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Smart Electric Vehicle Management vs. Battery Storage for Energy Communities: A Case Study from Denmark

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Abstract

Energy communities are emerging as a crucial component in the energy transition, enabling the generation, sharing, and efficient management of renewable energy at a community level. The integration of electric vehicles (EVs) with bidirectional charging capabilities could potentially further enhance the performance of these communities by optimising energy use and reducing costs. This paper investigates the impact of incorporating EV chargers with vehicle-to-building (V2B) technology on the electricity costs within an energy community reliant on photovoltaic (PV) energy production. We conduct a comparative analysis of the performance of V2B against unidirectional smart charging (V1G) and a stationary battery energy storage system (BESS) by employing an optimisation model informed by real-world data—including EV driving patterns, PV generation, electricity consumption, and the associated costs. The analysis covers both a summer and a winter week to account for variations in consumption, PV generation, and driving habits. Our results reveal that the V2B system consistently outperforms both V1G and BESS in reducing electricity costs, demonstrating up to a tenfold reduction in costs compared to the BESS during summer. These findings underscore the potential of bidirectional charging for potentially significant economic savings and its role in promoting low-impact CO_2 energy solutions within energy community settings.

1 Introduction

In the mission to combat climate change, the world is increasingly turning to innovative solutions that can mitigate environmental impacts and transform energy consumption patterns. Energy communities, where groups of individuals collectively generate, share, and manage renewable energy sources (RESs), are at the forefront of this transition. However, these communities often rely on intermittent energy sources, such as photovoltaic (PV) and wind energy, which offer less consistent output compared to conventional power plants [1]. To balance production and consumption, it is necessary to either shift demand to match energy generation or store surplus energy for later use [2, 3]. Although some degree of demand flexibility can be achieved, significant portions of household consumption remain constrained by fixed routines, such as work and sleep schedules, underscoring the critical need for effective storage solutions to ensure a stable and reliable energy supply.

1.1 Literature Review

A growing body of literature highlights the critical role of electric vehicles (EVs) in supporting the transition to low-carbon technologies, particularly when integrated into energy communities. These studies focus on various factors that influence the successful deployment and management of EVs within these systems. Key aspects under investigation include:

1. **Seasonal Variations in EV Charging Demand:** Studies emphasise the importance of understanding how seasonal fluctuations impact EV charging patterns, particularly in regions with variable weather conditions. These insights are crucial for optimizing energy use throughout the year [4–6].
2. **EV Market Dynamics:** Research into market trends for EV adoption provides an understanding of future growth trajectories, which directly influences infrastructure planning and energy community integration [4, 7, 8].
3. **Charger Market Trends:** As EV adoption increases, so does the need for sufficient charging infrastructure. Research in this field examines market trends and technological developments of charging systems, which are crucial for meeting the growing EV demand [4].
4. **EV Type Analysis for Charging Requirements:** Different EV models have varying charging needs. Research in this area focuses on understanding how vehicle characteristics—such as battery capacity and driving range—affect charging behaviour [4, 7–10].
5. **EV Charger Analysis:** Beyond vehicle types, the characteristics and performance of different EV chargers are examined, revealing their impact on overall system efficiency and user satisfaction [4, 9, 10].
6. **EV Scheduling optimisation:** Efficient scheduling of EV charging is crucial for reducing costs and maximizing grid stability. Various studies explore different scheduling algorithms and their effectiveness in managing peak loads and integrating RESs [4, 5, 7, 9].

7. **Variability in Driving Patterns Based on Day Type:** Understanding how driving patterns vary between weekdays, weekends, and holidays offers valuable insights for optimizing charging strategies and alleviating stress on the grid [4, 5, 9–11].
8. **Stochastic Methods for Predicting EV Charge Demand:** Stochastic models are used to account for uncertainties in EV charging demand, facilitating more robust planning and energy management [4, 5, 9, 10].

