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Factors influencing the economic success of grid-to-vehicle and vehicle-to-grid applications—A review and meta-analysis

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ABSTRACT

The growing number of plug-in electric vehicles (PEVs) has resulted in increasing availability of battery storage capacities. When PEVs are idle and plugged-in, secondary applications such as energy trading, frequency and load control can use this storage capacity. The existing literature on economic benefits of such applications shows inconsistent and contradictory results. To shed light on the reasons behind these different results, this paper uses a quantitative meta-analysis to identify key drivers of the economic benefits, based on 340 cases published between 2010 and 2018. The analysis shows that the two applications load leveling and participation in the secondary frequency market provide the highest economic benefits for PEV controlled charging applications. Increased charging power and efficiency as well as bi-directional charging capability significantly improve the economic benefits even when taking battery degradation into account. These findings highlight the importance of the charging technology and the last-mile charging infrastructure. Policymakers and grid operators should focus on integrating this technology into the existing infrastructure. Automakers can draw on our results to improve the charging technology of PEVs.

1. Introduction

Sufficient electricity storage capacity is one of the bottlenecks in the fight against climate change and the transition towards a carbon neutral economy. Intermittent power generation from solar and wind requires storage capacity in order to match fluctuating supply and demand. There is a growing interest in the storage capacity potential of plug-in electric vehicles (PEVs) that are charged from the grid. They include both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). While the former are driven only by an electric motor powered by an on-board battery, the latter have an additional internal combustion engine in their drive train and typically a battery with less capacity.

In many countries, the market share of PEVs among car sales is growing significantly. Reasons include governmental subsidies and a decrease in technology cost, such as battery manufacturing costs [1]. The global stock of PEVs increased from 5000 in 2008 to over 7 million PEVs in 2019 [2]. The total stock of PEVs worldwide is projected to reach between 140 and 240 million by 2030 [2]. Assuming an average capacity of 50 kWh, a total battery storage capacity of 7.5 to 12.5 TWh will by then be available.

This storage capacity can be used for secondary applications such as energy trading, frequency control and load control. With energy trading, PEVs are utilized to achieve price arbitrage in electricity spot markets [3] Frequency control is a necessity in alternating current electricity systems to stabilize the frequency as supply and demand vary. PEVs are capable of participating in both positive and negative frequency control markets if regulations allow [4]. Finally, load control is utilized to reduce load peaks to prevent damage to lines and transformers. These applications can be performed with grid-to-vehicle (G2V) and vehicle-to-grid (V2G) technology [5]. With G2V, the charging is moved to a more beneficial time period. V2G allows the return of electricity to the grid. However, V2G applications lead to an additional degradation of the battery [6]. The communication and control for the PEV charging can be decentralized or organized by a central planner. A comprehensive review on the required communication architectures is available in [7].

Whereas energy trading is solely performed to generate economic benefits, frequency and load control also provide stable electricity grid operation, avoid congestion and reduced expansion needs of electricity grids. In this sense, controlled PEV charging has been shown to improve voltage levels [8–10], shift loads to time periods with less electricity demand to avoid overloads in the electricity system [8,11–14] and even minimize the power losses that occur in these systems [8,10,15]. Ultimately, controlled PEV charging can relieve distribution grid congestion [16–19]. Similar controlled PEV charging approaches can

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List of Abbreviations

ANOVA	Analysis of variance
BEV	Battery electric vehicle
G2V	Grid-to-vehicle
OLS	Ordinary least squares
PEV	Plug-in electric vehicle
PHEV	Plug-in hybrid electric vehicle
RES	Renewable energy sources
V2G	Vehicle-to-grid

help to integrate larger shares of renewable energy sources (RES) by avoiding the congestion in electricity grids [20–26]. This is in addition to the already existing environmental benefits from the electrification of transportation as investigated by [27]. For an in-depth review on the potential upsides that controlled PEV charging can provide for electricity systems refer to [28].

One of the obstacles to implementing controlled PEV charging is that its economic benefits are difficult to quantify. There have been numerous studies on the economic benefits from G2V and V2G, but the overall picture is still fuzzy. Studies are difficult to compare because they consider different objectives, different market conditions, and different technical conditions. Overall, economic benefits from these applications lie between €–300[1] and €4140[2] [29,30]. While it is clear that different applications are associated with different benefits, even within a single application, economic benefits vary considerably. For example, [30] and [31] report revenues between €0 and €4090 for energy trading. This variation even holds on the country level, e.g., secondary frequency control in the USA can achieve between €23 and €4140 [32,33]. And even within a single publication, revenues can range between €–25 and €4000 [33]. These large variations in reported revenue from controlled charging have not been directly explained in the literature. Neither, to our knowledge, has any research been done to identify the key drivers that influence these variations.

The existing literature is not able to explain these huge differences in the economic benefits. There is broad evidence that controlled PEV charging applications have a reasonable revenue potential from energy trading [3,30,34], load control [26,33,35] and frequency control [4,36,37]. This has been shown for both BEV and PHEV [4,36,38], and for different countries [39]. However, the size of the benefits varies widely as described above. This could be attributed to varying modeling approaches between publications but also to different assumptions and base scenarios. An overarching understanding of what combines and differentiates the currently existing findings is still missing. Existing studies did not attempt to reconcile inconsistent findings. Therefore, it is still unclear, which G2V and V2G applications provide the highest economic benefits, and which drivers influence these benefits. The present paper closes this gap. Taking a wider view on the existing literature allows to aggregate and build on existing knowledge to learn more on the general effects rather the implementation success of individual use cases. The novel contribution of this study is to identify the factors that drive the economic benefits of G2V and V2G applications based on the vast existing literature on this topic.

In order to do this, a quantitative meta-study of a total of 340 controlled PEV charging cases in the literature is performed. The analysis identifies potential drivers of economic benefits and individually tests their correlation with reported economic benefits to narrow the parameter space. A multivariate approach is used to extract the most relevant drivers of economic benefits. The remainder of the paper is organized as follows. Section 2 explains the different economic G2V and V2G applications. Section 3 describes the methodology of our literature analysis. Section 4 presents the data. Section 5 discusses the results and Section 6 concludes.

2. Applications of controlled PEV charging

The following section describes the three applications of controlled PEV charging, energy trading, load control and frequency control.

2.1. Energy trading

This subsection summarizes the literature on charging cost reduction and price arbitrage as energy trading. Both rely heavily on varying electricity prices to generate benefits. For charging cost reduction the benefits stem from choosing the price-optimal time frame to perform the charging operation [3]. With price arbitrage, the additional discharging capability of V2G allows the trading of positive and negative energy. This can generate additional profits by selling energy from the PEV back to the market during periods of high prices [40]. In other terms, PEV charge their batteries when prices are low at the electricity market and discharge during times of high demand, low generation and overall high electricity prices. This can achieve further benefits for the energy system, e.g., increasing supply and demand fit and reduced market price volatility.

[3] and [30] compare both, charging cost reduction and price arbitrage applications. [30] find that charging cost reduction is economical in all cases, whereas price arbitrage strategies are only viable when wind power is available, likely a result from the increased price volatility that expands the potential for price arbitrage. [3] analyze PEV energy trading in the German market and find that charging cost can be reduced by more than 32%, which can be further expanded with increasing (dis-)charging power.

However, most research focuses only on price arbitrage strategies. [34] and [40] address applications in the UK. The former focus on the PEV movements throughout an electricity distribution grid and the limits this creates whereas the latter compare price arbitrage to other applications. [34] find significant economic benefits from price arbitrage alone. [40] report price arbitrage in combination with participation at the capacity market as economically viable whereas [34] compare different applications. [31,33] and [41] approach the topic from the standpoint of utilizing battery capacity from PHEV in the US market. Findings show that the achievable, low profits will not incentivize PHEV owners to participate in price arbitrage [41] and that significant profits can only be generated if battery degradation cost is disregarded [31]. [33] find that the profits of price arbitrage lag far behind what other applications promise. [42] draw a similar conclusion for their test case of Western Australia. [31] and [41] analyze multiple charging efficiency levels; [31] also looks at varying battery capacities and [41] at different years and regions in the US. [33] and [42] compare parameters for the cycle-life and the battery cost, depth of discharge and available capacity. Additionally, [33] include different years, charging powers, degradation cost and applications.

Overall, electricity trading can generate economic benefits with the utilization of PEV batteries, however the magnitude is rather low. Especially for price arbitrage, research shows that the cost may easily overpower available revenues. The factors that drive the cost to become higher than the revenues are not defined in the literature. Parameters that are often compared for varying results are the charging technology, charging power and battery capacity as well as its cost.

[1] Negative revenues are due to the applied accounting approach, see Section 4.2.

[2] All currencies are inflation adjusted to 2018 and converted to Euros from the original values reported in the literature and reported in Euros per vehicle per year, abbreviated as €.

2.2. Load control

Load control modifies the load in a distribution or transmission system to prevent load peaks that surpass system capacity. This can achieve significant benefits for the energy system, most important in the short term is the avoidance of equipment failure. In long-term planning load control can reduce the necessary grid expansion and therefore overall system cost can be lower.. Furthermore, the introduction of controlled PEV charging can smooth the renewable energy generation load to facilitate the expansion of photovoltaic and wind power generation. We differentiate between peak shaving and load leveling as G2V and V2G applications, respectively.

