles (EV). Of particular note is the Norwegian government has announced goals that all new noncommercial heavy-duty vehicle registrations by 2025 should be zero-emission vehicles [2]. Regional and local governments in several other countries have announced similar strategies, including the City of Reykjavik. In the summer of 2016, the Icelandic capital's government presented their action plan for achieving carbon neutrality by 2040. This included increased cooperation with local utility companies in promoting the adoption of electricity powered transport [3].

As the effective carbon emission reduction from increased rollout of EVs is directly linked to the local energy mix used to generate the required electricity, Iceland – similar to Norway – finds itself in a very favorable position: local electricity generation is 99.9% renewable and thus essentially carbon neutral [4]. There are significant environmental and economic benefits of transforming the Icelandic vehicle fleet into an EV fleet as shown in several studies (see e.g. [5-7]). In considering alternative technologies to reduce the carbon intensity of the Icelandic transport sector, electrification showed the most promising fuel demand reductions, CO_2 emission mitigation costs, and fuel supply economics [6, p626].

This paper pursues two goals: first, it aims to apply and test the use of EV batteries for balancing energy in Iceland. Secondly, it tests an agent-based modelling approach for such studies. This paper provides a short review of relevant theory and previous findings. The modelling approach is then introduced, followed by a sensitivity analysis using five scenarios. These results are then discussed in both an Icelandic and general context.

A. Literaure review

The concept of EV chargers feeding electricity back into the grid emerged in academic discourse alongside first considerations to electrify the transport sector in the mid-1990s [8]. Rather than viewing EVs as an additional load, it has been argued to also consider their potential additional services to the grid. The vehicle-to-grid (V2G) technology requires three crucial elements to become a reality. Vehicles need to be equipped with: "(1) a connection to the grid for electrical energy flow, (2) control or logical connection necessary for communication with the grid operator, and (3) controls and metering on-board the vehicle" [9, p269]. By using this technology, vehicle fleets can be managed more closely in coordination with the current local grid conditions. Effectively, vehicle batteries would then act as mobile electricity storage.

The main advantages of using V2G fleets in frequency regulation are their low activation cost, distributed nature, and very quick responsiveness to signals [10, 11]. However, a consensus among most of the literature is that, from an economic point of view, there is an opportunity for creating value for vehicle owners or fleets by providing these additional services or competing in balancing markets [9, 11].

From the consumer's perspective, V2G provides new monetization opportunities. Results from Germany have shown that single plug-in hybrid vehicles can earn 75 € per month by providing downward regulation services when certain conditions are met [11, 12]. In California, the potential annual earnings of individual battery electric vehicles from participating in the balancing market have been calculated to be up to 3,100 USD [9].

Given most market structures, however, the participation of individual vehicles is not feasible due to administrative and uncertainty constraints. Therefore, fleets of vehicles are a more viable option for V2G. Depending on the fleet size and composition, as well as internal structure, total annual net profits of EV fleets participating in a balancing market range from 135,000 USD to 450,000 USD annually [10]. For acceptance from consumers, it is vital that V2G services do not hinder the consumer's usage of the vehicle in any way [13, 14]. Yet the system services require availability of a certain capacity at certain times, thus individual vehicles acting alone bring a tremendous amount of uncertainty. This may render the gained flexibility on the grid operator's side practically useless due to the high risk of disconnecting unexpectedly. Aggregation of vehicles is recommended to ease the relative impact on the individual, as well as to reduce the uncertainty associated with the variation in usage patterns [12, 14, 15].

B. Icelandic Conditions

Three main factors relevant to the capital city region of Iceland are considered. First, data has been obtained from mobility surveys [16-18], regional governmental publications [19], and actual data from traffic sensors in Reykjavík provided by the municipal Department of Transportation [20], all specific to the capital city region.