These studies represent early efforts to integrate energy communities with smart EV charging systems. This approach has the potential to significantly enhance the self-consumption of PV production, maximising the use of locally generated renewable energy. In parallel with studies on energy communities, significant research has focused on bidirectional charging technologies. These works primarily explore Vehicle-to-Grid (V2G) systems, in which EVs can supply power back to the grid, thereby facilitating services such as peak shaving, frequency regulation, and grid balancing. However, most of these studies focus on interactions with the grid and do not directly consider energy communities or the integration of local RESs. For example, the work in [12] explored the use of V2G for frequency regulation. By leveraging real-world driving patterns, the study aimed to maximise the monetary value derived from the EVs' ability to store and dispatch electricity during peak demand. However, the study primarily focused on interactions with the transmission system, overlooking the complexities and opportunities of energy communities, where local production and self-consumption are more prominent.

In contrast, [13] adopted a macro-level approach by analysing the effect of both unidirectional smart charging (V1G) and V2G. The study varied the number of V1G and V2G-enabled EVs to evaluate the impact on overall grid stability and RESs integration. By simulating various EV configurations, the study demonstrated how V2G can alleviate the intermittency of RESs by offering flexible storage that adapts to fluctuations in supply and demand. This macro-scale analysis highlights the scalability of V2G technology for large-scale renewable energy integration, although it predominantly focuses on centralised energy models and does not specifically address localised, decentralised systems such as energy communities.

1.2 Contributions and Scope

This paper addresses a significant gap in the existing literature by analysing the integration of bidirectional charging within an energy community. While V2G systems have been extensively studied for their benefits at the grid level, there is a lack of research examining their integration into energy communities and the socio-economic implications, particularly when combined with simulated driving patterns and the habits of specific communities. Given that EVs, and cars in general, are typically in use for less than 5% of the time [14], their large batteries offer a valuable opportunity for energy storage while parked. Through bidirectional charging, EVs can be utilised for V2G, vehicle-to-home (V2H), vehicle-to-building (V2B), or other solutions (V2X), unlocking various applications that enhance the economic viability of EVs as a storage solution compared to stationary batteries.

This study examines three distinct scenarios within an energy community reliant on PV energy production: V1G, stationary battery storage systems (BESSs), and V2B. By employing an optimisation model that incorporates real-world driving patterns, realistic PV generation and electricity consumption profiles, as well as cost dynamics, we evaluate the performance of each system for both summer and winter periods. The primary objective of this paper is to quantify the economic advantages of V2B compared to BESS and V1G systems. Given the emerging nature of V2B technology, this research aims to offer a comprehensive evaluation of its potential to increase PV self-consumption and reduce electricity expenditures as the technology matures. With Denmark's EV market projected to surpass 2 million EVs by 2035 [15, 16], this paper extends its analysis to 2035, forecasting the long-term implications and benefits of V2B in future energy systems.

The structure of the paper is as follows: Section 2 provides a detailed account of the methodology, including the design of the case study, the data acquisition process, and the optimisation model employed. Section 3 presents the analysis outcomes, with a comprehensive discussion of the primary results and sensitivity analysis. In Section 4, conclusions are drawn and future research directions are proposed in light of the limitations of the study.

2 Methodology

In the following chapter, we present the methodology employed in this paper. We begin by introducing our case study, the Fælledby energy community project, followed by a detailed explanation of the data collection and processing methods. Next, we offer an in-depth discussion of the optimisation model. Finally, we discuss the key simulation parameters and their meaning.

2.1 The Fælledby Energy Community Project

This study focuses on the Fælledby project, an energy community currently under construction in the outskirts of Copenhagen, designed to encompass 1726 apartments. The project will include three distinct neighbourhoods, incorporating residential housing, a school and daycare facility, a hotel, supermarkets, and underground parking facilities [17].

Fælledby will encompass several PV installations to reduce the need to import electricity from the power distribution network. The inclusion of storage systems or the use of EVs as a flexible consumption resource should help reducing the electricity export to the power system. This design has the potential to substantially cut grid-related costs, including taxes and tariffs. While current Danish regulations prohibit energy sharing between buildings [18], if the EU regulations are applied, by 2035, Fælledby should be able to fully realise its potential as an energy-sharing community.

This study compares two different EV charging strategies with the use of a stationary BESS to minimise electricity costs. More specifically, we analyse the following three scenarios:

- **Unidirectional Smart Charging (V1G):** This baseline scenario focuses solely on unidirectional smart charging, where EVs are charged with the goal of reducing electricity costs and can reduce their charging power to follow an optimal schedule.
- **Battery Energy Storage System (BESS):** In addition to V1G, a BESS in each building is considered.
- **Vehicle-to-Building (V2B):** Our last scenario examines a fleet of EVs capable of bidirectional charging, essentially transforming the EVs in a flexible storage system for the energy community.