To compare peak shaving and load leveling, [26] and [43] vary charging technology and battery cost parameters. [43] also study the aggregation of different numbers of PEVs and the necessary infrastructure investments. They find that the economic benefits depends on the level of connectivity to the grid and on the charging technology. V2G provides higher profits than G2V [26]. [43] report that benefits on the system level grow with participation rate but on the PEV unit level, lower overall participation is beneficial for the individual.

Further publications focus on load leveling applications with PEV batteries in varying contexts. [44] compare different PEV charging rates to find an optimal electricity pricing strategy that benefits the grid as well as PEV owners in India. They find that benefits for the PEV owner and the grid increase with higher charging power, depend on the battery cycle-life, and are different for vehicle owners or a grid companies as operators. [45] find that a V2G scheme increases a power system's ability to integrate generation from RES, but from an economic standpoint this would not be viable due to the high battery cost. They assess variations in PEV characteristics, such as range and energy consumption as well as the operator of the application. [35] investigates a tariff model for V2G energy feed-in that is similar to RES feed-in premiums for the case study of Canada. He finds that, depending on the situation; charging power, charging station investments, or battery degradation cost can have the greatest impact on the benefits. Finally, [33] state that load leveling for PHEV is only economically viable if combined with frequency control regulation.

In conclusion, the load control service for electricity grids can provide economic benefits when charging powers are high enough, the right charging technology is used, and battery degradation cost is not prohibitively high. The cost of discharging a PEV battery can be an argument for peak shaving with G2V over load leveling approaches with V2G. From an energy perspective load control with PEV can smooth out the load curve, avoid equipment failure and reduce costly grid expansion investments. Authors focus on who the operator of an application is (vehicle owner, grid operator or PEV aggregator) and what the technical (charging technology, battery cycle-life, range and energy consumption) and cost (battery cost and infrastructure investments) parameters are.

2.3. Frequency control

Frequency control is needed to maintain a stable alternating current frequency by balancing supply and demand at each point in time. A surplus of generation or demand leads to increasing or decreasing system frequency, respectively. Controlled PEV charging can achieve benefits for the system as charging can be controlled to ramp up and down to counteract variation in other demand and generation and reduce frequency fluctuations. PEVs can monetize this services through the available frequency control markets. Frequency control markets are typically differentiated into primary, secondary and tertiary control for fast, medium and long-term interventions, respectively.

Research has compared the three available markets concerning their economic viability for controlled PEV charging participation. [4] compare all three markets for PHEV and BEV in Germany and find that the primary and negative secondary control markets promise the highest benefits for both vehicle technologies. Additionally, they focus on a range of technical PEV and cost parameters. Compared to the positive (additional demand), the negative (additional supply) secondary control market allows the integration of nearly twice as many PEVs before saturation is reached [4]. This indicates that G2V technology may be enough for a large share of PEVs. The results of [39] confirm the advantage of the secondary control market for PHEV in Germany and show that in the Swedish market, expected profits are significantly lower. This holds true for Singapore, where [29] show that the secondary market promises higher revenues than the tertiary market driven by the anticipated battery degradation cost. They also compared different electricity prices, battery cycle-life, charging powers and efficiencies.

Further research mainly addresses case studies in the secondary market . For the case study of Germany, [46] look at optimal contract parameters for PEVs in a secondary market with varying electricity prices and technical PEV parameters. [47] analyze the secondary market for different numbers of participating PEVs. Both find low revenues and even negative profits. The same case for the Netherlands is more positive, where economic benefits can be up to €750 for certain PEV user groups and depending on technical PEV as well as charging parameters [38]. For the case of the USA, differences between regions show varying revenue potential, with New York as the most promising [48]. Overall, private as well as utility vehicles provide positive benefits in the USA [36,49,50]. Here, [36] also compare variations in technical vehicle and charging parameters. V2G can achieve revenues that are up to 17 times higher than G2V for secondary frequency control in the USA but comes with the drawback of additional battery degradation [51–53]. Looking at the tertiary frequency control market, research has mainly addressed the UK and USA. [54] compare a wide range of technical PEV and charging parameters, vehicle numbers and battery cost. For the USA , it has been shown that both PHEV and BEV can participate in the tertiary frequency control market with profits of up to €200 and €1500, respectively [37,55].

In conclusion, existing research provides information on PEV participation in frequency control markets in multiple countries, for various sub-markets and under varying conditions. In many cases a multitude of technical PEV and charging characteristics but also cost parameters and different markets are compared. Although results in terms of profits are mainly positive, in aggregation it is still unclear which variables are the key drivers.

3. Methodology

3.1. Research question

As outlined in Section 2, it is clear that extensive research is available on the subject of secondary applications of PEV batteries. However, an overarching understanding of the economic benefit drivers of such applications has not yet been generated. To fill this gap, a quantitative literature analysis based on published research cases that estimate the economic benefits of such applications is performed. From these studies, situational, application and vehicle related variables that may influence the reported economic benefits are extracted.

The economic benefits suggested in the literature vary widely. An understanding of the causes behind these variations can lead to further improved application approaches. Economic benefits are measured either by *Revenue* or by *Revenue net of battery degradation cost* (referred to as *Revenue net*). The second subtracts the battery degradation cost of V2G applications, often considered as major variable cost, from the *Revenue*. Reported annual *Revenue* ranges from €−300 for tertiary control in Singapore to €4000 for price arbitrage in Iran [29,30]. The *Revenue net* varies between €−330 for tertiary control in the UK and €3400 for secondary control in the USA [33,34]. These variations are not only due to structural differences between publications, [33] report a *Revenue net* between €−160 and €3400 for all three applications. But even within one application , variations are rather large. [41] report a *Revenue* between €3 and €300 with price arbitrage. For frequency control, [29] and [39] find a *Revenue net* from €−1600 to €260 and from €−700 to €5200, respectively.

The existing literature often deals with a single application, country, vehicle type and charging technology and only a limited variation of these dimensions is analyzed. Research focused on a single application exists for energy trading (e.g., [31,41,42]), load control (e.g., [35,44,45]) and frequency control (e.g., [38,46,54]). An exception are [34] and [56] who assess applications from frequency control and energy trading for the UK and USA, respectively. Similarly, [33] model applications from trading, load control and frequency control for the USA. A multi-country approach is only taken by [39], who look at frequency control applications in Sweden and Germany.

Several literature reviews address the benefits of controlled charging in some way, but none focuses on the economic benefits of controlled PEV charging across multiple scenarios. [57] qualitatively specify the operation of controlled charging and its benefits. [58] describe the applications and claim that economic benefits are dependent on the charging and vehicle aggregation strategy. [59] focus on the interaction between fleet operators aggregating PEVs for charging and other players in the energy system. [60] address the literature on economic benefits of controlled charging applications but do not infer influencing factors nor explain reasons for large deviations. [61] focus on dispatching strategies of controlled charging to achieve economic benefits. [62] describe business models of controlled charging and the value they bring to different stakeholders in the energy system. [63] approach controlled charging by modeling PEV charging behavior and charging stations. Finally, [7] describe the underlying technological architecture that is needed for controlled charging and address some impacts on the economic benefits. In short, the existing literature does not provide an aggregated view of existing studies explaining the driving forces behind the economic benefits of controlled PEV charging applications.

In summary, research to date has addressed the secondary utilization of the battery capacity in PEVs. The resulting economic benefits vary widely, and a clear explanation of the causes has not yet been given. Consequently, this paper poses the following question: What are the key variables that drive the economic benefits of secondary PEV charging applications? To understand how the application, the location and other factors influence the benefits, an overarching perspective on the available cases in the literature is taken.

3.2. Research design

The analysis is based on a three-tier research design in order to understand the key drivers of economic benefits from controlled charging of PEVs. First, potential drivers from the literature are identified and collected for all published cases of controlled PEV charging. The analysis relies on variables that authors use as the inputs for their simulation models as potential benefit drivers. Additionally, control variables based on [64] are included. Second, the correlations of these potential economic benefit drivers are individually tested with the *Revenue* and *Revenue net* of controlled PEV charging. In the practical application of controlled PEV charging, the potential benefit drivers occur in combination with each other. Third a multivariate approach is used to test the combined effect of all relevant variables on the expected benefits to identify key drivers. The ordinary least squares (OLS) models for *Revenue* and *Revenue net* are designed as follows:

$$\begin{aligned} Revenue/Revenue\ net_i = \alpha_0 \\ + \alpha_1 \cdot Objectives_i \\ + \alpha_2 \cdot Market\ conditions_i \\ + \alpha_3 \cdot Technical\ conditions_i \\ + \alpha_4 \cdot Controls_i \end{aligned} \quad (1)$$

Eq. (1) describes the linear relationship between the two dependent variables *Revenue* and *Revenue net* and the set of independent variables *Objectives*, *Market conditions*, *Technical conditions*, and *Controls*. This equation allows to identify and quantify the combined effect of all relevant variables on the expected benefits from controlled charging. *Revenue* and *Revenue net* measure the economic benefits without and with battery degradation cost, respectively. *Objectives* includes the application performed and the operator. The *Market conditions* define the setting under which controlled charging is performed. The *Technical conditions* characterize the technical variables of the PEV and the charging infrastructure. Finally, the *Controls* describe author-, publication- and research approach-related control variables.

