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Effects of Integrating Electric Vehicles and Stationary Batteries in a Smart Urban Electricity Network

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Abstract

The aim of the European Union to drastically reduce greenhouse gas emissions in the following decades has a great influence on the transport and the energy sector. Electric vehicles and renewable energy sources are seen as outstanding possibilities on this way. An interrelation of these technologies seems to be a promising option. In our contribution we address some challenges, which come along with this interrelation. From a system perspective, more flexibility is needed. One option is to extend flexible demand through dynamic pricing, which stimulates a demand response. Electric vehicles can contribute to this objective when the comprehensive load shifting potentials are activated. In addition, the application of local storage devices is discussed to relieve local grids and support the integration of decentralized electricity generation by renewable energy sources.

In this contribution we analyze the effects of dynamic pricing for controlled and bi-directional charging of electric vehicles and the use of stationary battery systems in an urban electricity system. Therefore, we developed an optimization model for the application planning of the charging processes of electric vehicles and stationary storage systems. We demonstrate the high technical and economic potential for load shifting of the charging processes of electric vehicles with controlled charging. Furthermore, we identified positive and negative effects of real time pricing and load limits concerning cost and emission reductions and effects on grid loads. Only the use of stationary battery systems at home together with a load limit has positive effects for integrating photovoltaics and foster CO_2 emission reductions. With real time pricing the stationary battery systems are used for arbitrage at the day-ahead market.

Keywords: smart grid, battery charge, emissions, optimization, modeling

1 Introduction

The European Union aims to reduce greenhouse gas emissions in the following decades drastically [1]. Especially the sectors energy and transport are important for significant reductions [2]. In transport electric vehicles (EV) are seen as outstanding possibility to reduce emissions. Though EV are still expensive (mainly due to the high prices of lithium-ion batteries) their market share is still negligible. However, prices are falling and are assumed to fall further in the next years due to higher market volumes and production developments [3]. In order to achieve considerable emission reductions, it will be important to guarantee a 'clean' electricity generation mix.

In Germany this objective is tried to achieve mainly by increasing the share of renewable energy sources (RES). The mix of RES includes a strong part of fluctuating electricity generation by photovoltaic (PV) and wind energy. The integration of this growing share of fluctuating and hardly controllable RES is a major topic of current energy research. Therefore, the demand side comes into focus and the question how to use and establish load shifting potentials. Smart grid technologies might help in this context. Demand response with dynamic pricing is able to activate considerable load shifting potentials [4].

EV will become a new and considerable load demand. Especially the high charging power is seen as a main challenge especially in local distribution grids. On the other side, the high power and energy demand of EV along with long parking hours might bring a high load shifting potential that can be used automatized with controlled charging. Furthermore, with bi-directional charging, EV are usable as storage devices.

In the context of integration RES beside demand response also storage is widespread seen as important component. Therefore not only EV but also stationary storage systems (SBS) are of interest. With falling prices for lithium-ion batteries also SBS become more and more profitable. They can support load management in the grid or can be directly used for increasing self-consumption at end users.

EV are in general used in a small radius and parked most of the time at home and also SBS are located locally. Therefore these topics have a local impact.

In this contribution we evaluate with an optimization model the possibilities of how to integrate EV and local RES in an urban electricity system. We therefore use an exemplified distribution network of a city and determine the effects of controlled charging, demand response with real-time pricing or load limits. Furthermore, we evaluate the use of SBS on the grid level and at home.

In chapter 2 we give an overview of the developed model and the assumptions used. In chapter 3 we show the results and give a conclusion in chapter 4.

2 Modeling Overview and Method

We use an optimization model to minimize electricity expenditures of all end consumers of an urban electricity network[1] as shown in the target function (see (1)) with linear programming (LP). Implemented are the conventional electricity consumption of households, commerce and industry and the electricity charging by EV with different charging variants. As further storage possibility SBS are integrated. Lithium-Ion batteries are used as storage technology. On the generation side the fluctuating RES of wind and PV are integrated. The regarded region is split into sub regions, based on city districts and electricity transformer stations (TS). Power demands and power supplies are aggregated to these sub regions and are connected by high voltage distribution grid. In the following sections these modelling parts are explained.

The minimizing of the electricity expenditures uses the load shifting potentials by EV and the application of the SBS. Incentives for optimal application planning are given by implementing demand response possibilities based on dynamic pricing schemes, which is explained in section 2.5. The self-consumption of PV is incentivized by the German Renewable Energy Law (EEG).

$$\min \boldsymbol{C}^{total} = \sum_{t\in T, ts\in TS, evc\in EVC} \boldsymbol{C}^{EV,charge}_{t,ts,evc} + \sum_{t\in T, ts\in TS} \left(\boldsymbol{C}^{elec}_{t,ts} + \boldsymbol{C}^{LL}_{t,ts} + \boldsymbol{C}^{SBS}_{t,ts} \right) \quad (1)$$

Legend

C	costs
t	time step (1 h), element of T
ts	transformer station, element of TS
evc	EV class, element of EVC
EV	electric vehicles
elec	conventional electricity consumption of households, commerce, industry
LL	load limit
SBS	stationary battery systems

all variables are in bold face

2.1 Power Demand and Prices

The demand is clustered into the sectors of households, commerce and industry. The load profiles are given as input parameters. They are put together of the German standard synthetic load profiles (SLP) and a scaling factor for aggregation of each sub region supplied by TS. For households the

[1] Karlsruhe (300,000 habitants) in south-western Germany is taken as basis.

SLP H0 [5] is used. The scaling factor consists of the population numbers, the distribution of household sizes and their average electricity need (according [6]). For commerce SLP G0 [5] is used. For industry demand a combination of the single industry sector SLP [7] is used.
The energy price for electricity p_t^{EEX} is based on the EEX day ahead spot market price from 2008. For each sector of household, commerce and industry an additional price component is calculated, that integrates all taxes and charges (e.g. VAT, use of system charges) [8]. This price component amounts to $p_t^{HH} = 15.26$ ct/kWh for households, $p_t^{com} = 13.62$ ct/kWh for commerce and for industry $p_t^{ind} = 6.44$ ct/kWh [8]. These prices are derived from average electricity prices in 2008 [8].

