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Economic and sustainability-potential of carbon-neutral charging services for electric vehicle customers

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Summary

Life-cycle emissions of electric vehicles depend mainly on the type of electricity charged during the vehicle usage phase. This work characterises and discusses the range of potential green power services that show different levels of environmental quality. Key quality dimensions are additionality, regionality, source technology, balancing period, system flexibility and transparency. To assess the future marketing potential of any specific service, its environmental quality must be contrasted with its economic viability. Furthermore, necessary framework conditions are discussed and two exemplary services are investigated in detail: reactive balancing with strong additionality and transparency, and active balancing by shifting of charging times to accommodate hourly balancing of green power and demand. The arbitrage gains for smart charging are approximated using an illustrative linear program and comprehensive mobility data from Germany.

Keywords: sustainability, renewable energy, EV (electric vehicle), smart charging, case-study

1 Introduction

Global climate change has led many governments to issue ambitious targets for renewable energies and CO_2 mitigation goals for the transport sector. With respect to the latter, vehicle manufacturers increasingly expand their portfolio to battery electric (BEV) and plug-in hybrid electric vehicles (PHEV) (together: plug-in electric vehicles, PEV). While PEV provide the potential for individual transportation independent of fossil fuels, carbon-neutrality depends on the respective electricity mix. BEV are considered carbon-neutral on a well-to-wheel-basis (WTW) if electricity from renewable sources is used for charging [1]. To this end, PEV-purchase-incentives in Austria are granted on exclusive use of green electricity for charging [2]. Interestingly enough, this step received relatively little attention by the media. As Austria has a very high share of renewable generation in its power mix, mainly hydropower, the environmental sustainability of power production seems to be less of an issue in public perception. In countries with a large share of power production from fossil fuels, e.g. Germany, green electricity tariffs and power sector emissions are under more scrutiny.

This leads to the question, how entirely carbon-neutral charging can be ensured in carbon-intensive power systems? Innovative services are required, that match the increasing demand for charging PEV with renewable electricity production. If designed correctly for specific customer groups, these services could cater to customers' increasing interest in sustainable transport [cf. 3–5]. Furthermore, they could contribute to a more efficient use of renewables within the entire energy system [6]. New market participants could be

the providers of such services. Next to guaranteeing green power, the provider could market the vehicles' combined flexibility and act as an aggregator [cf. 7]. PEV manufacturers could consider becoming (or connecting their customers to) such a service provider in order to differentiate their products as more environmentally friendly than the competition. In addition, providing such services allows for a closer relationship with the customers beyond the classic after-sales business with periodical inspections.

A number of different approaches for the provision of carbon-neutral power for PEV as green power services are conceivable. Section 2 discusses related work with a focus on matching green electricity and PEV. This work aims to characterise and discuss such likely green power services with respect to their environmental quality and give a first estimate of the incurred costs (Section 3). Furthermore, necessary framework conditions for the efficient delivery of these services are discussed in Section 4. As a case study, two exemplary green power services are discussed in more detail to illustrate the applicability and implications of our considerations (Section 5). Section 6 concludes and outlines limitations and future work.

2 Related work

Renewables and electrified transport are often seen as a given pre-requisite for detailed studies on e.g. demand side management or the future development of power systems. This paper focuses on potential services that facilitate provision of green power specifically to PEV-customers

2.1 Green power marketing

Many studies have discussed green power marketing in Germany, as it is the world's "most elaborated and mature market for green electricity" [8]. The total German demand for green power products in 2016 was 24 TWh, almost 20 % of total household demand, and has been stable in recent years [9]. The vast majority of green power products in Germany rely on renewable energy certificates (REC), also called 'Guarantees of Origin'. REC guarantee that 1 MWh of green power has been produced and they come largely from Scandinavian or alpine hydropower [10]. The United States are another market where green power marketing plays a significant role: Beyond the obligatory REC-quota serving as investment incentive, almost 78 TWh of additional green electricity were consumed voluntarily in 2015, although the majority of this demand is likely to come from large non-residential consumers [11]. Commonly, customers with high income and strong altruistic and pro-environmental attitudes opt for green electricity tariffs (cf. review in [12]). Lee and Heo [13] give an overview of willingness-to-pay (WTP) for green electricity in selected counties and specifically in Korea. Taking a different approach, Herbes et al. [12] apply a neurological method to avoid participants' strategic bias and find that German customers tolerate a premium for green power of 3 - 19 %. Nienhueser and Qiu [4] find a significant increase in WTP for public charging of PEV through the guarantee of green power for the USA.