2.2 Data Collection and Preprocessing

In order to analyse the different scenarios, several inputs were needed, including electricity usage, PV production, and EV driving patterns. The project provided estimates of the annual electricity consumption for the apartments (4746.5 MWh), hotel (459.1 MWh), school and daycare (428.8 MWh), and supermarket (120 MWh) in Fælledby. These estimates were converted into hourly data using different consumption profiles. Apartment profiles were derived from the dataset provided in [19] with reference to the year 2023 in Copenhagen. The hotel's hourly consumption profile was derived using the same approach, following the research in [20], which suggests a comparable daily pattern for hotels. For the school and daycare, the consumption profile was generated according to [21], The supermarket profile was adapted from [22] and scaled to match the total consumption estimated in Fælledby. The resulting aggregated load profile for the analysed winter and summer weeks is highlighted by blue and green lines in Figure 1, respectively.

Fælledby will comprise 23 building zones, 22 of which will be equipped with rooftop PV systems. These systems will employ five distinct combinations of tilt angles and orientations to ensure a more uniform PV production profile throughout the day, as outlined in Table 1. The PV capacity is anticipated to reach 4771 kWp. Based on the installed capacity, tilt, orientation, and a converter efficiency of 98%, hourly PV production estimates were generated based on [23] using the most recent data from 2020, resulting in the annual PV output shown in Table 1.

Table 1 Characteristics of the planned PV installations.

Orientation	East	East	West	North	South
Slope [°]	15	30	30	30	30
Capacity [kWp]	1036.8	929.2	922.4	941.3	941.3
Output [MWh/a]	870.7	759.1	760.4	517.2	977.5

Finally, the EV penetration rate and driving patterns had to be estimated. Although Fælledby plans to provide parking and charging for up to 660 cars by installing 330 charges with dual outputs and individual power ratings of 11 kW, the usage of these chargers in 2035 is difficult to estimate. Based on calculations from [16, 24], an optimistic EV penetration rate of 87.9% for Copenhagen was projected, translating to approximately 574 EVs belonging to members of the Fælledby community. The weekly driving pattern for each EV was modelled using distributions derived from the *Danish National Travel Survey* [25, 26], which offers a comprehensive, statistical overview of passenger transport in Denmark, based on daily travel activities. The analysis focused on Copenhagen residents with a driving licence who live in car-owning households, using the latest available data from 2022 and 2023. To account for seasonal variations, the driving behaviour was modelled for both the winter (December to February) and summer (June to August) periods. Distributions for travel frequency, purpose (work, errands, leisure), starting time, charging duration, and travel distances were extracted from the survey, as detailed in [27]. The resulting availability of EVs for charging and discharging is illustrated in Figure 2.

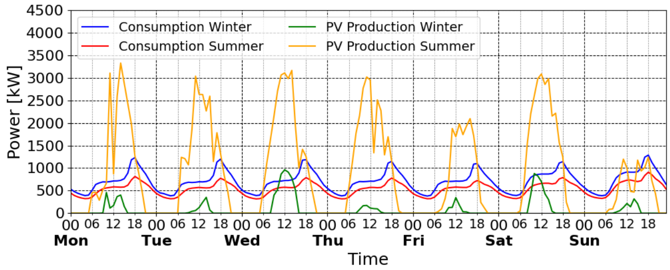

Fig. 1 Overview of electricity consumption and PV production for a winter and summer week.

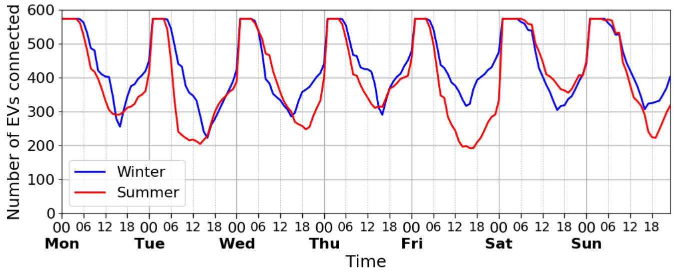

Fig. 2 Overview of the number of EVs connected in Fælledby over the course of both a winter (blue) and summer (red) week.