2.2 Electric Mobility and Stationary Battery Systems

Electric Mobility is implemented as flexible load with the capability of discharging to the grid. The representative mobility behaviors are taken from the German mobility studies *Mobilität in Deutschland 2008* (MiD2008) for private transport [9] and *Kraftfahrzeugverkehr in Deutschland* 2010 (KiD 2010) for commercial transport [10]. We differentiate three vehicle classes:

- private passenger cars
- commercial passenger cars
- light commercial vehicle (LCV) below 3.5 tonnes gross vehicle weight (GVW)[2]

Based on the mobility studies, we evaluated a technical and then an economic potential for possible EV penetration in each vehicle class. Therefore, annual mileage, parking place, daily mileage and parking time are analyzed. For private cars only charging at a private place (i. e. home) is considered. For commercial vehicles charging at a private place and at the own company is considered. Only datasets with the classification area type of large cities are used. We therewith evaluated an EV potential of 65 % of all cars and 71 % of all LCV.
These potential EV can be integrated into the model in four different ways, especially concerning charging:

- *EVno:* no EV is integrated
- *EVstart:* uncontrolled charging instantly after EV arrives at charging point
- *EVopt* controlled charging
- *EV2H* controlled charging and discharging to home

The model variant with *EVno* does not need any additional information for EV. For the variant *EVstart* we used the mobility profiles of the mobility studies and calculated the instant charging demand. For the variants *EVopt* and *EV2H* we integrated charging power boundaries for the EV that are dependent in time. Most important is the charging behavior of the vehicle users, which is initially undefined. To allow further analyses, we therefore assume two extreme behaviors

a) Instant complete charging: by arrival at a parking place with charging possibility the charging process is started instantly. When parking time is sufficient, the battery is completely charged for the next trip. This behavior allows full driving flexibility, as the battery is charged fastest possible but eliminates load shifting potential.
b) Minimum charging as late as possible: this charging behavior is only possible with an automated charging system and the knowledge of departing time and trip distance of the next trip. Charging latest possible eliminates any flexibility for the user, as there might not be sufficient energy to start a trip earlier or to drive a longer distance. Therefore, it is not likely for many drivers. But this behavior allows maximum load shifting potential.

With these two extreme charging strategies it is possible to quantify the state of charge (SoC) charging boundaries for an EV with known mobility behavior. In between these restrictions, the charging process is free and therefore defines the load shifting potential based on the SoC for an EV. These single boundaries are aggregated for all EV of each sub region. The methodology explained in detail in Kaschub et al. [11].
As Li-Ion batteries as well as lead-acid batteries have a constant current constant voltage (CCCV) charging process, the maximum charging power is not constant over the charging time. There exist already several approaches to implement this interrelation in mathematic equations [11]. For this model, the maximum available charging power $\mathrm{P}_{\mathrm{t,evc,ts}}^{EVSE,max}$ is restricted according function (2). The initial maximum charging power $\mathrm{P}^{\mathrm{EVSE,max,0}} = 3.5\ kW$ decreases linear with increasing SoC. This underestimates available charging power for most cases.

[2] Light commercial vehicles are defined excluding passenger cars. Light duty vehicles (LDV) include both LCV and passenger cars.

$$\mathbf{P}^{\boldsymbol{EVSE,max}}_{\mathbf{t,evc,ts}} \leq \mathrm{P}^{\mathrm{EVSE,max,0}} \left(1 - \boldsymbol{SoC}^{\boldsymbol{EV}}_{\boldsymbol{t,evc,ts}}\right) \quad \forall \mathrm{t} \in \mathrm{T}; \forall \mathrm{evc} \in \mathrm{EVC}; \forall \mathrm{ts} \in \mathrm{TS} \quad \mathrm{SoC} \in \{0, \dots, 1\} \tag{2}$$

The battery capacities for passenger EV are assumed to be 25.2 kWh and for LCV to be 36 kWh. The charging cycle efficiency is defined to 85 %.

The SoC is balanced by function (3). The energy stored in the battery $E^{\mathrm{EV}}_{\mathrm{t,evc,ts}}$ is the difference from the previous time slice caused by discharging to drive the EV, $E^{\mathrm{EV,drive}}_{\mathrm{t,evc}}$, the discharging to home $E^{\mathrm{EV2H,dischgr}}_{\mathrm{t,evc,ts}}$ and the charging of the EV $E^{\mathrm{EV,charge}}_{\mathrm{t,evc,ts}}$.

$$\boldsymbol{E}^{\mathbf{EV}}_{\mathbf{t,evc,ts}} = \boldsymbol{E}^{\mathbf{EV}}_{\mathbf{t-1,evc,ts}} - E^{\mathrm{EV,drive}}_{\mathrm{t,evc}}\, n^{\mathrm{EV}}_{\mathrm{evc,ts}} - \boldsymbol{E}^{\mathbf{EV,dischgr}}_{\mathbf{t,evc,ts}} + \boldsymbol{E}^{\mathbf{EV,charge}}_{\mathbf{t,evc,ts}} \quad \forall \mathrm{t} \in \mathrm{T}; \forall \mathrm{evc} \in \mathrm{EVC}; \forall \mathrm{ts} \in \mathrm{TS} \tag{3}$$

Further equations restrict the charging and discharging power and maximum battery capacity available; two equations convert energy values to SoC or power. Two further equations include a binary variable to separate charging and discharging time slices. Only in case of the model variant with *EV2H* or active SBS this binary variable is necessary. This makes for these two scenarios a mixed integer programming necessary.

The SBS is implemented similar to the EV, but with simplified assumptions. Therefore, no additional equations are required. Only a fourth EV class *stationary* is added. In several equations the SBS need some minor variations. Concerning the input data, the boundary values for maximum and minimum SoC are constant between 0 % and 100 % of battery capacity. Also there is no input for driving energy need $E^{\mathrm{EV,drive}}_{\mathrm{t,evc}}$.