Second, the Icelandic climate is expected to affect battery performance. The observed monthly mean temperatures in the past 15 years seldom exceed 15°C in July or fall below 0°C in December and January in Reykjavik [21]. Considering the optimal Lithium-ion battery temperature ranges lie between 15°C and 30°C [22], such batteries are not going to operate at their peak efficiency, effectively reducing the driving range of the vehicle by up to 20% [23, 24]. A benefit of the low temperatures, however, is that calendar life decay of the battery does not become a factor. Due to the low temperatures, induced reactivity of the cell when not used is minimal [22, 25, 26]. Thus, calendar life decay is not considered in the Icelandic scenario.

Finally, the Icelandic Balancing Market is set up to balance the prediction error in the forecast of all market participants' production and consumption schedules. Landsnet, the Icelandic TSO, is obligated to procure at least 40 MW in balancing capacity available for both upward and downward balancing [27]. To incentivize the submission of bids, an option-payment is made to all participating parties for the respective balancing period hour per submitted MW. The minimum bid for participation is one MW in size and needs to be available for the entire balancing period duration of one hour. An important feature of the balancing market is that it follows a pay-as-cleared mechanism. This entails that the highest accepted bid of one balancing period sets the clearing for the entire hour, and all accepted bids receive the same price as payment per MW for their bid capacity [28, 29].

II. Methodology

Given that driving behavior of vehicles is the most important factor for the availability of batteries for the provision of regulation services [12], an agent-based simulation was used. In the time-discrete simulation, a fixed set of agents are assigned individual vehicles from a pool of a total of 18 EV models theoretically available in Iceland. The driving behavior as well as the Icelandic balancing market and balancing energy requirement are simulated for model weeks for each month and the results are then extrapolated onto a calendar year. Through repeated runs of the simulation, multiple sets of observations are generated to provide robust results. The simulation has been programmed in R, averaging between 35 to 55 minutes per single simulation.

A. Assumptions

Due to the scope of the research and computational constraints, a set of simplifying assumptions had to be made:

- 50 kW DC-fast-charging infrastructure is available to all vehicles to the same degree
- The batteries of all considered vehicle models behave similarly, i.e. charge and discharge linearly over time with the charging power remaining constant throughout the charging process
- Complete charging cycle life expected of lithium-ion batteries is assumed to be 3000 cycles before the battery is replaced [30]
- Battery cell costs per kWh of storage capacity are assumed to amount to 250 USD/kWh [31]

B. Model design

As stated above, the simulation uses a time-discrete setting where a total of twelve model weeks are simulated in 15-minute blocks, creating 8064 individual timesteps and $k \in [1, K]$ as the index representing the current timestep, where K is the number of all timesteps. Three core model blocks have been run as part of this simulation. The first block simulates all aspects surrounding the agent's driving behavior, tracking the individual agent's performance as measured by charging costs, account balance, and avoided charging costs. Furthermore, the block tracks and updates all changes of the vehicle's states and battery status. The second block simulates the fleet operator, which aggregates the vehicles connected to the grid and dispatches them according to the current activation scenario in the balancing market, submits bids to the balancing market, and reimburses agents for their vehicle activation on a pro-rata basis. The third block simulates the balancing market itself, generates a balancing energy requirement for every simulated balancing period, and activates bids.

The internal structure of the VPP assumes that in all considered scenarios, unless otherwise specified, the VPP operator receives all option payments for submitted bids and uses these funds to pay activated downward bids. Payments received for upward regulation are split among all activated vehicles and the VPP operator, with the VPP operator retaining 30 % of the received payments. Should agents need to charge their vehicles when the VPP is not providing downward regulation, vehicle owners can do so at a retail price of 0.07 USD per kWh.

The driving of the agents is simulated using a non-homogeneous semi-Markov process in combination with sojourn times, an approach adapted from [32]. This provides a simple stochastic tool mimicking driving behavior of fleets. In the considered case, a three-state model is the most sensible. State 1 represents *home,* implying connection to the grid, State 2 *driving,* implying the vehicle is not stationary and not connected to the grid, and State 3 *elsewhere,* where the vehicle is considered to be stationary and not connected to the grid. Their connection is shown in Fig. 1.