3.3. Data collection

Relevant research from the existing body of literature is selected in a process suggested by [65] and [66] by (1) identifying, (2) screening, and (3) filtering relevant publications. All literature is included that matches the search criteria independent of the subject field (e.g., economics and engineering). Quantitative data [64] is (4) extracted, (5) enrichedbased on information provided both by the authors and gathered from third party sources [67] and finally (6) harmonized. The whole process is as follows:

1. Key publications are identified from high-ranked peer-reviewed journals that address economic benefits of controlled PEV charging. From these, key words are extracted to use them as filters for a broader search[3], not limited to peer-reviewed journals to avoid selection biases . [64] Based on these keywords 91 publications from major literature databases[4] are identified.
2. The selected publications are screened to confine them to those which refer explicitly to the benefits of controlled charging or G2V/V2G concepts for PEVs. Publications that do not provide economic data such as revenues on a PEV basis (e.g., [68–77]), which do not calculate their own controlled PEV charging case (e.g., [61–63,65,78]) or which do not match our research topic (e.g., [79–83]) are excluded.
3. Publications that do not perform their own analysis but review literature, do not evaluate the economic benefits quantitatively or look at detailed aspects of controlled charging also are excluded. This is the case, for example, for the assessment of the economics of battery degradation or the assessment of the willingness to pay for V2G vehicles.
4. As a result, data from 35 remaining publications is extracted. Since publications may include multiple variations of input parameters, this lead to a total of 340 cases from 35 publications.
5. Gaps in the data set are directly filled through author contacts and third-party sources. The latter are used for additional information such as *Electricity price* and *RES share* for a considered country in a given year.
6. Finally, to make cases comparable, all monetary variables are converted to 2018 values based on historical inflation rates and to Euros. Where possible, missing values are calculated from available information, e.g., the outcome variables as described in Section 4.1.

The publications included in this data collection process are shown in Table 1 and the data set is described in detail in Section 4.2.

[3] See Appendix A, Fig. 2.

[4] Science Direct, the digital library of the Institute of Electrical and Electronics Engineers (IEEE), EBSCO, Springer, JSTOR, ProQuest and Google Scholar.

Table 1
Number of controlled charging cases per publication.

Publication	Number of cases	Publication	Number of cases
[30]	4	[48]	2
[39]	18	[29]	5
[54]	26	[41]	43
[46]	8	[84]	82
[4]	10	[85]	8
[44]	6	[35]	2
[32]	1	[56]	2
[36]	4	[3]	2
[26]	4	[37]	16
[86]	1	[31]	6
[34]	2	[55]	8
[38]	4	[51]	4
[47]	2	[52]	6
[40]	1	[53]	3
[45]	16	[87]	3
[43]	6	[33]	1
[49]	1		
[42]	2	Total	**340**

4. Data

4.1. Variable description

The quantitative meta-analysis starts by defining variables that are potential drivers of the economic benefits of controlled PEV charging. They are gathered from expectations and results offered in the literature as well as from discussions with researchers in the area of energy markets. Five categories of independent variables and one category for the dependent variables are collected. The independent categories are objectives, market conditions, technical conditions, controls and cost. The dependent category are the economic benefits. Fig. 1 gives an overview of all potential drivers that are included in each of these categories.

The objective that can be performed with a PEV follows the logic outlined in Section 2. Variables include the *Application* and the *Sub-application* as well as the *Viewpoint*. The *Application* differentiates between energy trading, load control and frequency control. These are detailed in the *Sub-application* into charging cost reduction or price arbitrage; peak shaving or load leveling and secondary, primary or tertiary frequency control, respectively. In addition, the *Viewpoint* differentiates the economic benefits for an individual PEV owner, an aggregator that controls multiple PEVs, or an electricity grid operator. *Application* is expected to have a significant effect as shown in [33] and [34]. Additionally, the *Sub-applications* differ greatly in their economic benefits [3,4,26,43]. For the *Viewpoint*, contradictory effects have been reported [44,45] and this variable may be dependent on some moderating parameter. Market conditions describe the location and energy characteristics in which stakeholders implement their charging solutions. Location variables include the *Continent* and *Country* with the respective *Inflation factor* and the *Year of simulation* for which a given case examines an application. The energy characteristics comprise the *Energy archetype*, *RES integration*, *RES share* and *Electricity price* for the respective country. The *Energy archetype* groups countries with similar energy needs and energy production characteristics.[5] Location variables are expected to show a significant effect since they comprise several other influences, such as energy market regulation. Additionally, existing country comparisons show clear differentiation in terms of achievable benefits [39]. In line with this, the electricity price is likely to have an effect, especially on trading applications that highly depend on it. No effect is expected from the remaining energy variables since they have often not been reported and likely not been considered in publications.

Vehicle and charging variables are summarized under technical conditions. The vehicle variables comprise *Vehicle technology* (BEV versus PHEV), *Battery lifetime*, *Battery capacity*, *Driving range* and the *Provided capacity* for the application. The charging variables contain *Charging technology* (G2V versus V2G), *Charging power*, *Depth of discharge*; and *Efficiency round-trip*. Concerning PEV technology, BEV is expected to achieve higher benefits than PHEV, which is reflected in individual publications [36,38], because larger battery capacities result in higher flexibility in the usage. In line with this argument are higher benefits with increasing *Driving range*, *Battery capacity* and *Provided capacity* [31,42,45]. However, other findings are inconclusive on this topic [38,54]. For the charging variables, the *Charging technology* is expected to have a significant impact, with V2G showing higher *Revenue* [36,56] and *Revenue net* [43,52,53] than G2V. In addition to this, the literature predicts significant positive effects of increasing *Charging power* on *Revenue* [38,44] and *Revenue net* [3,29,33].

The cost variables of *Battery cost*, *Battery degradation cost* and *Infrastructure investments* are collected to harmonize findings between publications. Depending on the author, setting and research question, *Revenue*, *Revenue net* or both are reported. Additionally, the cost types included vary between publications. Typically, *Battery degradation cost*, *Infrastructure investments*, both or even a number of mainly small other costs are taken into consideration. Research has shown that the *Battery degradation cost* engulfs a large share of the revenues and can lead to losses rather than profits [3,30,31,34]. In the further approach, the mentioned cost types are utilized to harmonize *Revenue* and *Revenue net* between publications.

Control variables that are related to a publication itself rather than the findings in it are further gathered. These control variables are an important part of any meta-analysis and potentially moderate the effects that are present [64]. They relate to the publication, the author, and the approach taken in the research. For the publication the *Year of publication*, *Journal ranking*, *Data availability*[6] are gathered. For example, the *Year of publication* is included to understand, whether earlier studies differ from later ones. The authors are defined by their *Background*,[7] *Number of publications*, *Number of authors* and the *First author's gender*. The Approach is defined by the *Research method* and the *Aggregating model*.[8] Regarding their *Background*, researchers with a technology background may be more conservative and aim for perfect implementation compared to economics researchers.

The economic benefits in *Revenue* and *Revenue net of battery degradation cost* are gathered as dependent variables. *Revenue* are the incomes of the provided service without any of the related costs. For the *Revenue net*, the battery degradation cost from discharging to provide a service are subtracted. Unfortunately, the *Revenue net* cannot be calculated for all cases in the literature since the necessary information is not always provided by the authors.

4.2. Descriptive statistics

The resulting data set includes 340 cases from 35 papers that simulate controlled charging for the years 2005 to 2030. It includes all applications defined in Section 2. The greatest number of cases are available for frequency control, followed by trading, and finally load control. On a more detailed level, price arbitrage and secondary frequency control are the most popular with over 100 cases each; charging cost reduction and primary load control are the least interesting

[5] Countries are organized into five different energy archetypes: Oil export maximizer, next-wave electrifier, energy-hungry, traditionalist, and green pioneer.

[6] Share of variables out of all variables shown in Fig. 1 that could be gathered for a particular case.

[7] Differentiated between technology and economics backgrounds.

[8] Differentiated between the aggregation of multiple PEVs into a pool and individual PEVs to provide a services.