2.3 Electricity Generation by Renewable Energies

Only local electricity generation on the distribution grid level is considered explicitly. Generation capacities at transmission grid level are excluded from the considerations. Nevertheless combined heat and power plants (CHP) are neglected. Power generation from PV and wind is integrated due to the fluctuating nature.

We assume installed capacities for PV (250 MW) and wind (10 MW) based on the potential analysis by the local grid operator (SWKA-Netze). For now only a small share of this potential is installed. The time dependent electricity generation is derived from historical weather data of the year 2008 [12].

The self-consumption is incentivized by the German Renewable Energy Law (EEG). Therefore this part of the PV generation is calculated separately ($\boldsymbol{P}^{\boldsymbol{self}}_{\boldsymbol{t,ts}}$) and integrated in equation (10) with an incentive of p^{self}_{t} =8ct/kWh. The possible power is restricted by the PV power production and the demand of the households $P^{HH}_{t,ts}$ and the battery charging $\boldsymbol{E}^{\mathbf{EV,charge}}_{\mathbf{t,evc,ts}}$ that is given in equation (4). The demand for charging SBS is only regarded for self-consumption, when they are considered as home SBS. When located in the grid, *LOC* is zero.

$$\boldsymbol{P}^{\boldsymbol{self}}_{\boldsymbol{t,ts}} \leq P^{HH}_{t,ts} + \sum_{\overline{EVC}} \boldsymbol{E}^{\mathbf{EV,charge}}_{\mathbf{t,evc,ts}} + LOC \sum_{\overline{\overline{EVC}}} \boldsymbol{E}^{\mathbf{EV,charge}}_{\mathbf{t,evc,ts}} \quad \forall \mathrm{t} \in \mathrm{T}; \forall \mathrm{ts} \in \mathrm{TS}; \forall \mathrm{evc} \in \mathrm{EVC} \quad \mathrm{stationary} \notin \overline{EVC} \subset \mathrm{EVC} \quad \mathrm{stationary} \in \overline{\overline{EVC}} \subset \mathrm{EVC} \tag{4}$$

This assumption for self-consumption of a total sub region probably overestimates it, as the self-consumption has to be balanced on the level of single buildings without interaction of the grid.

2.4 Distribution Grid

The high voltage level of the distribution grid is implemented in the model. This includes high voltage cables and transformer stations with connections to the lower distribution level and the transmission grid (TG) level. The electricity flows in the grid are considered by a simplified power flow calculation which is known as matrix formulation of DC power flows [13]. A conversion in the "per unit" system[3] is omitted as it is not necessary in this case, where only one distribution level is implemented.

Two main functions represent the power flow and Kirchhoff's circuit laws. In the equation (5) the phase angle φ at TS^A is calculated by the power flows at the TS^B connected to TS^A. To implement the cable characteristics the reduced and inverted matrix B is necessary.

$$\boldsymbol{\varphi}_{\boldsymbol{t,ts^A}} = \sum_{TS^B} \left(B^{red,inv}_{ts^A,ts^B} \left(\boldsymbol{P}^{\boldsymbol{TS}}_{\boldsymbol{t,ts^B}} - \boldsymbol{P}^{\boldsymbol{from\,TG}}_{\boldsymbol{t,ts^B}} + \boldsymbol{P}^{\boldsymbol{to\,TG}}_{\boldsymbol{t,ts^B}} \right) \right) \tag{5}$$

[3] In power system analysis system quantities are expressed as fractions of a defined base unit.

$$\forall \mathrm{t} \in \mathrm{T}; \forall \mathrm{ts} \in \mathrm{TS};$$
$$TS^B \supset \overline{TS^B} \ni Tr02, Tr07, Tr09$$

The equation (6) calculates the power flows in the cables. These are depended from phase angle φ of both TS and the resistance x (reactance) of the cable.

$$\boldsymbol{P}^{\boldsymbol{cable}}_{\boldsymbol{t,ts^A,ts^B}} = 1/x_{ts^A,ts^B} \left(\boldsymbol{\varphi}_{\boldsymbol{t,ts^A}} - \boldsymbol{\varphi}_{\boldsymbol{t,ts^B}}\right) \quad \forall \mathrm{t} \in \mathrm{T}; \forall \mathrm{ts} \in \mathrm{TS} \tag{6}$$

Further equations are formulated to balance the incoming and outgoing load at TS, to sum the load from lower grid level and to split the two directional load flows into positive and negative direction.

For the grid under consideration [14, 6] we assume nominal capacity of TS with 2x 40 MW. The nominal capacity of high voltage cables[4] is assumed with 2x 71 MW, a resistance of 0.1 Ω and reactance of 0.38 Ω [15]. This urban high voltage grid has a high load density and is dimensioned with high tolerance.

2.5 Demand Response

One effective possibility to incentivize load shifting is dynamic electricity pricing, especially when real-time feedback systems are available and automation systems support scheduling, e. g. charging the EV [16].

In this model we integrated three tariffs:

I. The standard electricity price without variations during the year,
II. real time pricing (RTP) based on hourly average EEX day ahead spot market price and
III. load variable tariff that surcharges demand over a given load limit (LL).

The electricity price p_t^{EEX} is time depended and therefore usable for all three tariffs. Only input data has to be changed. For tariff I the average value with $p^{EEX} = 6.6ct/kWh$ of EEX day ahead spot market price of 2008 is used. The hourly average values thereof are used for tariff II. In tariff III, the price of tariff I is added with the surcharge of 10 ct/kWh when LL is exceeded. The demand that is surcharged $\boldsymbol{P}^{\boldsymbol{over\ LL}}_{\boldsymbol{t,ts}}$ is calculated with equation (7) and then integrated in equation (11).

$$\boldsymbol{P}^{\boldsymbol{over\ LL}}_{\boldsymbol{t,ts}} \geq \boldsymbol{P}^{\boldsymbol{TS}}_{\boldsymbol{t,ts}} - P^{LL}_{ts} + \boldsymbol{P}^{\boldsymbol{under\ LL}}_{\boldsymbol{t,ts}} \quad \forall \mathrm{t} \in \mathrm{T}; \mathrm{ts} \in \mathrm{TS} \tag{7}$$

The load limit is calculated based on the average conventional load of all sectors in a sub region. In average it is 130 % of the peak load without EV loads. The reduced LL is in average at 80 % of the peak load without EV.