Transition probabilities between the states have been determined relying on several studies on Icelandic driving behavior, and vary by 15-minute-intervals throughout the day. The general transition probability matrix $\boldsymbol{P}_k$ is the same for all agents at time step k and is defined as

$$\boldsymbol{P}_k = \begin{bmatrix} p_{11} & p_{12} & 0 \\ p_{21} & p_{22} & p_{23} \\ 0 & p_{32} & p_{33} \end{bmatrix} \quad (1)$$

The general formulation of the share of vehicles in a given state i at time k for a total number of agents, C, is calculated as

$$\varphi_{ik} = \sum_c \frac{(y_{ck}=i)}{C} \quad (2)$$

where y_{ck} represents the current state of agent c at time k. The general formulation for the individual probabilities can be written as such:

$$p_{ij} = f(\varphi_{2k}, \bar{\varphi}, x_{ki}) \quad (3)$$

where φ_u represents the current traffic volume of a defined fleet on the road at the observed time interval u, $\bar{\varphi}$ the diurnal mean traffic volume, and x_{ki} the probability vector of possible trip target states depending on current state i in the observed timestep k.

To secure that the vehicle remains usable for the agent even directly after providing electricity to the grid, avoids excessive battery aging, and limits charging times, two limits have been imposed on the charging and discharging through V2G: The upward limit of charging is set at 80% state of charge, the downward limit at 20% state of charge.

The balancing requirement for the balancing period hour is sampled from the data provided by Landsnet. It can be expressed as

$$W_z^r \sim N(\mu_h^W, (\sigma_h^W)^2) \quad (4)$$

where W_z^r is the required balancing capacity for the balancing period z which is sampled from $N(\mu_h^W, (\sigma_h^W)^2)$, the normal distribution of the balancing data for the respective hour of the day h, with a mean μ_h^W and standard deviation σ_h^W. To determine the market clearing price $\overline{\overline{P}}_z$, bid prices for the respective required direction are ordered following a merit curve as described by the Landsnet grid codes [29].

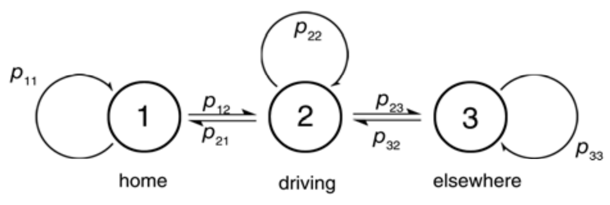

Figure 1. Modelled states and their connection

The cost of providing regulation services is directly linked to the aging of the battery due to the additional cycle aging. Their calculation is adapted from [11] and [30]:

$$C_\omega^{deg} = \frac{P_\omega^{bat} \tilde{E}_\omega^{max}}{L_\omega^{et}} \quad (5)$$

where C_ω^{deg} is the cost of battery degradation per unit of energy throughput at maximum allowed discharge cycles of vehicle ω, P_{bat} the battery pack investment costs per kWh of storage capacity, $\tilde{E}_\omega^{max}$ the size of the battery pack of vehicle ω, and L_ω^{et} the lifetime energy of vehicle ω throughput.

The marginal costs of providing one MW in up- and downward direction are crucial to the pricing of the bids submitted to the balancing market. They can be formulated as:

$$C^{\text{mc}} = \frac{\left(\sum_c C_{c\omega}^{deg}\right)}{C} E^{\text{MW}} - P^o - \text{C}^{\text{el}} E^{\text{MW}} \quad (6)$$

where C^{mc} are the marginal costs of providing one MW of regulation, P^o the option payment received for submitting a bid to the balancing market regardless of activation, and the term of $C^{\text{el}} E^{\text{MW}}$ calculates charging costs that are avoided by the bid submission for the entire pool. Avoided charging costs occur only in downward scenarios and thus are considered zero in upward balancing instances.