2.2 Controlled electric vehicle charging

Predominantly, demand side management is seen as an efficient way of integrating increasing renewable power production into the power system [e.g. 14–16]. Here PEV can play an important role, as they dramatically increase a household's power consumption and typically have long idling times [6,17]. This flexibility could also be the basis of new marketing perspectives on power markets [e.g. 18–20]. However, most sources approach the subject from the system perspective, i.e. balancing in order to improve the stability of the power system [e.g. 21]. This ignores customer expectations. To our knowledge, only Axsen and Kurani [3] and Ensslen et al. [22] consider customer acceptance of green power in combination with PEV in their tariff design studies. The former discover that especially early adopters consider PEV and renewables as inseparable. However, design options for the power contracts are limited to different contract durations, green power premiums and rooftop-photovoltaics installation. The latter indicate a slightly increased WTP by German vehicle fleet managers for minimizing carbon emissions through smart charging. Gohla-Neudecker et al. [23] call for exclusive green power for PEV in real-time, but from the system perspective and without considering the flexibility of vehicle charging. They find for Germany, that guaranteeing sufficient renewable power production at any time for uncontrolled charging might lead to extreme system costs when PEV market shares become significant. Controlled charging therefore has the potential to simplify the integration of

renewables [24]. In fact, Schuller et al. [25] find that smart charging can double the utilisation of volatile renewable energy compared to uncontrolled charging.

2.3 Research gap

In conclusion, the literature on electricity tariffs and power services that guarantee power provision from renewable sources for PEV-charging lacks depth, even though a decarbonisation of individual road transport is currently only conceivable with such a use of green power. We argue that the range of quality aspects for renewable power provision for PEV should be expanded in the direction suggested by the literature on green power marketing. This could enable service providers to enter this competitive market with the correct product. An overarching classification of viable green power services is necessary, along with a comprehensive analysis of the incurred costs. This leads to the research question:

How and at what costs can renewable electricity be provided to PEV-customers in the required quality?

3 Method

We approach this problem from three angles: Section 3.1 discusses the fundamental principles of achieving CO_2-neutral charging of PEV. An aggregator considering to enter the power market has to decide on his level of active involvement in balancing PEV and green power, or if he merely acts as a selector of an appropriate service offered by a third party (e.g. an established energy provider) for his customers. Such services are defined. In principle, this extends to enabling customers to optimally utilise power from a private photovoltaic system. Including the standard household consumption into the service can be understood as an add-on and does not disrupt interpretation of the vehicle as a primary flexibility provider of households. Next, we take a closer look at the specific service level of green power provision. The service level represents the green power 'quality' specifically matched to customer wishes in order to increase their attractiveness. Section 3.2 discusses fundamental aspects of green power services and discusses ways of facilitating this continuous range of qualities into a basis for service design. Section 3.3 then moves further towards implementation and has general considerations on the economic viability of the services and respective business cases.

3.1 Fundamental principles of balancing renewables and PEV

Beyond charging PEV with private photovoltaic panels, direct transmission between generation facility and individual vehicles is economically infeasible. Therefore, green energy must be allocated to consumers via some form of consumption balancing mechanism [26]. Balancing can be done either reactively by the supply side or with active participation of the demand side.

Reactive balancing describes the provision of electricity guaranteed to be from renewable sources via obtaining REC or contracting certified suppliers. REC are tradeable (often internationally) but they are criticised for a lack of transparency. Green power labels allow for more rigid requirements for environmental sustainability, such as specifying source technologies, locational limitations or tighter balancing time periods. However, the range of available labels and their specifics is vast and they differ significantly in quality, e.g. in source technology or investment requirements for new renewable capacity [cf. 27]. By introducing additional requirements, labels effectively add to traditional electricity tariffs by specifying an environmental quality, i.e. a service level, that service provider has to supply [cf. 28].

Active balancing facilitates the flexibility of the demand side. In the case of PEV, this means shifting charging to times of volatile renewable input. This so called 'smart charging' is argued to allow for a more efficient use of renewable and power grid resources [6] and therefore further reduce overall environmental impact. An extension to this approach encompasses feeding energy stored in the PEV back to the grid, i.e. 'vehicle-to-grid' [18]. Both variants enable a flexibility aggregator, i.e. a service provider of active balancing, to exploit arbitrage opportunities and generate revenues from offering grid services. However, this requires significant PEV-numbers and investments in bidirectional communication infrastructure [e.g. 29]. For active balancing, the service level agreement is bilateral: The customer agrees to provide his flexibility to allow the provider to react to market prices. Reduced customer prices can act as compensation for demand flexibility [e.g. 21].

3.2 Environmental evaluation

Carbon-neutral charging can be facilitated in a range of ways. A service provider of reactive or active balancing must consider both the environmental and economic implications of a green power service. In this chapter, we focus on the environmental contribution a particular service can make, encompassing both technical properties of the generation technologies as well as intangible, psychological factors such as additional valuation for regional production [cf. 8]. Table 1 defines six dimensions of environmental quality that could serve as indicators for a measure of environmental quality. We also include first suggestions on the scales with which each dimension could be measured.