With tariff I no additional incentive is given but the self-consumption. The RTP tariff (II) intends to incentivize load shifting into time slots with low prices. The LL tariff (III) intents to prevent high load peaks.

2.6 Considered Costs

The costs included in the target function (1) are calculated in the equations (8) to (11). In equation (8) the costs for charging the EV $\boldsymbol{C}^{\boldsymbol{EV,charge}}_{\boldsymbol{t,ts,evc}}$ is calculated. For the variant *EV2H* (explained in section 2.2) the discharging degrades the battery for non-mobility needs and is therefore monetized.

$$\begin{aligned} \boldsymbol{C}^{\boldsymbol{EV,charge}}_{\boldsymbol{t,ts,\overline{evc}}} &= \left(\boldsymbol{E}^{\mathbf{EV,charge}}_{\mathbf{t,\overline{evc},ts}} - \boldsymbol{E}^{\mathbf{EV,dischgr}}_{\mathbf{t,\overline{evc},ts}}\right) \\ &\quad \times (p_t^{EEX} + p_t^{HH}) \\ &\quad + 5ct/kWh\, \boldsymbol{E}^{\mathbf{EV,dischgr}}_{\mathbf{t,\overline{evc},ts}} \\ &\quad \forall \mathrm{t} \in \mathrm{T}; \forall \mathrm{ts} \in \mathrm{TS}; \\ &\forall \overline{\mathrm{evc}} \in \mathrm{EVC};\ \mathrm{EV_P}, \mathrm{EV_C}, \mathrm{LCV} \in \overline{\mathrm{evc}} \end{aligned} \tag{8}$$

The cost function (9) for SBS is similar to equation (8). The additional price component p_t^{HH} is only activated with LOC, when the SBS are available at households. In the other case they are located at TS in the grid. Then this price surcharge is not relevant.

$$\begin{aligned} \boldsymbol{C}^{\boldsymbol{SBS}}_{\boldsymbol{t,ts}} &= (\boldsymbol{E}^{\mathbf{EV,charge}}_{\mathbf{t,\overline{\overline{evc}},ts}} \boldsymbol{E}^{\mathbf{EV,dischgr}}_{\mathbf{t,\overline{\overline{evc}},ts}}) \\ &\quad \times (p_t^{EEX} + LOC\ p_t^{HH}) \\ &\quad \forall \mathrm{t} \in \mathrm{T}; \forall \mathrm{ts} \in \mathrm{TS}; \\ &\forall \overline{\overline{\mathrm{evc}}} \in \mathrm{EVC}; \mathrm{stationary} \in \overline{\overline{\mathrm{evc}}} \end{aligned} \tag{9}$$

The conventional electricity costs are summed in equation (10). The savings through self-consumption of RES are integrated here, too.

$$\begin{aligned} \boldsymbol{C}^{\boldsymbol{elec}}_{\boldsymbol{t,ts}} &= (P^{HH}_{t,ts} + \boldsymbol{P}^{\boldsymbol{NSH}}_{\boldsymbol{t,ts}})\ (p_t^{EEX} + p_t^{HH})\ TD \\ &\quad + P^{com}_{t,ts}\ (p_t^{EEX} + p_t^{com})\ TD \\ &\quad + P^{ind}_{t,ts} \left(p_t^{EEX} + p_t^{ind}\right) TD \\ &\quad - \boldsymbol{P}^{\boldsymbol{self}}_{\boldsymbol{t,ts}}\ p_t^{self} TD \\ &\quad \forall \mathrm{t} \in \mathrm{T}; \forall \mathrm{ts} \in \mathrm{TS} \end{aligned} \tag{10}$$

As electricity night storage heaters (NSH) have some distribution, they are also integrated as shiftable load $\boldsymbol{P}^{\boldsymbol{NSH}}_{\boldsymbol{t,ts}}$. One further equation restricts the heating demand.

The costs for load limit exceeding in equation (11) are only activated, when the load limit is activated.

$$\boldsymbol{C}^{\boldsymbol{LL}}_{\boldsymbol{t,ts}} = 10ct/kWh\, \boldsymbol{P}^{\boldsymbol{over\ LL}}_{\boldsymbol{t,ts}} \quad \forall \mathrm{t} \in \mathrm{T}; \mathrm{ts} \in \mathrm{TS} \tag{11}$$

[4] The high voltage cables 243-AL1/39-ST1A of DIN-EN-50182:2001-12 are used.

Not integrated are costs for control systems which are necessary for controlled charging and the application of the SBS. Furthermore, no investments or maintenance costs are integrated. Evaluations of economic feasibility or investment decision are e. g. given in [17].

2.7 Carbon Dioxide Emissions

The calculation of CO_2 emissions is not integrated in the optimization model but determined ex post with the resulting electricity consumption. We use hourly CO_2 emissions factors that are based on an electricity mix in the German electricity market in 2030 [18].

3 Results

The model we described in chapter 2 is used in a first step to evaluate the effects of integrating EV in the considered Smart Urban Electricity Network. Uncontrolled charging (*EVstart*) and controlled charging (*EVopt*) are analyzed in section 3.1 and section 3.2, bi-directional charging (*EV2H*) in section 3.4. In the second step (section 3.4) SBS are added and their influence is analyzed. In all cases the effects of the different tariff incentives and the integration of EV have been analyzed in respect to costs, load curve and the influences concerning the CO_2 emissions.