2.3 Optimisation Model

The optimisation problem was formulated as a mixed-integer linear programming one, aimed to minimise electricity costs for the energy community by determining the optimal charging and discharging patterns for each EV and the stationary battery. The problem was solved using the *gurobipy* solver for Python, with analyses conducted for both a winter and a summer week at an hourly resolution to account for varying demand and PV generation scenarios. Assuming complete knowledge of PV production, electricity prices, power consumption, and driving patterns throughout the period, the objective function was defined as follows:

$$\min_{\substack{E_{EV}(t)\\E_{BESS}(t)}} \sum_{t=1}^{168} (E_{IM}(t) \cdot p_{IM}(t) - E_{EX}(t) \cdot p_{EX}(t)) \quad (1)$$

subject to:

$$E_{IM}(t) - E_{EX}(t) = E_{LOAD}(t) + \sum_{n=1}^{574} E_{EV,n}(t) + E_{BESS}(t) - E_{PV}(t) \quad (2)$$

$$E_{IM}(t) \cdot E_{EX}(t) = 0 \quad (3)$$

where $E_{IM}(t)$ and $E_{EX}(t)$ represent the energy imported and exported during a given hour t at prices $p_{IM}(t)$ and $p_{EX}(t)$, respectively, from or to the power distribution grid. Constraint (2) links E_{IM} and E_{EX} to the decision variables $E_{EV,n}$ and E_{BESS}, which denote the energy absorbed or injected by either the n^{th} EV (out of the 574 projected ones), or the BESS. In this formulation, we assume that all the EVs that need to charge at time t are able to find an available outlet to do so. Meanwhile, Constraint (3) ensures that the community cannot both import and export electricity at the same time. Electricity prices were based on DK2 spot prices from 2020 [19] to align with the year of PV production, while 2023 taxes, tariffs, and VAT (25%) were applied [15, 28]. On average, the selling price is 0.03 €/kWh, while the buying price is 0.29 €/kWh.

Each EV was assumed to connect immediately upon arrival, and this happens at the times defined by the travel behaviour analysis (check Section 2.2). A battery capacity was assigned to each EV, with an average capacity of 75 kWh and a standard deviation of 10 kWh, reflecting a projected increase from current capacities. Energy consumption was standardised at 20 kWh per 100 km for all vehicles. Furthermore, the charge and discharge efficiency at a nominal power of 11 kW was conservatively set at 90%. To avoid overestimating the available energy, the initial state of energy (SoE) for the simulations was set to a conservative value of 20 kWh.

Further constraints for the different scenarios were imposed based on the parameters detailed in Table 2. All scenarios shared the same constraints on minimum and maximum EV charging power, state of charge (SoC), and the grid import/export limit of 3700 kW, representing the total power capacity of the transformers supplying Fælledby. In the BESS scenario, additional constraints were applied to the minimum and maximum SoC of the BESS, as well as the maximum charging and discharging power, which was set at 3240 kW as in the project description. The initial SoC for BESS was set at a low level of 20% to avoid influencing the optimisation results with a huge energy content at the beginning of the simulation. In the V2B scenario, EVs were assumed to support both charging and discharging, with a maximum discharge rate of 11 kW. Further constraints were imposed on the SoC and SoE of the EVs during V2B operation. Based on research from [29], a maximum SoC of 80% was chosen to minimise cycle degradation and preserve battery health. Furthermore, a minimum SoE of 20 kWh was enforced to ensure that EVs maintain a minimum range of 100 km, preventing any inconvenience for users. For a more detailed mathematical description of the constraints, the reader is referred to the work in [27], which is not reported here for the sake of brevity.

Table 2 Summary of the key simulation parameters and their corresponding scenarios.