Table 1: Description of environmental quality dimensions for green power provision (based on various sources)

Quality Dimension [measurement]	Description
Additionality [1/max. plant age]	Subscribers to green power services often aim to promote an increase in green power production [30,31], e.g. through using parts of the retail price for investments in additional capacity or by requiring a minimum share of power to be provided by newer plants.
Regionality [1/max. distance from consumer]	REC in Germany mostly come from Norwegian hydropower plants [8]. Some customers prefer production from more regional sources or even from neighbourhood photovoltaics. The Netherlands have adopted this aspect into their electricity taxation strategy and exempt locally produced renewable electricity from the surcharge that finances subsidies for renewables [32].
Source technology [ordinal ranking]	Some customers prefer one source of renewable energy to another. An example would be an aversion to local wind power because of noise, or to biomass due to the use of arable land away from food production. Photovoltaics is often found to be preferred over wind, which is in turn preferred over hydropower and biomass [e.g. 33]. This dimension further includes technology-specific considerations on environmental sustainability, such as an increased land use or life-cycle emissions of production facilities.
Balancing period [1/length of balancing period]	The 'life-time' of REC is a key-factor for determining environmental quality, especially for active balancing. Normatively, renewable power should be used at the time it is produced because otherwise additional demand from PEV is covered by thermal generation. This causes additional emissions that are unjustly distributed to all consumers [23]. Furthermore, banking REC implies a virtual storage for power, drawing away business from actual storage solutions sorely needed for covering lulls in renewable production [34]. Today, balancing periods range from one year to one hour [35] or even three years in e.g. California [36].
System flexibility [ordinal ranking according to controllability]	If a power system is more flexible, volatile generation or peak demand can be handled more efficiently. Active balancing can contribute to this scale and smart charging, vehicle-to-grid, and flexible input sources, such as biomass or hydropower, are rewarded.
Transparency [ordinal ranking]	Involved customers need to be able to verify the quality of their green power service through easily available and comprehendible information [37]. This transparency builds trust with the service provider or towards the respective green power label.

These quality dimensions are based on sources [8,37–39]. The literature yields many more and highly differentiated dimensions but it is the aim of this study to bundle them to some degree, in order to reduce complexity for new market entrants. Still, some dimensions overlap, e.g. system flexibility can help achieve short balancing periods either through flexible production or through flexible demand. Another example would be that some source technologies are not regionally available. However, it is theorised that each of these dimensions contributes to quality individually, i.e. has an inherent value to the customer. It is the goal of ongoing research to validate this list and discern the specific weights for these quality dimensions, in order to lay the basis for the quantification of valuation from the customer perspective.

Additive weighted aggregation of the normalised and dimension values of a particular green power service might yield a single 'environmental quality score'. A service provider could use this score to gain an initial understanding of a service's marketing potential and craft a service to his customers' valuation (cf. 28 [28] for considerations on product differentiation for energy services). However, this score should not be used as the only decision factor in practice, because quality aspects cannot compensate each other from an ecological perspective, e.g. regionality vs. balancing period [40].

3.3 Economic evaluation

A popular method to assess the economic potential of green power services is the cost-benefit-analysis [e.g. 41]. The main cost drivers for service providers will be market entrance barriers to the power market, electricity and REC-costs, and management costs for active balancing investments.

Since active balancing, even with short balancing periods, can be realised today with the help of established power retailers (e.g. *EE02* by *TÜV Süd* [42]), the incurred costs for these services depend on the cost of the certified power and are currently low. There is only a small cost increase in correspondence with quality. However, it remains to be seen if the current oversupply of low-quality international REC will persist if demand increases with growing PEV numbers in the next years. Prices might increase in the medium term, which increases procurement costs.

On the other hand, rising prices might lead to additional arbitrage opportunities for the service provider, especially if customers respond to green power service differentiation. While numerous studies have discovered a positive WTP for green electricity by itself [e.g. 13,31] and in combination with PEV [e.g. 4], it is unclear if these findings extend to services with higher environmental quality.

In fact, the economic impact of green power services – and in consequence the business models for aggregators – fundamentally depend on the activation of the demand side. Technical feasibility of smart charging with and without vehicle-to-grid was assessed in a number of pilot studies around the globe. Numerous authors have examined business models for aggregators based on providing power system services as additional revenue source [20,29,43]. Results diverge and depend strongly on the input factors and scenarios applied. The economic potential particularly increases with the number of available PEV. However, significant investments are needed for establishing the IT-infrastructure for (bidirectional) communication between service provider and PEV customer in most countries.

For illustration purposes, we compare the (static) economic feasibility of two green power services as could be made available in Germany: simple reactive balancing based on a popular label and active balancing with shifting charging to times of high availability of renewables. The results are discussed in Section 5.2.