The input values for weather data, EEX prices and electricity prices are used consistently from year 2008. For penetration of EV and the installed capacity of RES we use the potentials explained in section 2, as the historic penetrations in 2008 are not notable. The potentials represent therefore an extreme scenario. Real penetrations for the coming years or decades will be a share of this potential with a smaller impact. The fundamental effects will be the same. Therefore, we do not use scenarios for future years but evaluate comparable variants or settings. We know about the lack of consistence, especially for the prices in combination with high feed-in from RES. As long as there are similar marginal price differences in future as assumed here with historic values, the results for the application planning might be in similar dimensions.

In order to reduce complexity and help to illustrate the results we show always time periods of calendar week 24 and of the sub region TS07, unless another labelling is given.

3.1 Uncontrolled EV charging

An exemplary load curve with uncontrolled charging (*EVstart*) is shown in Figure 1. We have significant shares of the sectors households, commerce and industry. Together the electricity demand for the complete region and year is 2 195 GWh, the feed in of RES is 220 GWh. The charging demand of all modelled EV sums to 115 GWh and adds about 5 % demand to the region. This corresponds with the total electricity costs (+ 5 %) when assuming a single energy price (I) for electricity. The fear for strongly rising peak loads cannot be witnessed in this aggregation level of a whole city. Only small shares of higher peak loads are seen.

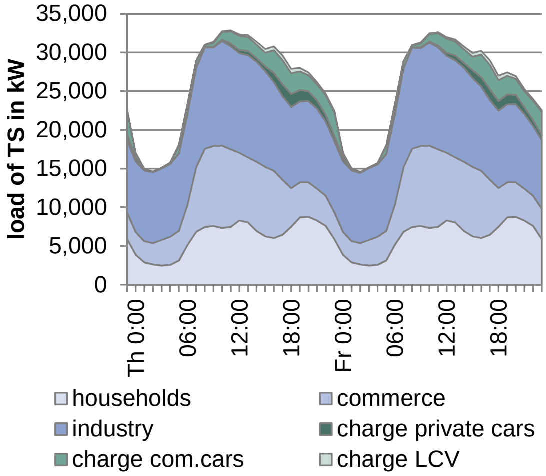

Figure 1: Load shares of region (EVstart, TS07)

The uncontrolled EV charging demand is spread over the whole day with a peak in the afternoon or the evening. In the night, during minimum load times, there is also no charging demand. Figure 2 shows the sub region TS07 with a high distribution of commercial electric cars that demand 64 % of the EV. Private EV have a demand share of 27 % and the remaining 9 % demand the LCV. In the other sub regions theses share vary strongly. The Figure 2 illustrates that there is no relation between EEX price and uncontrolled charging demand.

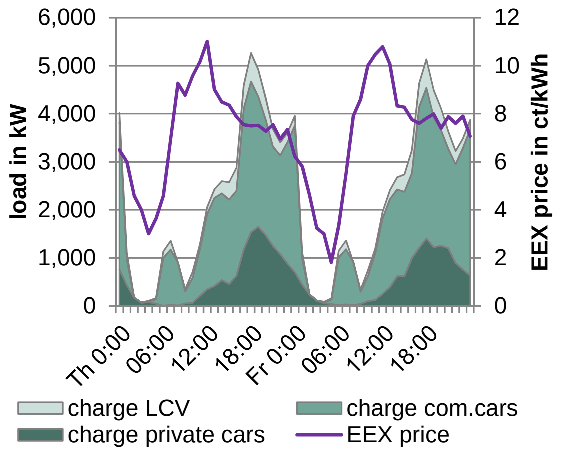

Figure 2: Charging loads (EVstart, TS07)

In Figure 3 the charging load of EV is integrated in the total load. The electricity generation of PV helps to reduce peak loads significantly. Therefore the load at the TS is reduced during midday and new but lower peaks are in the morning and evening. The virtual load limit is not activated and not relevant.

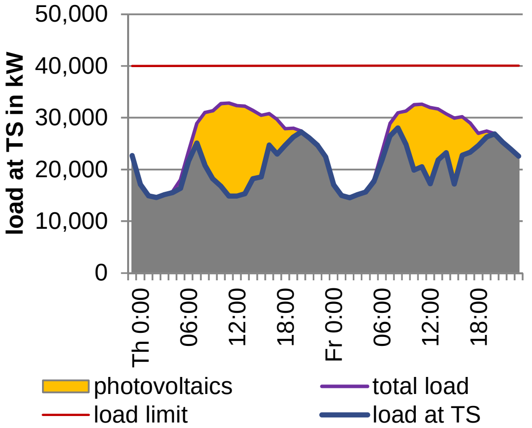

Figure 3: Loads at TS07 (EVstart)

3.2 Controlled EV charging

Controlled charging offers the possibility to further integrate RES into the electricity system or to reduce load in the grid. As the previously described situation is not critical, the question is, if there is really any potential. Otherwise only a cost reduction potential might be used by Demand Response actions.

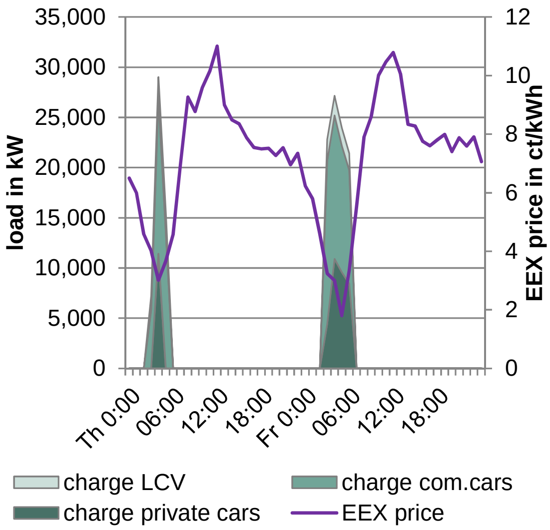

Figure 4: Charging loads (EVopt, RTP, TS07)

In Figure 4 the optimized charging load of EV with RTP (II) is collected to the two short time periods with minimum pricing. These time periods are often during night times where we previously saw minimum load. This means, that nearly the total charging load is shifted into the intended times. But now, the maximum charging load compared to uncontrolled charging is in this example about five times higher. This is comprehensible as every EV got the same RTP and the load shifting potential is given to shift charging from day to night time. Looking at the total load (cf. Figure 5), these new peaks occur in the previously off peak time. The previous peaks in the morning and evening are lowered. The new minimum load at TS is now during maximum PV feed in.