Parameter(s)	Value	Scenario
Min./Max. EV charging rate	0/11 kW	All
Min./Max. SoC EV	0/80%	All
EV charging efficiency	90%	All
Initial SoE EV	20 kWh	All
Max. power import/export	3700 kW	All
Min./Max. SoC BESS	10/95%	BESS
Max. (dis-)charge rate BESS	3240 kW	BESS
Initial SoC BESS	20%	BESS
BESS Capacity	4320 kWh	BESS
BESS Round Trip Efficiency	95%	BESS
Min. SoE EV	20 kWh	V2B
Max. EV discharging rate	11 kW	V2B
EV disch. efficiency	90%	V2B

3 Results

This section presents the findings of this study. We start by visualising the results for each season and scenario. Next, we evaluate the costs and net present value (NPV) of each technology. Finally, we conduct a sensitivity analysis concerning the number of V2G-capable EVs and chargers.

3.1 Overview of Scenarios

Before analysing the costs of the different scenarios, we provide an overview of the community's energy demands, as illustrated in Figure 3.

The top left graph depicts the *V1G Summer* scenario, characterised by an inadequate storage capacity that results in significant power exports while being dependent on power imports during non-PV hours. Notably, on Wednesday, there is a significant increase in export and a corresponding decrease in EV charging, attributed to the EVs reaching their maximum SoC.

The bottom left graph illustrates the *V1G Winter* scenario, characterised by an increase in power imports and a lack of exports due to low PV production. EVs are predominantly charged during off-peak and low-cost nighttime periods. Furthermore, since daily driving distances are short, daily charging is not required; instead, charging occurs on days with the lowest electricity prices, e.g on Wednesday in Figure 3.

The top centre graph represents the *BESS Summer* scenario. In comparison to V1G, both power imports and exports are reduced, as the BESS stores surplus PV power generated during the day for use at night. However, the battery capacity is insufficient to meet overnight demand entirely, necessitating power imports when prices are lowest, typically around 03:00.

The *BESS Winter* scenario is depicted in the bottom centre graph. Contrarily to V1G, the BESS is capable of meeting a