4 Necessary framework conditions

Generally, PEV lead to additional emissions from thermal power plants [cf. 24]. Current green power contracts, mostly using REC, merely virtually shift the green power available in the grid to *their* customers instead of others without preference for green power. However, due to the abundance of REC available from international hydropower and the low carbon prices, more demand will often not lead to additional investments in renewables. Ergo, green power would simply be redistributed to PEV instead of private customers and the additional demand would have only a marginal impact on green power generation. Gillenwater [30] strongly criticises REC for failing exactly in this regard and proposes major alterations to strengthen additionality and transparency [44]. New market mechanisms are essential for the efficient provision of green power for carbon-neutral mobility. They become even more important with growing PEV numbers and the resulting increasing electricity demands and volatility effects [34]. Sensible, system-friendly inclusion can be facilitated by the appropriate market and infrastructure. For example, Bertoldi and Huld [45] discuss active management of the demand side as the basis for 'energy efficiency credits' that could be traded much like REC. Furthermore, they promote shorter balancing periods for REC and amplify the importance of additional demand having to lead to additional investment incentives. One approach, largely using existing system structures, could be to construct an unbundled day-ahead spot market for REC. Such a market could provide the market signal needed to incentivise smart charging of PEV [34].

In addition to improved signalling, market entry barriers need to be lowered for new players such as aggregators and renewable energy providers. First steps should be taken to make balancing power markets more flexible [cf. 46], which opens up paths for revenue creation through grid services via PEV. Smart metering and the respective billing possibilities are a prerequisite for such considerations.

5 Case study: reactive balancing vs. active balancing with smart charging

The following section demonstrates our methodology by considering two specific green power services: a reactive balancing service based on the *ok-power (Händlermodell)*-label with strong requirements regarding additionality [47] and an active balancing service based on the *EE02*-label [42] and smart charging. The qualitative appraisal of the two services' environmental quality (Section 5.1) is followed by an illustrative calculation of their incurred costs and potential financial benefits to an aggregator (Section 5.2).

5.1 Environmental quality potential

To illustrate the idea behind the suggested method, the two green power services are placed within the quality framework defined in Section 3.2 in a qualitative way, roughly estimating the measurement scales. Due to the early nature of this research field, a comprehensive quantification of environmental quality has to be deferred to future work, which means that a numerical quality comparison between the two services is inadvisable at this point. Figure 1 displays the manifestations of the quality dimensions. Each dimension is considered independently, with the centre representing very low performance (e.g. little requirements on 'additionality') and the outside of the web representing high performance (e.g. very short 'balancing periods'). Please note, that the lowest performance, i.e. '0', is represented by the first line out of the centre for improved visibility (e.g. 'regionality' for active balancing service). Already by displaying the manifestations of each service in the web of dimensions, the quality specialisation for each service becomes apparent.

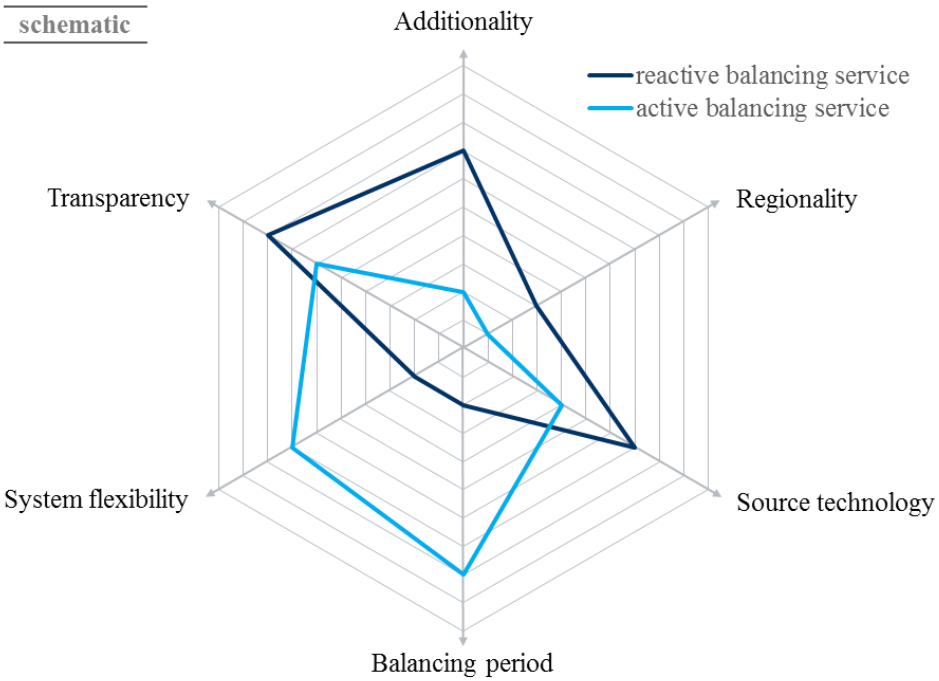

Figure 1: Estimate of the six dimensions of environmental quality for two exemplary green power services

We base the reactive balancing service on the label *ok-power Händlermodell* (Eng.: 'trader model') [47]. For this service, providers buy REC and power from specific generators according to predefined quality criteria. As generators receive only the price for the power and REC, there is no nominal investment contribution (i.e. no initiation fee). In detail, the service requires a third of the provided power to come from power plants younger than six years and another third younger than twelve years. This leads to a high 'additionality'-score. We assume that the service only allows German REC and demand has to be balanced within one year. The

service guarantees 100 % supply from renewables and excludes power plants burning landfill or mine gases, leading to a notable score in 'source technology'. Some 'system flexibility' is provided by the inclusion of e.g. biomass or hydropower but there is no flexibility on the demand side, as there is no incentive for controlled charging of PEV through this service. Specific information on the requirements of the service is easily found online.