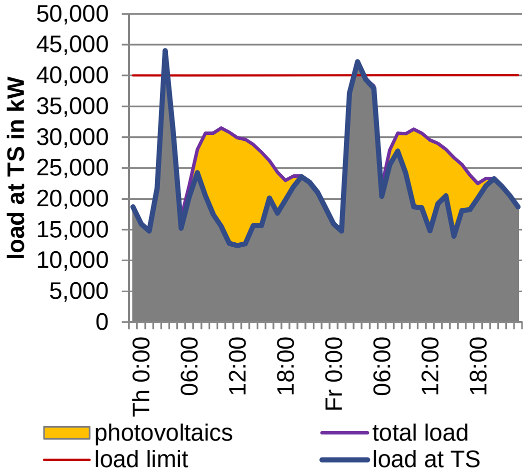

Figure 5: Loads at TS07 (EVopt, RTP)

In Figure 6 the maximum and minimum SoC boundaries for all private EV from sub region TS04 can be seen. On Thursday the charging upstroke is steeper than on Friday. On Friday the charging duration is longer and therefore the stroke higher. Nevertheless, not all degrees of freedom have been used for optimized charging process.

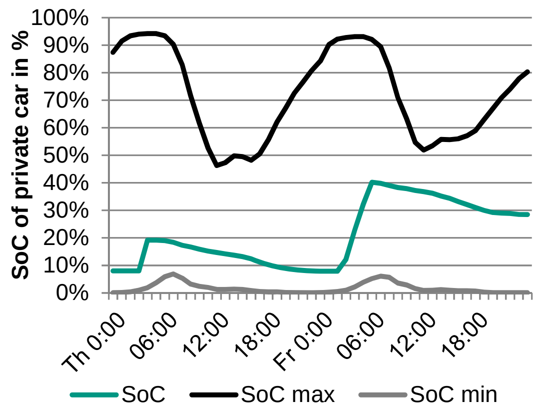

Figure 6: SoC of private EV (EVopt, RTP, TS04)

Figure 7 shows the optimized charging load of EV that is in this case incentivized by LL (III). As the standard LL is uncritical, we show examples for reduced LL. The charging processes are distributed to the whole day but still with spots. The peaks are substantive smaller to RTP, but still doubled to *EVstart*. The effect is a reduced peak load and a less varying demand curve at TS (cf. Figure 8).

The load demand of TS07 is delivered by two high voltage cables as shown in Figure 9, whereas the load of one cable is higher than of the other. The cables are not stressed.

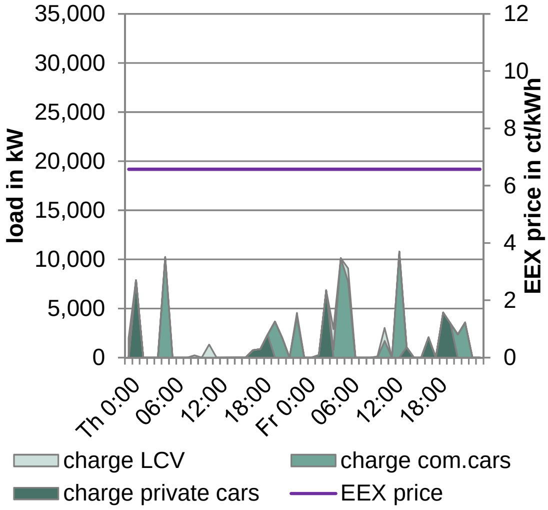

Figure 7: Charging loads (EVopt, LL low, TS07)

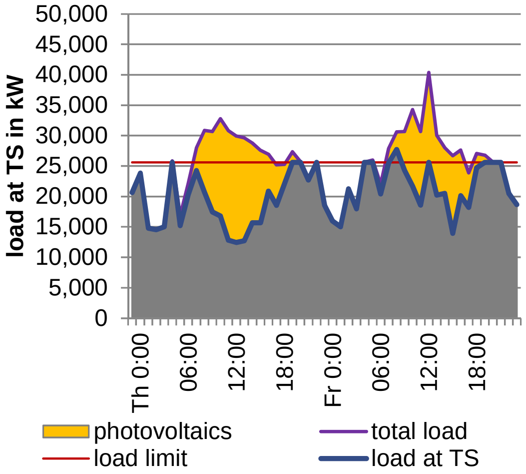

Figure 8: Loads at TS07 (EVopt, LL low)

Table 1 shows an overview of the results for the total region and allows comparison of the variants. We selected as reference the variant with uncontrolled charging and without dynamic pricing. In variant *EVno* the missing 5 % EV charging load in comparison to reference is also visible in total costs and emissions. Also maximum and minimum loads are reduced, as we expected. The comparison of *EVstart* with RTP to reference shows once again that uncontrolled charging is done during times with high EEX prices. The higher peak load in reference compared to *EVstart* with RTP might be a result of the load shifting from night storage heating, which is in the other variants not of relevance.