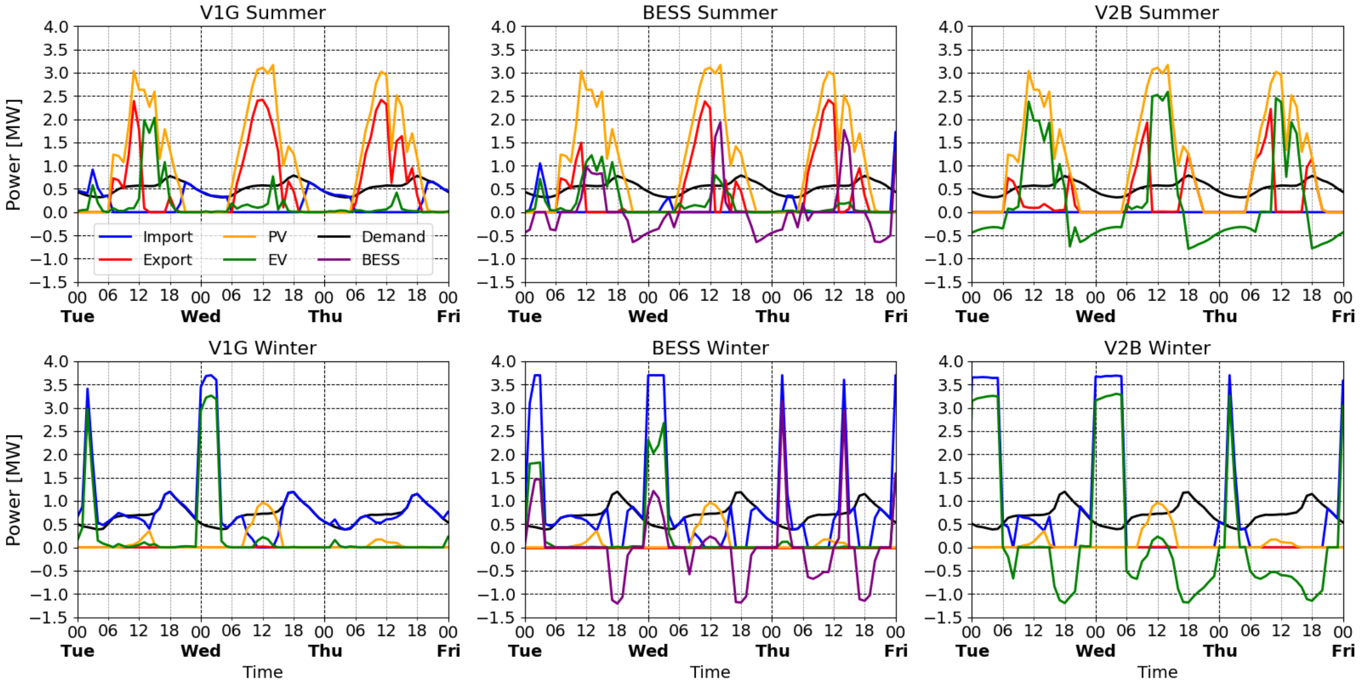

Fig. 3 Results for three selected days of the simulated summer (top) and the winter (bottom) weeks for V1G (left), BESS (center), and V2B (right).

portion of the peak demand during periods of high electricity prices around 18:00. On specific nights, power imports reach the maximum grid connection capacity of 3700 kW to charge the BESS and/or meet overnight demand. On Thursday, notable charge and discharge cycles occur during the day, driven by higher morning prices compared to midday prices.

The top right graph displays the *V2B Summer* scenario, in which power imports are only required on Mondays, resulting in no imports visible for the visualised days. The EVs store enough energy generated from PV production throughout the day to meet demand during periods with no PV generation. In addition, surplus PV energy is sold during times of high electricity prices.

Finally, the graph on the bottom right illustrates the *V2B Winter* scenario. Similarly to the BESS scenario, the grid connection of 3700 kW is fully utilised on certain nights for charging and meeting residential demand. However, power imports decrease during specific hours due to the larger aggregate storage capacity of the EVs. The availability of EVs at home, shown in Figure 2, influences their ability to meet the community's energy demand. This is particularly evident on Tuesday, when daytime availability is lower than on other days.

3.2 Economic Analysis

The first metric for evaluating the results is the total net expenditure on electricity. This metric reflects the overall costs associated with electricity procurement, offset by the revenues generated from electricity sales. The net costs for each scenario, calculated for both the summer and winter week, are presented in Table 3.

Table 3 Comparison of electricity costs for each scenario.

	V1G	**BESS**	**V2B**
Net costs summer week [k€]	8.96	2.81	0.24
Net costs winter week [k€]	42.1	36.2	33.7
Estimated annual costs [k€/a]	1422.8	1160.4	978.7

The V1G scenario results in the highest costs in both seasons. In contrast, the V2B scenario proves to be the most economically efficient, yielding the lowest net costs in both summer and winter weeks. Compared to the BESS scenario, the V2B scenario saves the community roughly 2563 € in the summer and 2571 € in the winter. When compared to the V1G scenario, the savings are even more significant, amounting to approximately 8400 € and 8715 €, respectively. These results indicate that the V2B scenario is more effective than both the BESS and V1G scenarios at utilising the electricity produced by the PV panels during the summer week. Furthermore, the V2B scenario also demonstrates advantages during the winter week, when PV electricity production is minimal.

The costs were annualised by scaling them to 28.9 winter weeks and 23.1 summer weeks, ensuring that the ratio of PV production to electricity consumption reflected the annual distribution. This method was adopted because PV production and electricity consumption are the primary factors influencing total costs. The corresponding estimated annual costs are provided in the last row of Table 3. The results illustrate how the weekly price differences accumulate over time, revealing distinct cost disparities across all three scenarios. Given that the V2B scenario was the most cost-effective during both the

Table 4 Summary of key cost parameters for the economic analysis.

Parameter	Value	Unit
CAPEX BESS	579	€/kWh
CAPEX BESS Total	2502.5	k€
OPEX BESS	8	€/kW
OPEX BESS Total	25.3	k€/year
Additional CAPEX V2B AC	0	k€/unit
Additional OPEX V2B AC	0	k€/year
Additional CAPEX V2B DC	2.9	k€/unit
Additional CAPEX V2B DC	1716.3	k€
Additional OPEX V2B DC	0	k€/year
Lifetime BESS/EV Chargers	15	years
Discount Rate	5	%

Table 5 NPV of V2B and BESS scenarios.

	BESS	V2B AC	V2B DC
NPV [k€]	1.2	4580	2870

summer and winter periods, it also emerges as the least expensive option on a yearly basis. Compared to the V1G scenario, the V2B scenario offers annual savings exceeding 400 k€. Furthermore, it yields over 180 k€ in savings relative to the BESS scenario. Consequently, the residents of Fælledby would experience a significant reduction in their electricity expenses.