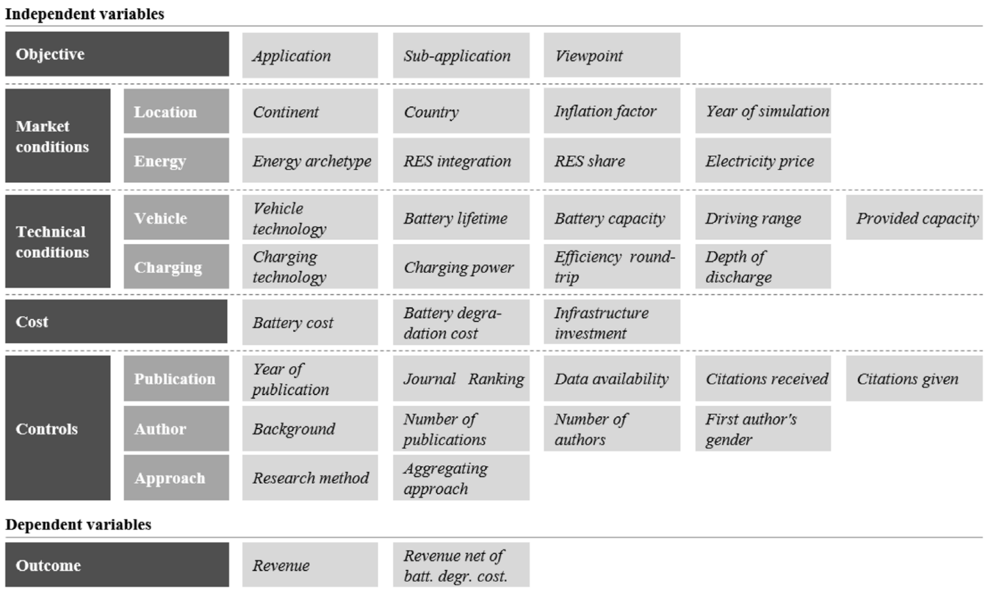

Fig. 1. Variables extracted from the literature.

Table 2
Summary statistics for numeric variables. Shown are the number of observations, variable means, standard deviations, minima, medians and maxima for all numeric independent and dependent variables.

		Num. obs.	Mean	Std. Dev.	Min.	Median	Max.
Market	*Inflation factor*	340	1.09	0.06	1.0	1.09	1.17
	Year simulation	273	2011.51	6.83	2003.0	2009.0	2030.0
	RES share	340	13.36	9.34	0.6	10.38	47.2
	Electricity price	340	0.17	0.19	0.03	0.09	1.15
Technical	*Battery lifetime*	47	6.0	4.41	1.4	4.7	12.0
	Battery capacity	340	20.52	10.7	4.0	16.0	99.0
	Driving range	340	112.35	80.75	16.09	89.28	425.0
	Provided capacity	340	16.76	8.51	2.8	14.7	69.3
	Charging power	312	9.4	10.62	1.0	7.2	63.0
	Efficiency round-trip	340	0.79	0.14	0.01	0.85	1.0
	Depth of discharge	340	0.82	0.1	0.2	0.8	1.0
Cost	*Battery cost*	340	315.88	204.77	0.0	259.06	1684.51
	Battery degradation	233	178.88	316.42	0.0	42.12	1901.93
	Infrastructure cost	99	107.35	108.36	0.0	75.8	628.42
Controls	*Year of publication*	340	2012.53	2.41	2010.0	2012.0	2018.0
	Journal ranking	340	2.24	0.51	0.26	2.2	3.97
	Data availability	340	54.97	1.3	51.0	55.0	58.0
	Citations received	340	210.85	192.13	7.0	116.5	598.0
	Citations given	340	26.7	9.12	15.0	24.0	73.0
	Number of publications	340	70.3	106.37	1.0	20.0	668.0
	Number of authors	340	3.66	1.23	1.0	4.0	7.0
Outcome	*Revenue*	248	346.02	834.4	−295.41	66.84	4138.4
	Revenue net	325	246.46	866.26	−1897.7	47.53	5213.52

to researchers with only 11 cases each. The distribution of cases per publication varies from six publications that only investigate one case each to three publications with more than 20 cases (Table 1). The data set covers 12 countries from North America, Europe, Australasia and Asia with 90% of all cases being from the USA, Germany, Singapore and the UK. The 340 cases are evenly distributed between BEV and PHEV simulations, however 90% of cases are interested in V2G rather than G2V charging strategies.

The descriptive statistics of the data set are shown in Tables 2 and 3. The dependent variables of *Revenue* and *Revenue net* have a mean of €341.65 and €244.46, respectively. The sample includes two variances of *Vehicle technology* and *Charging technology*, which are BEV and PHEV, and G2V and V2G, respectively. Some variables are highly skewed with a high number of occurrences for individual values, e.g.: *Research method*, *RES integration* and *Charging technology*. Only a single *Research method* is a practical demonstration; all other cases are simulations. Since most cases do not explicitly include RES, *RES integration* is generally not available.

Revenue is available for 248 cases and *Revenue net* for 325 cases out of the total of 340 cases. Benefits are largely clustered between €−1000 and €1000. The bulk of available cases were published in 2010, 2011, 2014 and again in 2016 and 2017. Multiple publications report negative revenues for both frequency and load control applications. The existence of negative revenues results from the way these revenues are calculated. When performing a PEV charging application, the electricity costs of the PEV charging process are directly considered in the revenues rather than as a separate cost type. Negative revenues can therefore occur if the cost of electricity purchased exceeds the payments received from ancillary service compensations [33]. Across the different *Years of publication* there is a continuous publication activity in this important field, but a positive or negative trend towards the benefit of controlled charging applications cannot be directly identified.

Table 3
Summary statistics for categorical variables. Shown are the number of observations, number of unique values the categorical variable can take and maximum occurrence of an individual value for independent categorical variables.

		Num. obs.	Unique	Occurrence Max.
Objective	*Application*	340	3	168
	Sub-Application	340	7	109
	Viewpoint	303	3	234
Market	*Continent*	340	4	171
	Country	340	12	169
	Energy archetype	340	5	216
	RES integration	340	3	305
Technical	*Vehicle technology*	335	2	169
	Charging technology	340	2	303
Controls	*Background*	340	2	220
	First author's gender	340	2	304
	Research method	338	2	337
	Aggregating model	340	2	198

However, there is a slightly higher degree of volatility in the *Revenues* in earlier studies. The same applies to *Year of simulation* as can be seen from Figs. 3 and 4 in Appendix B.

5. Results and discussion

In this section the impact of variables extracted from the literature on the revenues of controlled PEV charging applications is tested. Initially, base effects through correlations between individual independent variables and the revenue types are established. These base effects generate an understanding of the parameters that are related to either of the revenue variables. As a second step this knowledge is used to build a multivariate OLS model. The OLS model shows the relative importance of parameters in predicting the economic benefits. Cost variables are excluded because they are used to harmonize *Revenue* and *Revenue net* between publications to achieve comparable dependent variables.

5.1. Base effects

To estimate the base effects, the variables in the objective, market, technical, and control categories are correlated with the two outcome variables (refer to Fig. 1 for a complete list of variables in each of those categories). Overall, there are significant correlations with the outcome variables in each of the described categories, which are therefore used in the multivariate analysis in Section 5.2.

The objective variables are tested against the dependent variables with an analysis of variance (ANOVA). The categorical values of all three variables, *Application*, *Sub-application* and *Viewpoint* can be significantly differentiated concerning both dependent variables (see Table 4). The mean of the *Revenue* increases from €206.22 to €357.15 and €569.45 for trading, frequency control and load control. The same trend can be observed for *Revenue net* with €151.18, €237.57 and €523.84, respectively. Trading can be differentiated significantly from load control but not from frequency control for *Revenue* and *Revenue net*.

The ANOVA on the *Sub-application* is significant for both revenue types. The mean *Revenue net* is €450.50 for charging cost reduction and only €120.70 for price arbitrage. Concerning frequency control, it drops from €549.95 for secondary control to €361.79 for primary control and finally to €−337.30 for tertiary control. The load control applications have the most extreme difference between €52.86 and €994.82 for peak shaving and load leveling, respectively. Tertiary control, the *Sub-application* with the lowest mean benefit can be significantly differentiated from almost all other objectives for *Revenue* (except for peak shaving) and *Revenue net*. The take-away is that the *Sub-application* allows for an even clearer separation than the *Application*.

The *Viewpoint* also correlates with both revenue types. Therefore, the economic benefits are likely different for fleet aggregators, vehicle owners, or grid operators with a mean *Revenue net* of €−297.07, €327.98 and €728.40, respectively. For the multivariate approach, the variables *Sub-application* and *Viewpoint* are included to represent the objective variables.

For variables describing the location as part of the market conditions, the variables *Continent* and *Country* are correlated significantly with the dependent variables, see Table 5. However, *Continent* shows an association close to zero and *Country* a very weak association with the dependent variables. The literature does not contain enough variation in the parameters for each country and case classification to countries is skewed. Some countries have less than two cases and others nearly 170. Unfortunately, this does not allow a reliable conclusion in a multivariate approach and both variables are excluded. *Inflation* is also excluded, because it does not significantly correlate with either of the revenue variables. The *Year of simulation*, the year in which a case is set to take place, significantly, negatively correlates with both revenue types. This shows that revenues of controlled charging decline over time. In summary, only the *Year of simulation* is included in the multivariate approach.

For the energy-related variables, both *Electricity price* and *Energy archetype* are significantly correlated with both dependent variables (see Table 5). The *Electricity price* has a weak association with the revenue variables. The very weak association of *Energy archetype* is similar to *Country*, since *Energy archetype* is defined on a country level and groups each country into five categories. *RES integration* is only significant for *Revenue* with an association close to zero. *RES share* is only significant for *Revenue net* with a very weak association. Overall, the variables *RES share* and *Electricity price* are used to represent the energy-related variables in the multivariate analysis.