The exemplary active balancing service on the other hand strongly focuses on the hourly balance (or shorter if possible) of supply and demand and is based on *TÜV Süd EE02* [42]. For this case study we assume that this service is coupled with a sufficient number of flexible PEV that react to financial steering signals relayed by an aggregator. This leads to a high score in 'system flexibility' as well as 'balancing period'. The service requires 100 % supply from renewables. However, burning of secondary gases is included, leading to a lower score in 'source technology' than for the reactive balancing service. 75 % of the surcharge of green power compared to grey power must be reinvested in additional renewable capacity or sustainability projects. As additional costs for procurement or certification are subtracted from the surcharge and such projects are regularly criticised for ineffectiveness [cf. 30], this aspects leads only to a low score in 'additionality'. *EE02* in its basic form puts no focus on regional production but *TÜV Süd* offers an additional module where 'regionality'-requirements for 50 % of delivered power can be added to the certification. We do not consider this module for this service, as, in practice, the label allows for the criterion of real-time delivery to be relaxed for achieving 'regionality'. Another module not included for this case study requires CO_2-compensation of life-cycle emissions. We assume that detailed information on this active balancing service are available online but not quite as comprehensively as for the reactive service. Given that we assume demand to be modelled on aggregated standard load profiles, it will be difficult for customers to track if their real-time usage has been balanced adequately.

A quantification of quality for the two theorised services is not possible at this point. However, looking at the popularity of existing labels could provide some indication towards quality weights. Although the literature on this issue is sparse, Reichmuth [37] provide some numbers for the popularity of labels in 2011: power services certified with the *ok-power*-label supplied 4.7 TWh to German customers. Products certified by *TÜV Nord* (8.9 TWh) and *TÜV Süd* (6.8 TWh) were in higher request. Unfortunately, *EE02* is not shown individually. However, *EE02* is a prerequisite for the product *GreenPower@EXAA* by the Austrian market maker EXAA. Since trade on this market has ceased since mid-2016 [48], the relevance of the dimension 'balancing period' could be smaller than e.g. 'additionality'. However, intensive further research is required to derive inter-dimension weights robustly.

5.2 Economic potential

Before we analyse the economic potential of the two green power services, we must consider the perspective of the service provider: For reactive balancing, the service provider could simply make a standard supply deal with a power provider who meets the quality requirements. Alternatively, he could properly enter the market and buy power and appropriate REC from the central market platform to deliver to his customers. In this case, considerations on the economic potential for the service provider are the same as for power retailers.

Facilitating smart charging for active balancing on the other hand, requires significant investments in appropriate IT-solutions for information exchange on PEV-availability and price curves (e.g. through an app or as part of an energy management system for the entire household) as well as the real-time optimisation backend (requiring server capacity). Another important topic is IT-security since the charging data could provide information on customers' mobility behaviour [cf. 7]. The rest of this section is chiefly dedicated to exploring the saving potentials from smart charging, rather than the business case of conventional retailers.

5.2.1 Assumptions and data

Table 2 summarises fundamental parameters for this case study and their origin in literature. We assume a vehicle manufacturer with a market share of 15 % of the total number of PEV in Germany as the service provider, who acts as the sole aggregator for his customers. Supposed vehicles use on average 20 kWh per 100 km (including charging losses) over small, medium and large cars. The vehicle manufacturer sold a representative share of PHEV in total PEV numbers in 2016 with an average effective range of 35 km. This should correspond to roughly 40 % of vehicle miles travelled with electricity only (based on [49]). The model assumes that PHEV drive electrically until the battery is drained and recharge when possible. We further

assume customers to charge exclusively at home, with a maximum of 3.7 kW. Due to synchronisation of charging events, the total peak load through vehicle charging is expected to increase. Therefore, the aggregator is assumed to limit the total charging load to 150 % of the current peak load by PEV as a service to the grid-operator. Under these assumptions, this amounts to around 9.6 MW. BEV-owners plug in for 75 % of the time the vehicle is parked at home and PHEV for 33 % of home parking times.

Table 2: Parameters and fundamental values for the case study

Parameter	Value	Unit	Source
PEV in Germany (01/2017)	54,997	-	[50]
– of which BEV (01/2017)	34,022	-	[50]
PEV market share OEM	15 %	-	own assumption
Average annual mileage (private)	ca. 13,400	km/a	[51]
Average power consumption	20	kWh/100km	own assumption
Battery capacity (BEV | PHEV)	40 | 7	kWh	own assumption
Max. charging power	3.7	kW	own assumption
Max. total load limit (of orig. peak)	150 %	-	own assumption
Average share of BEV plug-in time	75 %	-	own assumption
Average share of PHEV plug-in time	33 %	-	own assumption

To approximate PEV charging behaviour, we use load curves derived from representative German mobility data of daily vehicle use patterns [51] and appropriate assumptions on PEV-adoption. This procedure was introduced by Kaschub et al. [52] and yields the charging behaviour of a specified number of PEV over one representative week. The normalised charging profile is scaled up to represent the current number of PEV in Germany (cf. Table 2), yielding a nominal load profile for one week. To account for changing vehicle availability during the week, we use data from the German study 'Mobilität in Deutschland' (Engl.: Mobility in Germany) by infas and DLR [17] (via [53]).