However, our analysis so far does not account for the capital expenses (CAPEX) and operational expenses (OPEX) associated with each technology. To gain a more comprehensive understanding of the economic value of BESS and V2G, we evaluate the net-present value of money (NPV), using the cost estimates and parameters specified in Table 4 and further detailed in [27]. The NPV is calculated as $\mathrm{NPV} = \sum_{t=0}^{T} \frac{CF_t}{(1+r)^t}$, where CF_t denotes the cash flow in year t, with r as the discount rate, set at 5% (150% of the one suggested by the National Danish bank) and T as the time horizon, matching the expected 15-year lifetime of the battery and bidirectional chargers. The initial cash flow, CF_0, is defined as the additional CAPEX for either the BESS or the V2B EV chargers compared to the standard V1G ones. We assume that 574 EV charging outlets are installed to be able to supply all the EVs that need to charge simultaneously. For $CF_t > 0$, the cash flow is determined by subtracting the OPEX from the savings. The savings are defined as the reduction in electricity costs relative to the V1G scenario, which serves as a baseline due to its zero CAPEX (no additional installations or upgrades beyond the planned installation). The CAPEX for the BESS encompasses installation, the inverter, and the battery management system. In contrast, the additional CAPEX and OPEX for a V2B AC charger, compared to V1G, are considered negligible since these costs are associated with the EV rather than the charger. However, for the DC V2B charger, there is an additional CAPEX of 2.9 k€/unit, as outlined in the community project description, while the OPEX remains null, assuming maintenance requirements are identical to those for V1G chargers.

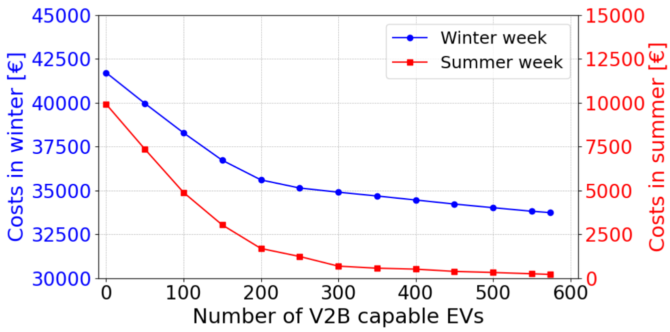

Fig. 4 Sensitivity analysis of electricity costs relative to the number of EVs with V2B capability for winter and summer weeks.

The NPV for both the BESS and the AC and DC V2B outlets is presented in Table 5. The V2B system demonstrates clear economic advantages, regardless of the charger type. In this case study, V2B emerges as a more attractive investment compared to the BESS, which barely reaches a break-even point. This is primarily due to the BESS's limited capacity, constrained by the community's energy design, and the fact that the cost of the EVs are covered by the inhabitants because they primarily are a mean of transportation.

3.3 Sensitivity Analysis

Two sensitivity analyses were carried out with respect to the electricity costs and NPV. The first sensitivity analysis aimed to determine how the number of EVs with V2B capability influences the net electricity costs for Fælledby, helping to identify the minimum number of EVs required to establish a viable business case. In this analysis, only the number of EVs with V2B capability was varied, while the total number of EVs and outlets remained constant at 574. A total of 13 simulations were conducted for both summer and winter, with each simulation progressively reducing the number of EVs with V2B capability.

As illustrated in Figure 4, the relationship between electricity costs and the number of V2B-capable EVs shows similar trends in both summer and winter. Between the maximum of 574 and 300 EVs, the cost increases slightly in a linear fashion, with the winter scenario exhibiting a marginally steeper slope. This suggests that, with a reasonable number of EVs, both summer and winter scenarios perform almost equivalently to the scenario with 574 V2B-capable EVs. However, when the number of V2B-capable EVs falls below 300, the costs begin to rise exponentially. This indicates insufficient EVs to effectively utilise excess PV production or to perform peak shaving during high-price periods. As the number of V2B-capable EVs continues to decrease, the system's capacity to store excess PV energy and perform peak shaving diminishes, leading to a more pronounced increase in costs.