The vehicle variables are all in some way battery-related and are likely well represented by the *Vehicle technology* which differentiates between BEV and PHEV. This is apparent from the significant correlations between *Vehicle technology* and the other variables in the vehicle section (see Fig. 5 in Appendix C). The *Vehicle technology* correlates significantly with both revenue variables (see Table 6) and is therefore included in the multivariate model. On the same significance level, the *Battery lifetime* shows a moderate association with *Revenue* and *Revenue net*. Nevertheless, the *Battery lifetime* is not included in the multivariate approach since this information was only available for 47 out of the 340 cases. In contrast to the *Battery capacity*, the *Capacity provided* represents the share of a battery that is made available for controlled charging applications, excluding, for example, a minimum guaranteed driving capacity. Only the *Battery capacity* but not the *Capacity provided* is significant for the *Revenue* variable. Consequently, we only include the *Battery capacity* in the multivariate model. The *Driving range* does not have a significant relation with either revenue types of controlled charging. Overall, the *Vehicle technology* already explains a large share of the variation in the electric *Driving range* of a vehicle. For these reasons, all vehicle-related factors are included via the variables *Vehicle technology* and the *Battery capacity*.

Concerning the charging variables, the *Charging technology* itself does not show any correlation with the dependent variables. This is rather unexpected since the difference between G2V and V2G opens a new dimension of charging control, namely discharging, i.e., providing energy to a system. The *Charging technology* alone may not correlate with *Revenue* or *Revenue net* in the available data, but since it is such a central decision for controlled charging applications, and interactions with other design variables are possible, it is included in the multivariate approach. The variables *Charging power* and *Depth of discharge*, which are significantly correlated with at least one of the dependent variables are also included in the multivariate approach. Finally, the efficiency measure; *Efficiency round-trip* is significantly correlated with

Table 4
Correlation of objective and revenue variables. Shown here are the coefficients and significance of an ANOVA between the categorical independent and the dependent revenue variables. Number of observations: *Revenue*: 248, *Revenue net*: 325.

		Revenue		*Revenue net*	
Application	Trading$^+$	206.22***	(62.95)	151.19***	(43.83)
	Frequency control	150.93	(97.54)	86.38	(90.79)
	Load control	363.23*	(188.7)	372.65**	(166.04)
	F	2.53*		2.74*	
Sub-application	Charging cost reduction	450.49*	(235.27)	787.8***	(253.07)
	Price arbitrage	168.89***	(65.04)	458.0***	(103.16)
	Primary control	292.11***	(34.09)	699.09*	(358.95)
	Secondary control	523.95***	(106.88)	887.26***	(140.35)
	Tertiary control$^+$	0.01	(13.79)	−337.3***	(94.25)
	Peak Shaving	22.99	(18.01)	390.16***	(97.48)
	Load leveling	1115.88***	(322.62)	1332.12***	(307.38)
	F	19.18***		9.18***	
Viewpoint	Fleet aggregator$^+$	129.64***	(31.7)	−27.7	(92.06)
	Vehicle owner	261.22***	(76.1)	355.69***	(107.54)
	Grid operator	564.77*	(335.84)	756.1**	(340.57)
	F	7.09***		6.59***	

$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$, $^{+}$*Intercept*.

Table 5
Correlations of market and revenue variables. Shown here are correlations between selected independent and the dependent revenue variables, reported as R^2-values and significance of a one-way ANOVA for categorical; and r-value, and significance of Kendall's Tau for non-categorical independent variables.

		Revenue	*Revenue net*
Location	*Continent*	0.055***	0.056***
	Country	0.181***	0.182***
	Inflation	−0.026	0.025
	Year simulation	−0.247***	−0.186***
Energy	*Energy archetype*	0.159***	0.096***
	RES integration	0.047***	0.011
	RES share	−0.038	0.113***
	Electricity price	−0.212***	−0.189***

$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

Table 6
Correlations of technical and revenue variables. Shown here are correlations between selected independent and the dependent revenue variables, reported as R^2-values and significance of a one-way ANOVA for categorical; and r-value, and significance of Kendall's Tau for non-categorical independent variables.

		Revenue	*Revenue net*
Vehicle	*Vehicle technology*	0.043***	0.058***
	Battery lifetime	0.343***	0.575***
	Battery capacity	−0.101**	−0.009
	Capacity provided	0.019	0.055
	Driving range	−0.038	0.017
Charging	*Charging technology*	0.005	0.0
	Charging power	−0.012	0.103**
	Efficiency round trip	−0.096**	−0.066*
	Depth of discharge	0.299***	0.238***

$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

both dependent variables. Therefore, it is also included. The full results are shown in Table 6.

Of the publication-related control variables, all show at least one significant correlation with either of the revenue variables (see Table 7). The negative correlation coefficient of *Year of publication* indicates that later publications are more skeptical of controlled charging applications and forecast lower benefits. Higher ranked journals seem to publish more research that is positive with respect to controlled charging, as indicated by the positive, significant correlation coefficient of *Journal ranking*. Additionally, the *Data availability* significantly correlates with *Revenue net*. Finally, both the number of *Citations received* and *Citations given* significantly correlate with the revenue. This indicates that studies that report higher *Revenue* are slightly more likely to receive citations; however, studies that report lower *Revenue* are based on more sources. The *Data availability* and the *Citations received* are only collected ex-post and can therefore not have influenced the results. Therefore, and because of the very low association levels, only the variables *Year of publication*, *Journal ranking* and the *Citations given* are included as publication-related control variables in the multivariate approach.

Table 7
Correlations of control variables. Shown here are correlations between selected independent and the dependent revenue variables, reported as R^2-values and significance of a one-way ANOVA for categorical; and r-value, and significance of Kendall's Tau for non-categorical independent variables.

		Revenue	*Revenue net*
Publication	*Year of publication*	−0.14***	−0.066
	Journal ranking	0.176***	0.246***
	Data availability	0.028	0.081**
	Citations received	0.08*	0.036
	Citations given	−0.185***	−0.009
Author	*Background*	0.046***	0.028***
	Number of publications	−0.032	−0.002
	Number of authors	−0.157***	−0.111***
	Gender	0.011	0.003
Approach	*Research method*	0.001	0.0
	Aggregation approach	0.055***	0.007

$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

Concerning the author-related variables, there are significant correlations of the *Background* and the *Number of authors* with the benefit variables. The *Background* of authors can be either economics or engineering and seems to influence both *Revenue* and *Revenue net*. The means are €95.18 and €472.20 in *Revenue*, and €52.99 and €353.84 in *Revenue net* for economics and engineering backgrounds, respectively. Authors with an engineering background tend to report higher expected benefits from controlled PEV charging. This stands in contrast to the initial expectation from Section 4.1. One explanation for this is the high correlation between *Background* and both the *Application* and *Sub-application* variables. Authors with an engineering background provide most cases for frequency and load control whereas economics authors provide most trading cases. Therefore, only the multivariate approach in Section 5.2 can provide clarity regarding the overall effect of the *Background*. Additionally, a lower *Number of author* results in higher reported benefits. The *Number of publications* and the *Gender* of an author do not correlate with the benefit variables. Both are therefore excluded from the multivariate approach.

Table 8
Multivariate model for both revenue variables. The intercept represents price arbitrage (*Sub-application*), grid operator (*Viewpoint*), BEV (*Vehicle technology*), G2V (*Charging technology*), economics (*Background*) and single PEV (*Aggregation*). Shown here are regression coefficients, significance and standard errors in parentheses. For the OLS estimators, we apply robust standard errors for small sample sizes.

Category	Variable	Categorical values	*Revenue*		*Revenue net*	
	Intercept		−109493.01	(132814.4)	89558.16	(91778.4)
Objective	*Sub-application*	*Charging cost red.*	3169.03	(2815.15)	575.27**	(243.49)
		Load leveling	1283.08*	(679.23)	1404.51***	(419.79)
		Peak shaving	−13.28	(1457.94)	943.06*	(484.89)
		Primary control	399.43	(787.07)	747.43	(598.84)
		Secondary control	1451.16**	(727.9)	1402.56***	(308.36)
		Tertiary control	1199.21*	(726.89)	551.33*	(302.87)
	Viewpoint	*Fleet aggregator*	1137.16	(910.46)	−28.29	(239.6)
		Vehicle owner	854.1**	(335.21)	546.36**	(249.02)
Market	*Year of simulation*		53.68	(87.37)	−34.3	(27.55)
	RES share		−21.17	(104.04)	−17.24	(13.65)
	Electricity price		84.27	(129.36)	133.53	(136.7)
Technical	*Vehicle tech.*	*PHEV*	498.16	(466.42)	1161.31***	(368.76)
	Charging tech.	*V2G*	1238.35***	(394.19)	364.16*	(207.66)
	Charging power		40.21	(26.44)	29.53***	(9.99)
	Battery capacity		6.98	(9.4)	38.78**	(15.84)
	Efficiency round-trip		436.11	(293.63)	836.46*	(501.94)
	Depth of discharge		191.2	(928.86)	−371.57	(784.17)
Controls	*Background*	*Engineering*	−1316.93	(1330.2)	−5.16	(271.08)
	Aggregation	*Multiple PEVs*	565.75	(1310.44)	−64.46	(177.7)
	Year of publication		1.9	(122.06)	−12.39	(63.49)
	Journal ranking		−691.05**	(315.06)	24.24	(125.78)
	Citations given		−79.29	(55.18)	47.98**	(20.72)
	Number of authors		−550.89	(505.44)	27.8	(94.73)
Number of observations			205		244	
R^2 (Adjusted R^2)			0.465 (0.397)***		0.470 (0.415)***	

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

The approach of a publication is described by the *Research method* and the *Aggregation approach*. The *Research method* differentiates between practical demonstrations (e.g., field experiments) and simulations but does not significantly correlate with the dependent variables. The data set may be a restricting factor since we were only able to collect one case where the authors chose a practical demonstration as their research approach. More differentiation in data is available concerning the *Aggregation approach*, where 41% of all cases only examined individual PEVs and the remaining 59% aggregate multiple PEVs to a controlled pool that jointly full-filled controlled charging applications. This leads to a significant correlation with the *Revenue*, which is why we include the *Aggregation approach* in the combined multivariate model as a control variable.