Power price data from EXAA [48] is used as the price signal that the aggregator adheres to and propagates as the real-time-price to his customers. It relays the time-specific valuation of green power supply in central Europe. As stated above, trade ceased on this market in mid-2016. Therefore, we use the average daily price curve of 2015, the only consistently liquid year. The curves were aggregated analogous to the charging load. For 2015, prices on GreenPower@EXAA were on average 2.2 % (0.7 EUR/MWh) higher than on the Austrian energy only market and the price profiles of the two markets are strongly correlated [34]. Figure 2 gives an overview of the two curves. It is assumed that the customers react perfectly to the signal, i.e. with high price sensitivity.

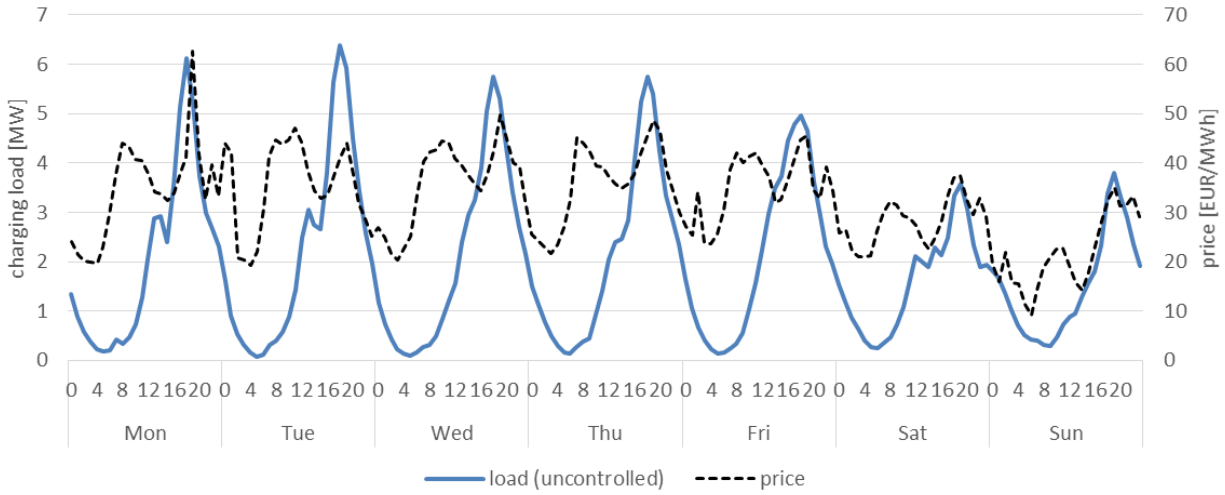

Figure 2: Average weekly load profile and prices [48,51]

5.2.2 Method

For the calculation of the potential for the active balancing service, the objective of the model is to calculate the annual savings potential through smart charging compared to uncontrolled charging. For smart charging, the model minimises total charging costs for one week (1), while the daily energy demand for each day $Q_{\tilde{d}}^{target}$ has to be met (2). Since most PEV are available until 6 a.m. (cf. Figure 2), charging for the following day is allowed until 6 a.m. of that day $\tilde{d}$[1]. Perfect information is assumed. The variables are the hourly power consumption of all vehicles $q_{t,d}$ for each hour t and each day d. The maximum charging power for every hour is limited by $q_{t,d}^{max}$, a specific maximum system load that is the product of the maximum charging power, the number of vehicles and the hourly availability (3). Furthermore, the hourly charging load must remain below the absolute total limit Q^{limit} guaranteed to the grid operator (4). Only unidirectional charging is allowed (5).

$$\min \sum_{d} \sum_{t} q_{t,d} \cdot p_{t,d} \qquad t \in \{1, 2, \dots, 24\}, d \in \{Mon, \dots, Sun\} \tag{1}$$

$$\text{s.t.} \quad \sum_{t} q_{t,\tilde{d}} = Q_{\tilde{d}}^{target} \qquad \forall\, t, \tilde{d} \in \{[Sun\ 6\ a.m., Mon\ 6\ a.m.), \dots\} \tag{2}$$

$$q_{t,d} \leq q_{t,d}^{max} \qquad \forall\, t, d \tag{3}$$

$$q_{t,d} \leq Q^{limit} \qquad \forall\, t, d \tag{4}$$

$$q_{t,d} \geq 0 \qquad \forall\, t, d \tag{5}$$

This simple, deterministic linear program is solved with the Excel Solver using *Simplex LP* and completes within seconds on a normal consumer laptop. The resulting hourly arbitrage costs are aggregated over a week and then scaled up for the entire year. A specific model for the reactive balancing service is not necessary as charging processes are not influenced.