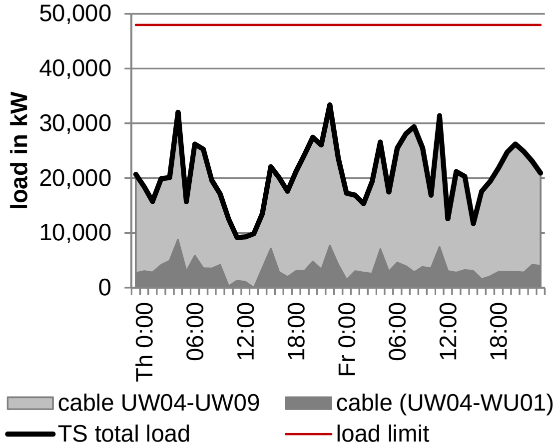

Figure 9: Load by cables (EVopt, LL, TS04)

The variants with *EVopt* are not reducing costs compared to reference. However compared to *EVstart* with RTP the costs can be reduced. RTP increases peak load and is less suitable to self-consume PV for charging. LL is suitable for several objectives. It can reduce load, if the LL is chosen appropriate. An undervalued LL reduces the monetary impact and also the peak load reduction,

Table 1: Overview of results for EV charging integration variants for the whole region and year

EV integration	***EVno***	***EVstart***		***EVopt***		
dynamic pricing	---	---	***RTP***	***RTP***	***LL***	***LL low***
costs (in % of reference)	95.0	reference	102.8	101.3	99.9	100.9
peak load in MW	400	425	395	553	406	425
minimum load in MW	28	35	35	28	65	64
possible share of PV self-consumption for charging in %	---	40.0	40.0	4.4	40.6	43.7
CO_2 emissions for EV charging (in % of reference)	---	reference	100.0	96.4	98.1	95.5
total CO_2 emissions in % of ref.	94.7	reference	100.1	99.9	99.9	99.8

as it is not possible at all times to remain under the LL. Levelling the load is also to some degree possible with a LL, as maximum and minimum load converge. Furthermore the LL does not reduce self-consumption. Rather, a reduced LL increases slightly self-consumption.
Controlled charging in combination with dynamic pricing is not suitable to reduce CO_2 emissions significantly. However, the average CO_2 emissions for charging EV slightly decrease, although this was no optimization objective of the model.

3.3 Electric Vehicles to Home

The feed of electricity from EV batteries to the grid is discussed and promoted for long time, especially by Kempton et al. [19]. But the possibilities of providing system services, called vehicle to grid (V2G), seem not profitable in the current German electricity system [20, 21]. In this contribution we consider discharging of EV not for market based system services but for direct use at home, often called vehicle to home (V2H).
As the use of the EV battery is for mobility purpose, we implemented additional degradation costs for V2H services (cf. section 2.6). With the assumed cost factor the possibility of discharging is never used in the variants of *EV2H* with RTP or LL. Therefore, we removed this degradation cost factor for the following analyses.

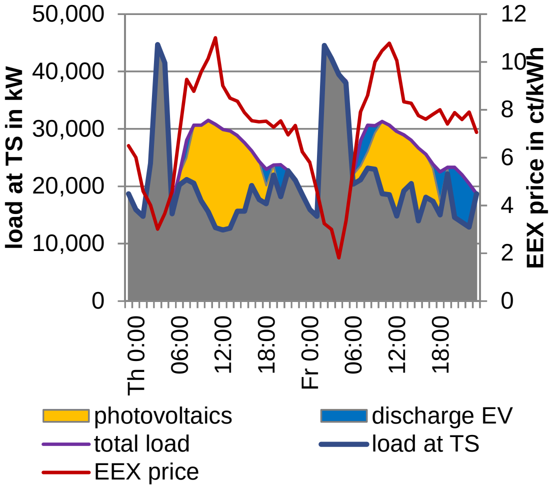

Figure 10: Loads at TS07 (EV2H, RTP)

The possibility of discharging with RTP is then used for arbitrage of EEX prices. In Figure 10 this usage is illustrated. During low price times the batteries are charged and during high price time, the households are supplied by discharging EV. During times with PV self-consumption the EV storage is not needed, but in the morning and in the evening, when self-consumption of PV electricity is not sufficient for supply of the households.
V2H is only used minimal for dynamic pricing with standard LL. The limits are not restrictive enough.
With reduced LL and reduced cable capacity of high voltage grid level discharging is used in some situations (cf. Figure 11). The application is now similar to the described variant with RTP. In this variant the discharging is used only for times with load exceeding the LL or to prevent grid shortage.

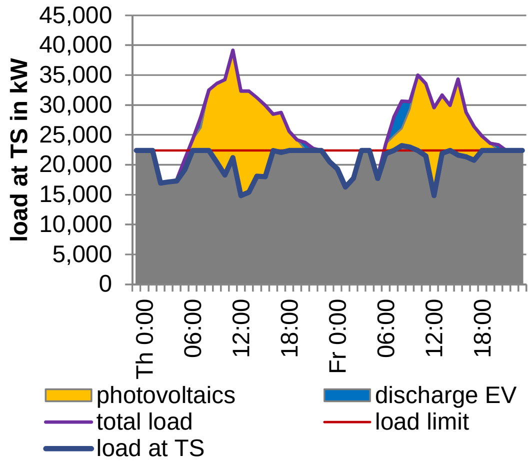

Figure 11: Loads at TS07 (EV2H, LL low and grid restriction)

In Table 2 an overview of results is given similar to Table 1. For variant *EV2H* with LL there is almost no difference to *EVopt* with LL, as discharging is not used (therefore not displayed in table). Only for reduced LL and restrictive grid situation, discharging of about 32 GWh occurs. This causes higher total costs. For RTP the use of discharging has only small effects. Almost 100 GWh are discharged, which results in doubled CO_2 emissions for EV charging.
In summary, the possibility of *EV2H* is useful, when no additional costs for battery degradation are assumed. Otherwise it is not profitable.

3.4 EV and Stationary Batteries

An alternative for discharging EV is the installation of a SBS. As a SBS is always available it is more flexible and application less restricted. We do not assume costs for SBS investment or degradation; but we assume cycle efficiency. EV are parked most of the time at home and therefore discharging to home is the most probable application. SBS can also be located at home and can be used as alternative to *EV2H*. Another possibility is the operation in the grid by the grid operator.

The application of a SBS with RTP is similar to *EV2H* with RTP. The SBS is used to store power during times with low price and discharge it during times with high price – for arbitrage of EEX prices. The SoC of the SBS is exemplary illustrated in Figure 12. In comparison with the EV battery, in this variant the whole capacity is used for this application. The capacity of the SBS is assumed to equal the battery capacities of the EV.