Overall, the base effect analysis results in 17 independent variables that are included in the multivariate approach in Section 5.2. Although all three objective variables show significant correlations, only the variables *Sub-application* and *Viewpoint* are included to avoid multicollinearity and achieve a high level of detail. Concerning the market variables, the variable *Year of simulation* is considered and the variables *RES share* and *Electricity price* are included as proxies for the energy situation in the respective locations. The variables *Vehicle technology* and *Battery capacity* are considered as vehicle variables and *Charging technology*, *Charging power*, *Efficiency round-trip* and *Depth of discharge* as charging variables. These represent the main characteristics describing a PEV and its charging applications while again avoiding multicollinearity. Control variables for the multivariate model are *Year of publication*, *Journal ranking* and *Citations given*; *Background* and *Number of authors*; and *Aggregation approach* for the three categories publication, authors, and research approach.

5.2. Multivariate results

Now an OLS regression model is applied to find the combined effects on *Revenue* and *Revenue net*. Since the individual correlations of the previous section are susceptive to omitted variables bias, a combined OLS model offers insights into the relative importance of the independent variables. The variables selected in Section 5.1 provide the basis for the OLS model and can be found in Table 8. Overall, the objectives and the technical conditions of controlled charging are the most significant drivers of the economic benefits , this outcome is stable to the inclusion of control variables. The OLS model is shown in Eq. (1). Four different models are applied, two for each dependent variable, of which one includes the control variables whereas the other does not. All four models have an overall significance on the 1%-level. The models explain 39.7% and 47.0% of the variance with control variables, and 34.8% and 38.9% without control variables for *Revenue* and *Revenue net* respectively. The full outcome of the OLS model with controls is shown in Table 8 and without controls in Appendix D in Table 9.

Sub-application and *Viewpoint* represent the objective of controlled charging; both have significant coefficients in some of the categorical values. For *Sub-application*, price arbitrage represents the model intercept. All other applications with significant coefficients show higher *Revenue* and *Revenue net*. The highest *Revenue* can be expected from secondary control followed by load leveling and tertiary control applications. Charging cost reduction, peak shaving , primary control and price arbitrage cannot significantly be differentiated concerning the expected *Revenue*. The different *Sub-applications* can be separated more clearly from price arbitrage for *Revenue net* with the exception of primary control. Again, load leveling and secondary control promise the highest overall benefits, followed by peak shaving and charging cost reduction. The overall result is therefore that load leveling and secondary frequency control provide the highest revenues. It is intuitively understood that controlled PEV charging does not fit all applications in the same way. Applications differ in their energy demand and their time-dependency, which leads to a varying fit with the availability of PEVs [4,33].

For the *Viewpoint*, the grid operator is taken as intercept. There is a significant difference to the vehicle owner for both dependent variables. However, the difference between grid operators and fleet aggregators, both of which control a multitude of PEVs, is not significant. It seems that individuals generate higher benefits from controlled charging than aggregated PEV fleets. This is in line with the findings of [44] and [37], who report higher benefits for vehicle owners compared to grid operators and fleet aggregators. However, [45] report contrasting findings where grid operators achieve higher benefits than vehicle owners. The major difference between these studies is the location and the energy sources, where [45] analyze a case from the Netherlands and consider generation from RES, the other two focus on India and the USA without RES generation. Grid operators may additionally benefit by counteracting negative impacts from RES generation through controlled PEV charging. This may be reflected in the overall effect, since only 35 out of 340 cases include RES generation. Additionally, the current state of research does not provide a data set that allows the integration of a country's variables in the OLS model since too few cases are available per country. An integration of the continent as a proxy shows non-significant coefficients. Consequently, it is important to consider the objective variables; *Sub-application* and *Viewpoint* when looking at the achievable benefits of controlled PEV charging. Overall the highest benefits can be expected from vehicle owners that participate in the secondary frequency control market or perform load leveling applications.

The market variables *RES share* and *Electricity price* are not significant in the OLS models. Although they are individually correlated with *Revenue* and/or *Revenue net*, their explanatory values within the OLS model are insignificant. Both variables are collected mainly from third party sources as they were not reported in the publications. They have probably not been considered in the simulations published, which explains the non-significant results. Additionally, two variations of the OLS model shown in Table 8 are tested, which include the *Energy archetype* or the *Continent* as an aggregation of different countries instead of the *RES share* and *Electricity price* proxies. These two location-related variables do not have a significant effect either. Based on this analysis, market variables do not have a significant effect on economic benefits. However, this result is driven by a lack of data. Future research might come to a different conclusion. Therefore, more research on market conditions is needed.

The technical variables significantly influence the benefits, most notably the *Vehicle technology*, *Charging technology*, *Charging power* and *Battery capacity*. The *Vehicle technology* is significant only for *Revenue net*. When switching from a BEV to a PHEV to perform controlled charging applications the *Revenue* does not change but the expected *Revenue net* will increase significantly. This is not intuitive since the difference between BEV and PHEV for a controlled charging application is solely the decreased battery capacity leading to a shorter service provision time. The results of [4] and [36] who compare the *Vehicle technology* also contrast with this finding. This could be attributed to the correlation between *Vehicle technology* and *Country* as seen in Appendix C, Fig. 5 and the fact that the current research does not provide the same number of cases for all combinations or variables. 85% of the cases looking at controlled PHEV charging take place in the USA where, with the exception of Iran, the highest *Revenue net* is reported for BEV and PHEV applications. Concerning the *Charging technology*, the advantages of V2G in offering services by introducing (discharging) in addition to extracting energy (charging) provides additional *Revenue* and *Revenue net*. The disadvantage is the battery degradation cost, but the overall effect is still positive since V2G results in higher benefits than G2V. The *Revenue* increases three times as much as the *Revenue net*, which must be attributed to the battery degradation cost of V2G. All publications confirm the higher benefits of V2G, except [4] who report higher *Revenue* but report lower *Revenue net* from V2G compared to G2V. This shows that, although the overall effect of V2G is beneficial, in certain cases the battery degradation cost can lead to a disadvantage compared to G2V. The *Charging power* is significant for *Revenue net*. A higher *Charging power* increases the flexibility that can be offered and consequently the benefits that can be achieved. However, with a higher *Charging power* the service can only be provided for a shorter duration given the same battery capacity. It seems that, especially for the *Revenue net*, the first effect is predominant. A higher *Efficiency round-trip* significantly increases benefits by reducing the losses of the system. This is intuitively understood and supported by [29] and [41]. This becomes even more important if battery degradation cost is considered, where an increase in *Efficiency round-trip* adds three times as much to *Revenue net* as it does to *Revenue*. A higher *Battery capacity* has a significant, positive effect on the *Revenue net*. This might be driven by the increased capability to generate revenue and the reduced battery degradation since larger batteries need to be cycled less to provide a given capacity. Finally, the *Depth of discharge* is often used to calculate the discharging effects on the battery. A lower *Depth of discharge* is beneficial in this case [29] but, in contrast, a higher *Depth of discharge* frees up more capacity to generate *Revenue*. This is reflected in the negative and positive coefficients for *Revenue net* and *Revenue*, respectively. However, since these coefficients are insignificant the *Depth of discharge* does not necessarily influence achievable benefits which is line with [46]. Overall, the technical variables must be well considered in controlled PEV charging applications since they affect both the *Revenue* and the *Revenue net*. *Charging technology*; *Charging power* and *Efficiency round-trip* are key drivers. The effects of the *Vehicle technology* are somewhat inconclusive. The highest economic benefits can therefore be achieved with V2G technology, a charger with high charging power and efficiency, and a PEV with a large battery.

The control variables are mostly insignificant in the OLS model, showing little bias from author or approach-related variables. Neither the *Background* of the researcher nor the *Aggregation* model has an effect on the reported benefits of controlled charging. Of the publication-related variables, the *Year of publication* and the *Number of authors* are not significant. The *Journal ranking* shows a significant, negative impact on the *Revenue*. This suggests that higher ranked journals are more conservative with regard to the published economic benefits, which does not hold for *Revenue net*. This contrasts with the findings of the individual correlation tests in Section 5.1, where *Journal ranking* correlates significantly and positively with *Revenue*. In combination, this suggests a correlation between the independent variables such that higher ranked journals publish cases where objective, market and technical conditions are rather favorable. The overall OLS model controls for these conditions and the more conservative approach of higher ranked journals is thus apparent. The *Citations given* show a significant, positive effect on *Revenue net* suggesting that more extensive research publications conclude higher *Revenue net*. Several of the other control variables are individually correlated with the two dependent variables but are insignificant in the OLS model. Therefore, these control variables do not have a big enough impact to stand out over objective and technical variables of controlled charging. The exception is the slightly higher conservative tendency for high ranked journals. Comparing the previous results to an OLS model without control variables, there are the same general effects on the variable level as described, with the exception that the objective and technical variables reach a higher significance but *Depth of discharge* remains non-significant. See Appendix D, Table 9 for the OLS model excluding the control variables.