5.2.3 Results

The assumptions above lead to an annual energy demand of the PEV of almost 17 GWh or on average 1544 kWh per PEV and year, independent of the charging strategy.

For the reactive balancing service, the service provider could simply enter a cooperation with a traditional retailer and provide his customers with a contract meeting the quality requirements. There is no additional cost for this case, but the service provider loses the potential benefit of much closer and more continuous customer relations. This is particularly interesting for a vehicle manufacturer. If the service provider actually enters the power market, the market entrance costs are equivalent to the smart charging-case below. If the service provider would like to incentivise customers with a rebate on the power price of e.g. 5 % against a common power price of 0.285 EUR/kWh for *ok-power*-certified power (including the base price), this would result in additional annual costs of over 242,000 EUR or around 29 EUR/vehicle.

For the active balancing service, the service provider decides to participate actively on the power and REC markets and must bear market entry costs. The fees for trading on the EEX-intraday and day-ahead market amount to around 43,500 EUR per year, most of which is a fixed participation fee. There is also a one-time market entrance fee of 25,000 EUR, which is not included for the considerations below. Variable trading fees amount to about 0.055 EUR/MWh but strongly depend on how many and which markets are to be used for trading [54][2].

[1] E.g., the energy needed for a Wednesday must be charged between Tuesday 6 a.m. and Wednesday 5:59 a.m.

[2] We assume the service provider to buy half of the required energy from the day-ahead and half from the intraday market (15-min auction), without having to issue corrective bids on other short-term markets due to forecast errors.

The model defined in the previous section estimates the energy costs with smart charging. The charging times are moved to the times of minimum power costs. The optimised and the original load curve (left axis) are depicted in Figure 3 as well as the price curve (right axis).

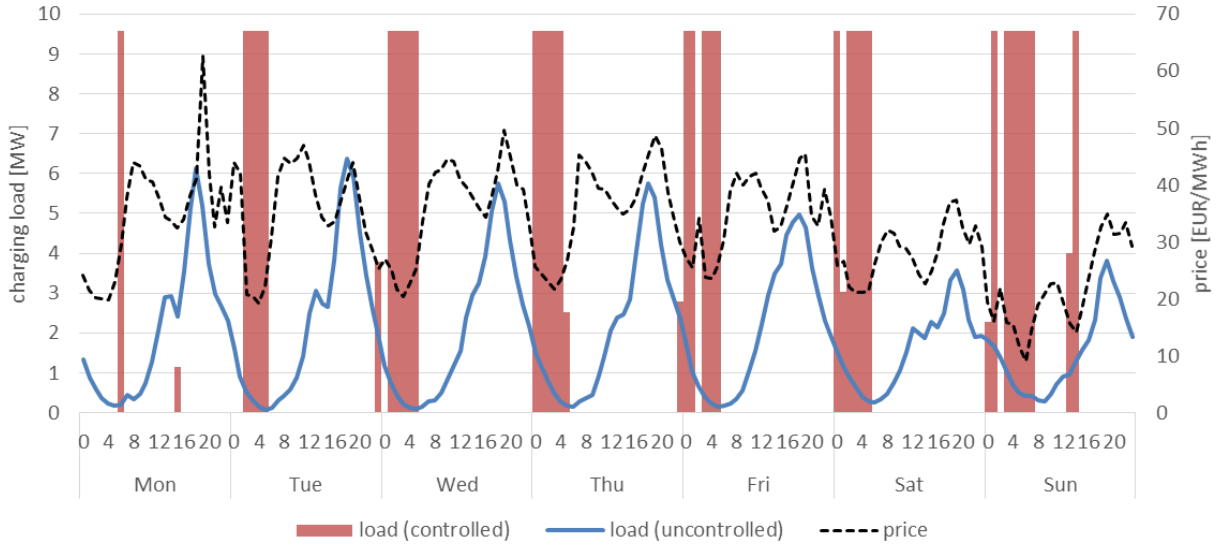

Figure 3: Optimised load curve for the exemplary week compared to original load and prices

By shifting the charging times according to the price for green power, the service provider can generate arbitrage gains of almost 249,000 € per year (30.18 EUR/PEV and year) and around 40 % of time-specific electricity costs. Table 3: Daily cost comparison for one exemplary week [in EUR]Table 3 shows the daily costs and the gains through controlled charging[3]. Please note how most of the demand for Monday is shifted to the cheaper Sunday.