The resulting charging peaks and discharging peaks have large influence for the power load of TS and the supplying cables (cf. Figure 13). The charging peaks are similar to those of EV charging in the variant *EVopt* or *EV2H* with RTP. However, the discharging peaks are much stronger and cause an inverted load flow at TS and in the supplying cables. Not relevant is the location of the SBS. The application is similar (cf. Table 2) no matter if located in grid or at home. The SBS can reduce the total costs by storing and discharging of nearly 300 GWh, which is more than two times the energy need for EV charging. Through the efficiency loss of the SBS the total CO_2 emissions increase marginally. Another important difference to the variant of *EV2H* is the minimum power of about -330 MW that means an inverted load flow.

The variant of *EVopt* with SBS at home and LL is similar to the variant without SBS as the SBS is hardly used and no other changes in the variants are seen.

In the variant of *EVopt* with SBS at grid with LL the SBS is used for about 6 GWh charging with slight positive effects compared to the SBS in the grid. In all variants the emissions for EV charging are reduced by about 10 to 15 %, as the charging hours are different to the variants without SBS.

Table 2: Overview of results with storage integration variants for the whole region and year

EV integration	***EV2H****		***EVopt & SBS@HH***		***EVopt & SBS@Grid***	
dynamic pricing	***RTP***	***LL low***	***RTP***	***LL***	***RTP***	***LL***
costs (in % of reference)	100.8	103.6	98.0	99.0	97.6	98.8
peak load in MW	553	410	568	411	567	430
minimum load in MW	28	67	-332	82	-330	85
discharging sum in GWh	97	32	266	0.3	291	5.8
possible share of PV self-consumption for charging in %	2.8	36.8	13.5	58.4	14.7	62.7
CO_2 emissions for EV charging (in % of reference)	203.7	127.6	85.1	90.0	90.8	89.3
total CO_2 emissions in % of ref.	101.2	100.1	102.7	99.5	103.0	99.4

* EV2H is optimized without costs for degradation of discharging to home

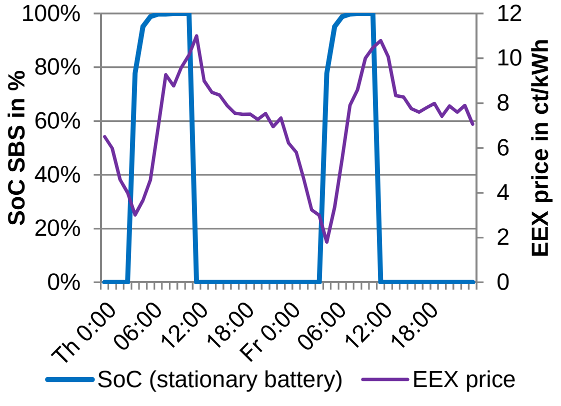

Figure 12: SoC of SBS and EEX price (EVopt & SBS@Grid, RTP, TS04)

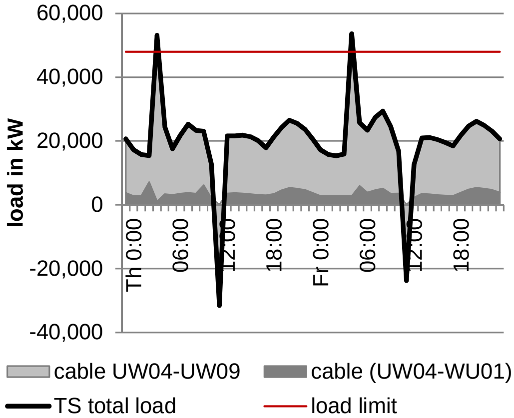

Figure 13: load by cables (EVopt & SBS@Grid, RTP, TS04)

4 Conclusions

In this contribution we analyzed the effects of dynamic pricing for controlled and bi-directional charging of electric vehicles (EV) and the use of stationary battery systems (SBS) in an urban electricity system. We therefore developed and applied an optimization model.

We identified a high technical and economic potential for load shifting of the charging process of EV with controlled charging. The effects of dynamic pricing differ strongly between the pricing schemes. Real time pricing (RTP) is suitable for load shifting into times periods with low prices. As the load shifting may generate new load peaks it has to be used with caution. RTP is not suitable to integrate electricity generation by local renewable energy sources (RES) that is uncoupled from the price signal or incentive. A load limit (LL) is suitable to level peaks and valleys and increases self-consumption of local RES. Both dynamic pricing schemes marginally reduce the total costs compared to uncontrolled charging variants under the same pricing.

Bi-directional charging of EV (EV2H) is only used in the model, when no degradation cost factor for the battery is assumed, but the effects are minimal. Only for small dimensioned grids and a reduced load limit the possibility of discharging has a positive effect for load levelling, but increases the total costs.

The SBS in combination with RTP is used for arbitrage at the day-ahead market that reduces total costs. This application of SBS has negative impact on the grid usage with higher positive and negative peak loads. SBS with LL is only used by the model for increasing self-consumption at home. Comparable to variant with EV to home, SBS in the grid are helpful for reducing grid usage rate.

The use of load limits is suitable to slightly reduce total CO_2 emissions, whereas RTP has a slightly negative effect (especially in combination with SBS). The calculations of CO_2 emissions are based on an electricity mix in the German electricity market in 2030 [18]. For other countries the impact might differ considerably.

The chosen model approach has some limitations. The necessary aggregation of all demand sectors, RES and especially of the EV for each sub region neglects some important interrelations. First of all the charging behavior is unified in an unrealistic way. Therefore, the described charging effects especially with RTP are most likely exceeding real behavior. A first approach to enhance the modelling here is done [11] and has to be extended.

At all times, the local loads supplied by a transformer station are higher than RES feed-in in these districts. The integration of RES might therefore mainly challenge the low voltage level [22]. Also the dependency of self-consumption and renewable supply by PV is simplified and therefore probably the self-consumption is overestimated. Therefore research is necessary with modelling of single building demands, supplies and storage devices. In this context the research by Paetz et al. [4] should be extended.

Concerning dynamic pricing an appropriate combination of load limit for increasing self-consumption and levelling the load and a RTP to integrate a surplus of supply from transmission grid should be evaluated too.

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