Unfortunately, some variables could not be compared consistently across publications as they were not provided in the publications, nor could they be retrieved by direct author contact or through third party sources. Among these was the share of PEVs compared to the size of the balancing market. Very few authors provided a PEV share that they assumed (e.g., [33]) and although multiple publications included the number of PEVs in their simulation, this number cannot be used because the unit of analysis compared to the country is unclear. Nevertheless, the number of PEVs in relation to the balancing market size is interesting because one significant problem for both frequency and load control markets is the fact that achievable revenues decline as more participants enter the market [26,33]. Further, the information on charging locations (e.g., home, work or both) was often not available in the publications. This, however, could be an important point that

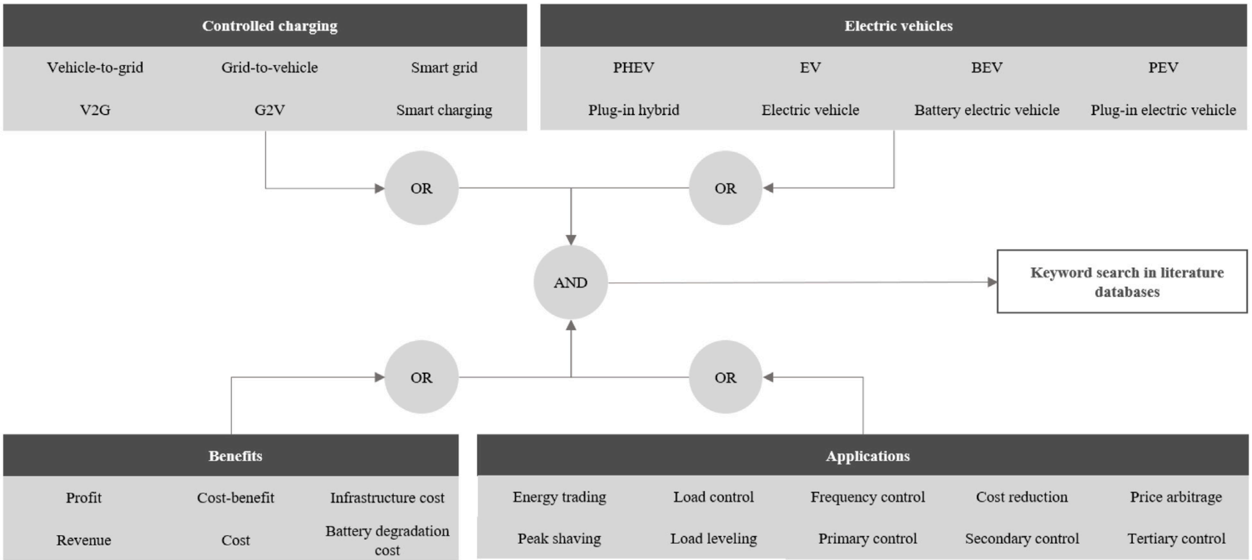

Fig. 2. Keywords for literature database search and their combinations.

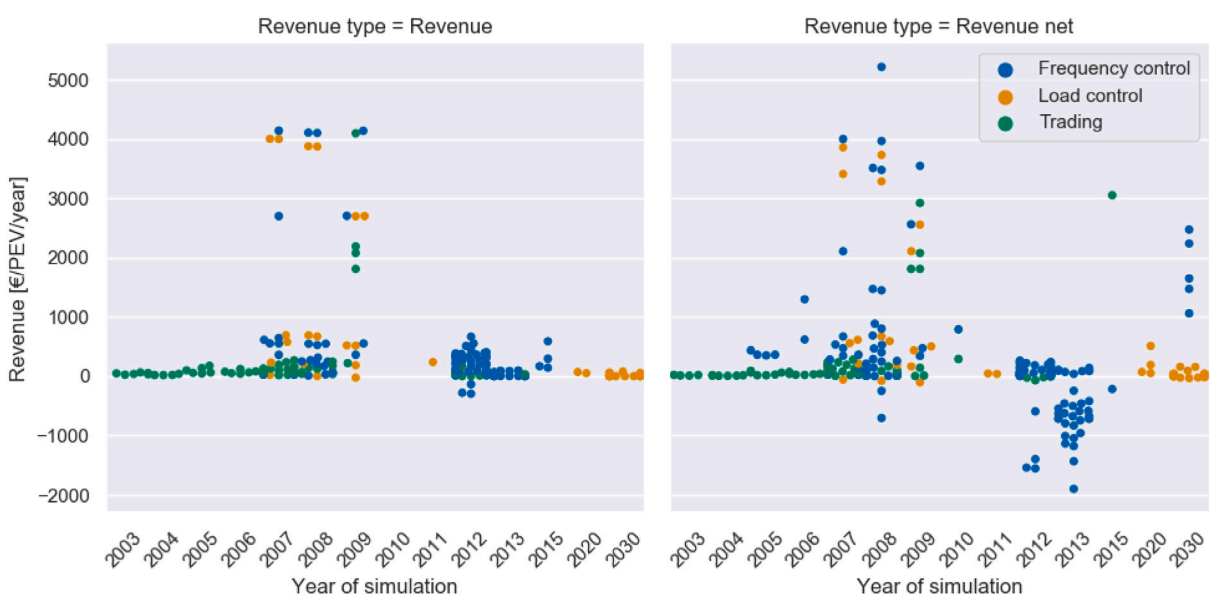

Fig. 3. Revenue types for all cases included in the data set, pooled by year of simulation.

defines the time of charging and therefore the fit for time-dependent applications.

In summary, objective and technical variables of controlled PEV charging applications are the key drivers for the size of expected benefits. An application in the secondary control market or for load leveling promises the highest benefits whereas peak shaving and price arbitrage will probably miss the desired benefits. Overall, vehicle owners can profit more than grid operators or fleet aggregators. From a technical point of view, V2G technology in particular, in combination with high charging power and efficiencies as well as large PEV battery capacities, can provide the highest revenues.

6. Conclusion and implications

This paper has analyzed the economic benefits of controlled PEV charging. Based on the vast literature, a broad range of economic benefits is found. This paper aimed to understand the reasons for large variations in these benefits by identifying key drivers that determine the economic results of controlled PEV charging. Based on a data set with 340 cases of controlled PEV charging, individual effects of potential key variables are examined and a multivariate approach is applied. Objectives and technical variables are the key drivers for economic success of controlled PEV charging. Secondary frequency control and load leveling are the most promising applications. Benefits are especially high for vehicle owners rather than aggregators or grid operators. The technical variables show a significant influence for the vehicle and charging technology. For example, switching from G2V to V2G generates additional benefits. Higher charging power and efficiency can further enhance the economic benefits.

These results shed light on the inconsistent and partly contradictory results of existing studies on the economic benefits of G2V and V2G applications. The novel contribution of this paper lies in the identification of the most promising applications and the most promising factors affecting the economic benefits. These results therefore allow for a more focused discussion of new business models in the area of G2V and V2G applications.

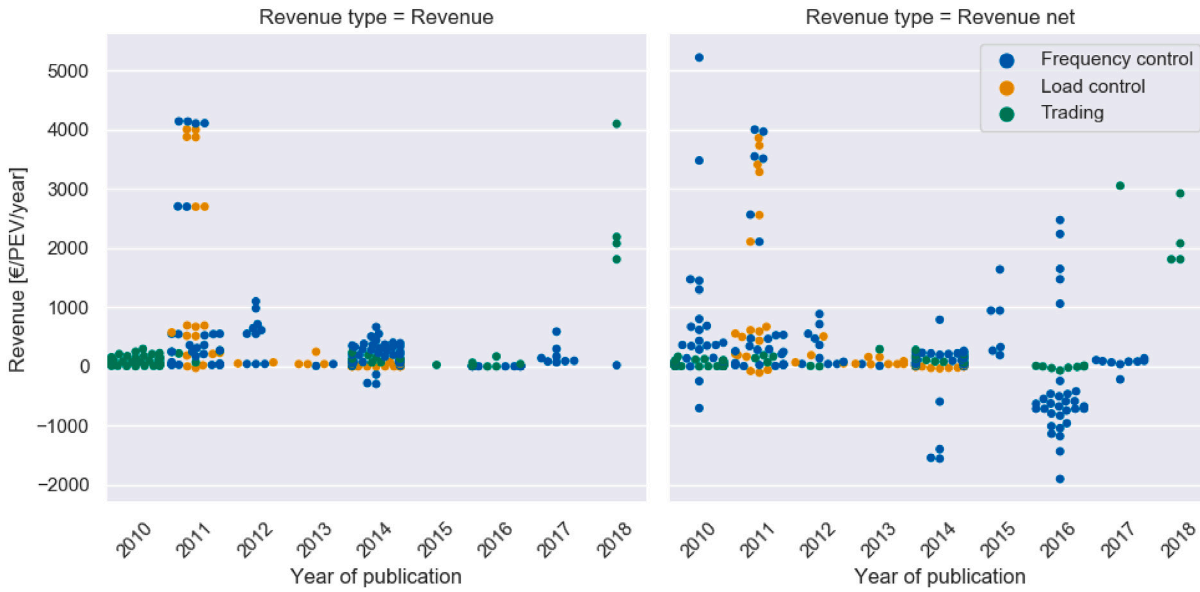

Fig. 4. Revenue types for all cases included in the data set, pooled by year of publication.