Table 3: Daily cost comparison for one exemplary week [in EUR]

Day	Controlled	Uncontrolled	Delta	
Mon	319.67	1,900.14	1,580.47	83.2 %
Tue	886.10	1,969.22	1,083.12	55.0 %
Wed	1,101.70	1,933.13	831.43	43.0 %
Thu	1,280.50	1,987.54	707.04	35.6 %
Fri	1,202.79	1,872.67	669.88	35.8 %
Sat	1,143.86	1,142.40	-1.46	-0.1 %
Sun	1,029.58	933.33	-96.25	-10.3 %
Sum week	6,964.20	11,738.43	4,774.23	40.7 %
Sum year	363,133.26	612,075.19	248,941.94	40.7 %

The service provider can now decide if he forwards these savings to the customer, as financial incentives are considered a major reason for PEV-customers to participate in smart charging schemes [e.g. 7]. According to Will and Schuller [5] customers expect around a 20 % discount. The remaining 20 % and potential additional revenues from marketing the vehicle pool's flexibility, e.g. on balancing power markets, must suffice to cover operational costs and pay for investments in making controlled charging possible with a profit. Illing and Warweg [55] stress, that European aggregators can only make a profit if a distribution grid operator directly steers charging curves to improve grid stability, avoiding the uncertainty of customers' failing to react to price incentives (which was not considered in this model). The potential profits are comparable to the arbitrage-gains determined here and grow with PEV numbers. In a later study, Illing and Warweg [29] estimate that aggregator-business-cases are profitable on the reserve market with a pool size greater than 75,000 PEV. Additional profits can be generated if the vehicle can feed energy back to the grid. Schuller and Rieger [20] estimate profits on the secondary reserve market above 730 EUR/vehicle and year.

[3] However, price variability is likely to decrease with increasing PEV numbers as more aggregators enter the market and exploit arbitrage. Eventually, this will reduce aggregator revenues and threaten their business case.

Figure 4 shows the estimated cost structure for smart charging with EXAA-prices and a total power consumption of almost 17 GWh. Notably, trading costs are comparatively small and barely visible. Further cost components, such as development for the software backend or running personnel, billing and IT-costs are not included, but could be derived from Ernst&Young 2013 via [55].

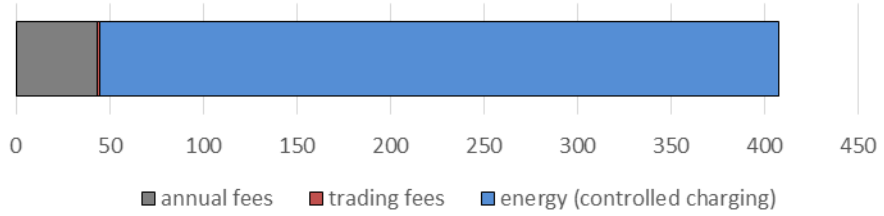

Figure 4: Cost structure for smart charging and EXAA-prices [in 1000 EUR]

Besides these economic benefits, also environmental benefits can be achieved. Since we used a price curve which is chiefly influenced by green power provision, charging was shifted to times of excess renewable supply. By increasing demand in these hours, prices will rise and scarcity signals could lead to additional capacity being built in the long run and to the power mix becoming cleaner. In addition, avoiding unnecessary load peaks avoids additional system costs (and less land use and resource use) for grid expansion or curtailment of volatile renewables. Furthermore, the service provider can maintain a much closer customer relation. This additional exposure could lead to additional marketing potentials for the provider.

6 Conclusion, limitations and outlook

Since carbon-neutral charging of PEV is a way to minimise transport emissions, we established a characterisation framework for green power services according to their environmental and economic feasibility. The six dimensions of environmental quality lay groundwork for their understanding and their perceived environmental impact, and its resulting appreciation. This quality appreciation can be contrasted to the economic potential and aid service providers in finding the most efficient approach to the topic of carbon-neutral charging for their individual customers. We illustrated the suggested framework with a case study on two specific green power services: a reactive balancing service with strong requirements on additionality and good transparency and an active balancing service with hourly balancing and smart charging.

The main limitations of this work are the limited validation for quality dimensions and simplicity of the model, including perfect information and limited data foundation. It has to be noted, that the power traded at GreenPower@EXAA came mostly from controllable hydropower and not volatile renewables. Moreover, trading volumes were so small that our described aggregator would have had significant market power. Secondly, we consider only WTW-emissions, ergo between power production and vehicle use, in accordance with the definitions by Ensslen et al. [1]. Emissions from vehicle and especially battery production or end-of-life-emissions, are specifically not included. The scope of this analysis could be expanded to a complete and complex life-cycle-assessment of PEV and green power emissions. As a compromise, Moro and Helmers [56] suggest a concise method to link WTW- and life-cycle-considerations, which might be a direction of future research.

Future work must focus on making the presented formalisation applicable by determining the environmental quality score (i.e. scales and individual weights of the respective dimensions) through empirical research of customers' preferences. Furthermore, the economic implications strongly depend on the dynamics on the power and vehicle market. Power market simulation allows for the discussion of these implications for the various green power services. The consideration of different perspectives on the correct electricity mix, i.e. annual or time-specific mix or even marginal mix according to Jochem et al. [24], are another possible direction of future research.

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