C. Scenarios

The central scenario at the basis of the analysis is considered the most plausible one. To test the effects of adjustments of various factors, five additional scenarios have been constructed. The variable adjustments are presented in Table I. Factors tested are the impact of increasing the fleet size, providing free charging to the agents regardless of VPP activation, reducing the charging speed, lowering the minimum bid size for balancing market bids to ease market access, and the effect of decreased battery pack costs.

To evaluate performance of the VPP, the activation frequency of the VPP bids in relation to the total number of submitted bids and in relation to the total number of balancing periods in a year are observed. The agent's benefits from participating are evaluated by comparing the sum of charging costs they avoided through providing downward regulation services as well as their end-of-year account balances showing if reimbursement for providing upward regulation potentially can offset charging costs incurred outside the activation of the vehicle.

TABLE I. CONSIDERED SCENARIOS

Scenario name	Adjusted variable	New value
Larger fleet	Fleet size	200
Free charging	Electricity costs for Agents	0 USD/kWh
	Electricity costs for VPP	0.07 USD/kWh
Slow charging	Charging power	25 kW
	Charging speed	0.33 kWh/min
Lower minimum bid size	Minimum bid size	500 kW
Optimistic battery costs	Battery pack costs	200 USD/kWh

III. RESULTS

Through repeated runs of the simulation, between 25 and 50 data sets have been generated for each considered scenario. The results were very consistent, giving reason to consider them robust and suited for further analysis. Key results are highlighted below.

A. Bidding performance

The bidding of the VPP is crucial for all further analysis of the performance. Key observations are shown in Table II. In all scenarios, the VPP does submit frequent bids into the balancing market. In all scenarios, the VPP bid almost exclusively at night between 20:00 and 8:00 the following day. Only in the large fleet and lower minimum bid scenarios are bids occasionally submitted outside this window.

When comparing balancing directions, a large discrepancy in submission frequency between balancing direction is observed in most scenarios. With the exception of the optimistic battery costs scenario, upward balancing bids are submitted more frequently. One reason for this can be found in the driving behavior of local drivers, which limits the downward availability due to limited discharging while driving. A secondary factor is the employed bidding strategy which effectively devalues bids that are less likely to be activated. In the most plausible scenario, 2.5% of all submitted upward bids are activated whereas 54.2% of submitted downward bids are activated.

In total, roughly 10% of the submitted bids from the VPP have been activated in the most plausible scenario. In relation to all balancing periods in a year, the VPP is activated 2.6% of the time in the most plausible scenario.

The increased bid submission frequency (as in the large fleet and lowered minimum bid scenarios) translates into significant increases in bid-activation frequency, doubling the most plausible scenario activation frequency. Decreasing the charging speed has adverse effects on both submission and activation of bids. Within this model, this can be traced back to the increased marginal costs associated with increasing the charging speed as well as an increased share of the fleet required to secure the bid capacity for the duration of the balancing period.

The optimistic battery costs scenario results in both upward and downward bids being submitted as often as one another. In this case, downward bids have an acceptance rate of 1%, while 23% of upward bids are accepted. This is caused by the decreased marginal costs due to reduced battery costs. Due to the lower marginal costs, downward bids are less frequently activated, while the upward activation increases significantly.

An ANOVA test has been used to study the significance between the respective groups' activation frequencies using a significance level of $\alpha = 0.05$. It confirmed that there is a statistically significant difference between the different groups, $F\ (6,193) = 529.7$, $p < 2^{10\times-16}$. A post-hoc Tukey's HSD showed that between the individual groups, a similarity in activation frequency exists between the most plausible and the free charging scenario (p=0.999). This observation is expected, since the provision of free charging to the agents through the VPP only has financial implications and should not affect the bidding behavior or bid prizes.