Some constraints on the available data might limit these findings. Since there is only information included that has been provided by the publication or by the author(s), implicit modeling assumptions cannot be captured. Examples of such assumptions would be the assumed driving or charging behaviors of PEV owners. Furthermore, missing variables limit the inclusion of cases that are otherwise available. This applies especially to the multivariate model, where cases with missing values are excluded. Finally, the cases researched to date are a major constraint for this type of analysis. In particular, the conclusions concerning country, application, and vehicle type could be improved if additional cases were available in the literature.

Further challenges and opportunities arise for controlled PEV charging from new services such as battery swapping, ride sharing. The implementation of battery swapping (as suggested by [e.g.,88]) instead of traditional chargers is likely to increase the potential of controlled charging as more battery capacity needs to available and charging becomes even more flexible. Contrary, PEV ride sharing (see [e.g.,89]) would reduce the potential as vehicle utilization would likely increase. Additionally research is needed in these cases to clearly define the impact that can be expected on the economic benefits of controlled PEV charging. In any case, the technical limitations of sharing the PEV battery for secondary applications, such as battery degradation and life span limitations, remain. The economic effects of battery degradation have been addressed by distinguishing between *Revenue* and *Revenue net*. For a more in-depth view on this topic refer to [90].

The findings in this paper have important implications for practitioners and academics. Owners of PEVs and aggregators should look into secondary control or load leveling applications for the highest expected economic benefits. Vehicles that can handle a higher charging power and are V2G-capable are better suited to create economic benefits. Moreover, the charging infrastructure must also provide the aforementioned capabilities and have a high efficiency level. PEV automakers can also benefit from this study. The inclusion of chargers with V2G-capabilities, higher charging powers and improved efficiencies can drive the value of a PEV up when owners are considering the options of controlled charging. Manufacturers can use this as an additional sales pitch. The findings in this paper also provide directions for researchers working on controlled PEV charging applications. When simulating controlled charging applications, researchers need to include the relevant objectives and correctly specified technical variables. Researchers should especially take the available vehicle and charging technology into consideration as both have proven to be important in terms of the economic benefits. Additional country comparisons and an increased understanding of market saturation levels would be beneficial in order to add more data points to existing studies. Research comparing the situations in different countries for individual applications will help understand potential effects of varying market designs. Research on varying, system-wide PEV penetration levels can identify saturation levels for which the benefits of controlled PEV charging decline. Finally, the multitude of simulation studies could be reassessed with experimental or real-world research approaches.

CRediT authorship contribution statement

C. Heilmann: Conceptualization, Data curation, Formal analysis, Writing - original draft. **G. Friedl:** Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Literature research

See Fig. 2.

Appendix B. Descriptive statistics

See Figs. 3 and 4.

Appendix C. Correlations of independent variables

Shown here are the correlations between independent variables of controlled charging. We report R^2-value of a one-way ANOVA for categorical; and r-value of Kendall's Tau for non-categorical independent variables. All correlations with a p-value larger than the 10%-Level are set to 0 (see Fig. 5).

Appendix D. Multivariate model excluding control variables

See Table 9.

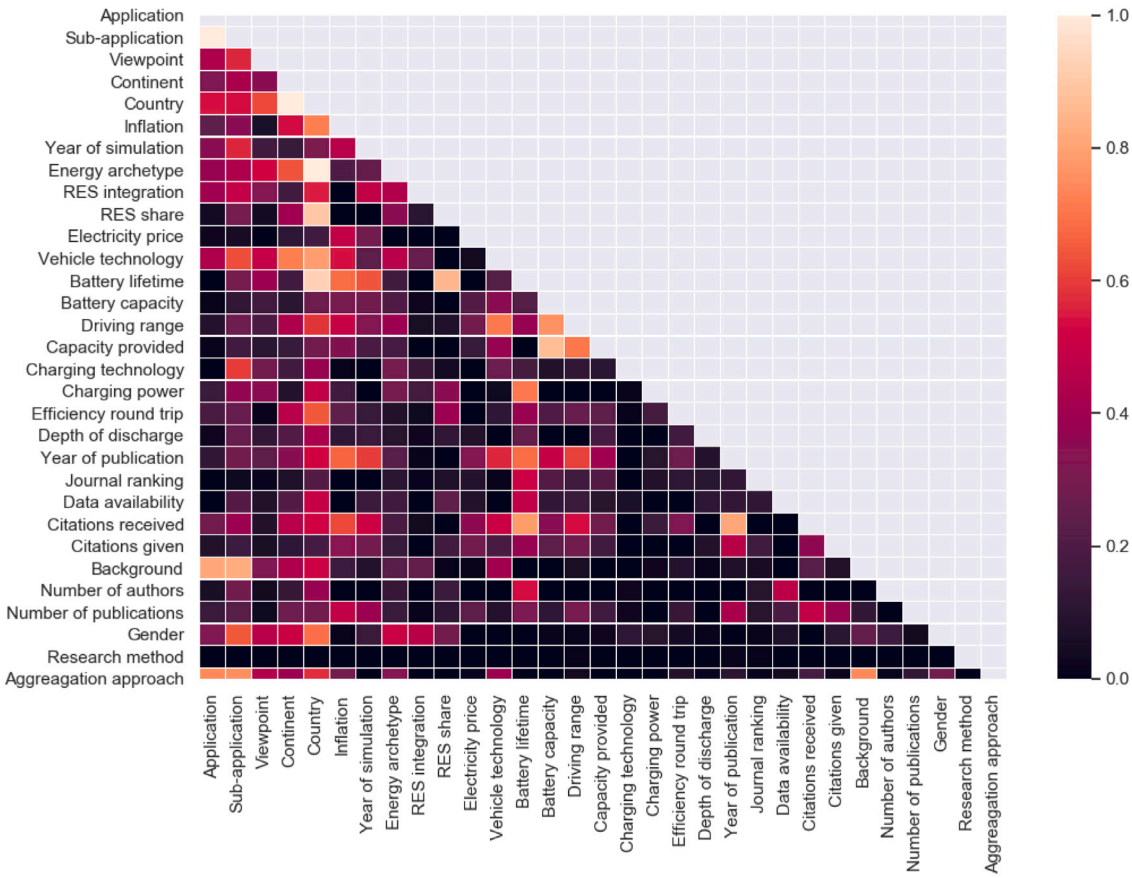

Fig. 5. Correlations between all independent variables in the data-set.

Table 9
Multivariate mode for both revenue variables excluding control variables. The intercept represents price arbitrage (*Sub application*), grid operator (*Viewpoint*), BEV (*Vehicle technology*), G2V (*Charging technology*) and single PEVs (*Aggregation*). Shown here are regression coefficients, significance and standard errors in parentheses. For the OLS estimators, we apply robust standard errors for small sample sizes.

Category	Variable	Categorical values	*Revenue*		*Revenue net*	
	Intercept		38197.73	(33519.73)	45875.62*	(27330.4)
Objective	*Sub application*	*Charging cost red.*	1104.49***	(345.19)	787.49***	(253.85)
		Load leveling	1374.3***	(365.51)	1190.97***	(331.75)
		Peak shaving	872.37**	(434.84)	882.7***	(202.46)
		Primary control	527.29	(636.71)	598.54	(527.16)
		Secondary control	1323.17***	(344.88)	1277.62***	(268.1)
		Tertiary control	957.62***	(339.06)	373.17	(237.01)
	Viewpoint	*Fleet aggregator*	804.82**	(328.23)	−137.39	(297.81)
		Vehicle owner	881.56***	(299.45)	242.41	(334.2)
Market	*Year of simulation*		−20.73	(16.48)	−24.26*	(13.28)
	RES share		4.84	(10.52)	−3.57	(7.28)
	Electricity price		−38.98	(61.69)	114.54	(189.56)
Technical	*Vehicle tech.*	*PHEV*	824.9**	(339.1)	841.68***	(293.41)
	Charging tech.	*V2G*	636.68***	(187.75)	397.57**	(183.87)
	Battery capacity		10.02	(12.99)	21.48*	(12.88)
	Charging power		24.3**	(10.65)	14.21**	(6.98)
	Efficiency round-trip		601.76**	(286.89)	1136.86**	(551.83)
	Depth of discharge		374.98	(808.66)	110.91	(700.4)
Number of observations			205		244	
R^2 (Adjusted R^2)			0.400 (0.348)		0.429 (0.389)	

$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

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