The second sensitivity analysis, shown in Figure 5, examines the impact of the number of V2B-capable DC outlets on the NPV when treated as the limiting factor. The findings suggest that the optimal number of DC outlets is around 300. Therefore,

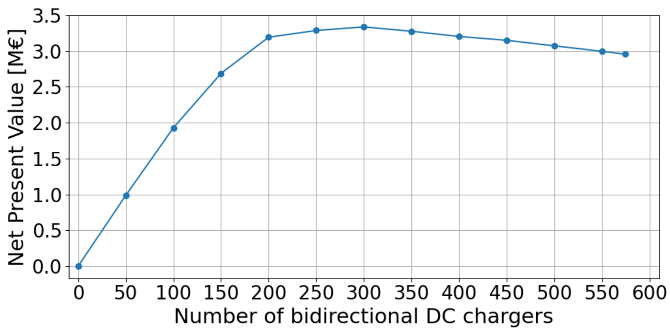

Fig. 5 Sensitivity analysis of the NPV relative to the number of bidirectional capable DC outlets.

reducing their number to 300 increases the NPV by approximately 0.4 M€ compared to the NPV for 574 outlets. At 300 outlets, the NPV reaches its maximum, nearly 3.4 M€. Regardless of charger type, the NPV remains quite high, underlining the strong economic viability for V2B.

4 Conclusion

This paper sought to compare the economic impact of deploying unidirectional charging, unidirectional charging combined with a BESS, and bidirectional charging in a planned energy community in Copenhagen, Denmark. The main findings of this work can be summarised as follows:

- Based on the assumptions made, the simulations show a significant economic advantage in implementing V2B, as the NPV of the V2B system remains considerably higher than both the BESS and the V1G systems. Moreover, the V2B scenario consistently outperforms the other two, both in winter and in summer.
- In summer, the significant aggregated storage capacity of the EV fleet facilitates the capture of sufficient PV production to meet nighttime consumption. In winter, the ample availability of EVs allows for charging when electricity prices are low and discharging when prices are high.
- The proposed BESS capacity of 4.32 MWh, as specified by the energy community project description, is insufficient to fully meet the energy demand during periods when PV production is unavailable in both summer and winter.
- A system comprising approximately 300 EVs and chargers with bidirectional charging capability is deemed optimal, as any additional increase beyond this point leads to marginal reductions in electricity costs and a decline in NPV.

The findings indicate that bidirectional charging could become a key element in the evolution of energy communities. By allowing EVs to serve multiple purposes beyond transportation, significant energy savings can be realised. Additionally, V2B maximises the use of local PV production. The NPV calculated in this study underscores the practical feasibility of this approach, and highlights the notable benefits it offers over both BESS and V1G systems. However, it is essential to highlight that the study's findings rely on energy community members being allowed to freely share energy between buildings without grid tariffs, which is currently not permitted in Denmark. Therefore, the conditions for energy communities in Denmark should be improved. Additionally, a widespread adoption of bidirectional charging is essential, alongside the development of grid codes that allow for power injection from EVs.

4.1 Future Research

Based on the findings of this study, several promising direction for future research should bet explored. First, investigating the accuracy of prediction tools for optimising energy storage in communities is essential, particularly regarding their practical viability. Additionally, future work could focus on gathering and utilising driving data from EV owners to enhance the prediction accuracy. Furthermore, simulating scenarios with imperfect knowledge by incorporating prediction models for PV production, electricity prices, consumption, and driving data would yield a more realistic assessment of the value of V2G systems. Extending these simulations to cover an entire year could provide further insights. Comparative studies across different global contexts could also offer valuable insights and inform international legislation, facilitating the broader adoption of EV technologies. Lastly, it is important to explore strategies for engaging with EV owners, especially considering the potential side-effects associated with V2G, to ensure successful implementation.

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6 CRediT authorship contribution statement

F. Pastorelli: Conceptualization of this study, Supervision, Writing–original draft preparation, Literature review. **T. Unterluggauer:** Conceptualization of this study, Supervision, Writing–original draft preparation, Visualization. **B. J. Höyer and M. M. Wagner:** Methodology, Software, Validation, Formal analysis, Investigation, Data curation **M. Secchi:** Writing–Review and editing. **M. Marinelli:** Writing–Review and editing, Supervision, Funding acquisition.

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