B. Financial performance

The second facet of the EV-VPP participation in the Icelandic balancing market is the financial side. Both individual agents and the VPP operator seek to profit from participation. Table III presents the average annual results for both agents and the VPP operator. Benefits for the agents are presented as the baseline of payments of the average agent at the end of a year, avoided charging costs, and end- of-year total benefits, which are the sum of avoided charging costs and the end-of-year baseline. This indicates that in most scenarios, the agents spend more money on charging outside of activation than they receive in reimbursement for providing upregulation service, as shown by the negative balance. However, when considering the avoided charging costs as well, most agents in most scenarios will likely end the year with a net-benefit, on average 27 to 175 USD, through saved fuel costs due to providing downward regulation services. The only instances where this does not apply are the slow charging scenario and the optimistic battery costs scenario. In both instances, the suffered degradation costs of the battery

TABLE II. ANNUAL FINANCIAL RESULTS, GROUP MEANS IN USD

Scenario	Balancing direction	Bids submitted	Mean number of won bids	Win frequency	Activation frequency
Most plausible	Upward	1,924	48	2.5 %	0.5 %
	Downward	333	179	54.2 %	2.1 %
	Total	2,257	227	10.1 %	2.6 %
Large fleet	Upward	2,726	72	3 %.	0.8 %
	Downward	795	441	56 %	5.1 %
	Total	3,521	513	14.6 %.	5.9 %
Slow charging	Upward	1,322	2	0.2 %	< 0.1 %
	Downward	179	101	57 %	1.1 %
	Total	1,501	103	6.9 %	1.2 %
Free charging	Upward	1,933	47	2.4 %	0.5 %
	Downward	321	180	56 %	2.1 %
	Total	2,253	227	10 %	2.6 %
Lower minimum bid size	Upward	2,552	78	3 %	1 %
	Downward	969	528	55 %	6 %
	Total	3,521	606	7 %	7 %
Optimisitc Battery costs	Upward	1,784	412	23 %	4.7 %
	Downward	1,724	17	1 %	0.2 %
	Total	3,508	429	12 %	4.9 %

TABLE III. ANNUAL FINANCIAL RESULTS, GROUP MEANS IN USD

	Agents				VPP Operator		
Scenario	***Mean end-of-year baseline***	***Mean fleet baseline standard deviation***	***Mean avoided charging costs***	***Mean end-of-year benefits***	***amount paid***	***amount received***	***End-of-year baseline***
Most plausible	- 49	30	76	27	4,544	11,497	6,953
Large fleet	- 16	11	111	95	11,259	29,057	17,798
Slow charging	- 80	49	52	- 28	3,124	7,156	4,033
Free charging	25	15	150	175	12,097	10,544	- 1,553
Minimum bid size	- 6	6	130	130	13,280	20,118	6,834
Optimistic battery costs	- 42	26	8	- 34	79	19,518	19,440

through regulation and charging outside of VPP activation are not covered.

The VPP operator also has the potential to accumulate profits throughout a year ranging from 318 USD to 19,440 USD. As hypothesized above, there is a notable difference between the most plausible and the free charging scenarios' financial performance despite the similar bidding behaviors. While agents benefit most in the free charging scenario, the VPP operator ends the year with a small deficit of 1,553 USD on average.

Due to the decreased marginal costs in the optimistic battery costs scenario, the margin between average clearing prices resulting in VPP activation and the average upward bid is increasing compared to the other scenarios. The average upward clearing price in the most plausible scenario with VPP activation is 72 USD/MW, while the average successful VPP bid price is 67 USD/MW. In the optimistic cost scenarios, these numbers decrease to 60 USD/MW and 46 USD/MW respectively. Thus, the VPP operator is profiting not only from the increased upward activation but also from the pay-as-cleared market mechanism.

Considering both bidding behavior and financial performance, it can be observed that the unsuccessful submission of bids is a significant driver behind the VPP's income. Scenarios with a large number of submitted bids by the VPP and a low upward balancing activation frequency tended to record higher received payment numbers by the VPP. The presence of the incentivizing payment plays a crucial role for the VPP's liquidity.

IV. DISCUSSION

A lot of the observed phenomena confirm previous scholarly findings, especially with regard to the impact of the adjustment of the different factors [11, 12, 33]. It is important to distinguish between results specific to Icelandic conditions and findings that could potentially be applicable outside of Iceland. The results are only reliable within conditions found in the model. The authors, however, are confident that general themes can be considered robust to allow further discussion.

Thus, free charging should be considered the most attractive option from the vehicle owner's point of view. A frequent downward activation would therefore be desirable from all participants' points of view. Through the expected continued drop of battery costs, the marginal costs of providing such services are expected to decline and with it the submitted prize for the downward bids.

Consequences of this drop can be seen in the optimistic costs scenario, where the downward activation frequency has decreased. The trend thus may negatively affect the attractiveness of participating in an EV-VPP for individual vehicle owners in relatively small markets such as the Icelandic one. In more competitive, larger markets, this effect may not be as severe.

Easing the access to the market by lowering the minimum bid size has shown great potential to strengthen the VPP's position. Increased bid submission has led to an increased likelihood of activation for participants, thus increasing their benefit, while the VPP operator is faced with increased downward regulation bid payments, inhibiting the growth of benefits. The effect of decreased battery costs combined with easier market access may provide very interesting opportunities. Through the decreased costs of downward balancing and an increased upward balancing activation, combined with an expected increase in bid submission, the VPP operator's income may rise considerably. This could enable the provision of free charging to participants and offset the decreased charging through providing downward regulation.

The retail electricity price also plays a crucial role in determining the downward bid prices, as the avoided charging costs are directly linked to it. Both involved parties have considerably different interests with regard to the retail price. A lower retail price would decrease the avoided charging costs, thus decreasing vehicle owners' savings from participation. Yet it would lead to an increased downward activation frequency in the Icelandic market, thus increasing the share of charging provided through VPP activation. An increase in downward activation increases the costs for the VPP operator. Thus, the VPP operator should favor a higher retail price to decrease both the activation frequency of downward bids and consequently the costs associated with the activation for downward balancing.

As this analysis considered relatively small fleets, it may be the case that a point of diminishing returns exists for the fleet size, both for the VPP operator and the vehicle owners. Lowering the charging speed has had a predominantly negative effect on the results of the simulation. The negative effect associated with the increased number of vehicles required to supply the minimum bid and the increased marginal costs could potentially be offset by an increased fleet size and decreased battery costs. Otherwise, a lowering of the minimum bid size may make slower charging a more viable option.

V. CONCLUSION

This research studied the viability of an EV-VPP in the Icelandic balancing market using an agent-based simulation. The impact of several factors on the performance of the VPP has been tested, reaffirming previously observed relationships. It has been shown that an EV-VPP can participate in balancing markets under the right circumstances. Furthermore, agent-based simulations produce interesting and robust results, and thus appear suited for applications in this context.

Small fleets of 100 or 200 vehicles can provide balancing energy reliably and at reasonable costs, though the potential to accumulate benefits is limited. With expected declining battery costs, the ability to provide upward regulation services of EVs should increase. More frequent activation and thus excessive battery aging may necessitate smarter bidding to mitigate the effects. Vehicle owners benefit most when they receive cheaper or free charging through providing downward regulation. A larger fleet, easier market access, and decreased battery costs all had significant effects on the bidding behavior and activation of the VPP. A combination of different factors could potentially increase the viability of an EV-VPP for both vehicle owners and the VPP operator.

Further analysis is needed to determine how a more dynamic balancing market model, more accurate charging behavior modelling, or adjusting the VPP internal management and profit sharing regime might affect the results. Moreover, the long-term effects and other cost factors should be considered in future research.

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