The Value of IS to Ensure the Security of Energy Supply – The Case of Electric Vehicle Charging

Completed Research Paper

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ABSTRACT

Replacing the internal combustion engine through electrification is regarded as crucial for future mobility. However, the interactions between a higher number of electric vehicles and the impacts on power plant capacities have not been sufficiently investigated yet. Hence, this paper develops an approach to evaluate the energetic impacts on current power plant capacities that result from a higher market penetration of electric vehicles by 2030. The key aspect of the approach is the quantification of smart charging processes in energetic and economic perspectives. It was found that the implementation has significant energetic and thus economic benefits because of an improved integration of the additional electricity demand. The value of information systems which enable smart charging processes is shown by the calculated cost-saving potentials, resulting from a reduced expansion of the power plant system.

Keywords

Electric Mobility, Smart charging processes, Security of Energy Supply, Economic Appraisal

INTRODUCTION

Over the last decades, there has been continuous growth of the demand for individual mobility, seen particularly in increasing car sales. However, recent trends indicate a fundamental paradigm shift in the automotive industry. This trend has been initiated by a gradual substitution of electric vehicles[1] (EVs) for vehicles with a combustion engine (Urbschat and Bernhart, 2009). The main motivations for this development are political and social, with the most important being environmental requirements of future mobility. In this regard, the introduction of electric vehicles is seen as an important strategy to achieve climate protection goals. Concurrently, the German electricity industry is undergoing a period of technological and structural upheaval as a result of the German Federal Government's "Energy Concept for an Environmentally Sound, Reliable, and Affordable Energy Supply" (Federal Ministry of Economics and Technology and Federal Environment Ministry, 2010). The increasing demand for electric vehicles poses further challenges for the electricity industry. In this context, the rising electricity demand could force power producers to increase their power plant capacities. The associated additional investments could significantly reduce the attractiveness of the electric mobility concept. Moreover, any expansion of the fossil power plant system is in contradiction with climate protection goals. In this respect, the intelligent utilization of green Information Systems (IS) can contribute to higher energetic and environmental sustainability (Watson, Boudreau and Chen, 2010). For example, investments in smart charging technologies to realize controlled charging processes are a potential substitute for investments in the power plant system. By reducing the need for increases in power plant capacities, IS can therefore create significant saving potentials. Due to these reasons, our paper focuses on two research questions:

(1) Which power plant capacity might result from an increasing electricity demand of EVs by 2030 and what are the energetic and economic impacts on the current power plant system in Germany?

(2) Are investments in smart charging technologies to control charging processes of EVs a suitable alternative to an expansion of power plant capacities?

The analysis presented in this paper is based on data for the German energy market, which may serve as test market for many approaches as ours.

[1] In this paper, we focus on battery electric vehicles (BEVs) and plug-in hybrid vehicles (PHEVs).

RESEARCH BACKGROUND AND RELATED WORK

The need for an analysis of the security of energy supplies can be seen in the influence a higher market penetration of EVs would have on the future electricity demand. Several studies have investigated the impact of an increasing number of EVs for the electricity sector. A lot of basic grid related research, due to the additional electricity, demand has been conducted (e.g. Freire et al., 2010; Kempton and Tomic, 2005b; Green, Wang and Alam, 2011). Additionally, some studies examined possibilities of Vehicle to Grid (V2G) concepts (e.g. Rezania and Pruggler, 2012; Kempton and Tomic 2005a; Tomic and Kempton, 2007); the basic idea is that EVs provide power to the grid while parked. Studies that examine the impacts of a future higher number of electric vehicles on power plant capacities mainly focusing on technical effects while neglecting the economic impacts (e.g. Clement-Nyns, Haesen and Driesen, 2010; Perujo and Ciuffo, 2009). These studies also discuss the question whether energy security can be ensured despite a higher market penetration of EVs. However, no existing study investigates the economic costs to ensure security of energy supply by adjusting power plant capacities to meet the additional future electricity demand. We deal with this topic, comparing the cost/benefit ratio of a possible power plant capacity adjustment to the cost/benefit ratio of an alternative smart grid technology adoption (see, e.g. Corbett, 2011 for DSM application).

	Security of energy supply	EV usage impact on			Focus	
Publication		Powerplant Capacity	Smart Grid / Smart Technology	Grid	Economical	Technical
Clement-Nyns et al. 2010	X	X		X		X
Perujo and Ciuffo 2009	X	X		X		X
Green, Wang and Alam 2011	X			X		X
Corbett 2011			X		X	X
Lund and Kempton 2008			X	X		X
Kempton and Tomic 2005a			X		X	
Kempton and Tomic 2005b		X	X	X	X	
Tomic and Kempton 2007				X	X	
Rezania 2012			X	X	X	
Freire et al. 2010				X		X
This paper's research contribution	**X**	**X**	**X**		**X**	

Table 1. Research Contribution

Security of energy supplies is warranted if all consumers can be supplied with uninterruptable electricity to meet their demands. A power plant capacity bottleneck is defined by insufficient capacities of the electricity producers to fulfill a given demand (Costantini et al., 2007). One of the main parts of a green electricity strategy and one instrument to increase the security of energy supply is demand side management (DSM) that helps to reduce or time-shift demand (Browne, O'Regan and Moles, 2009). This concept plays a key role within the electric mobility concept since it controls the charging processes of EVs to integrate the additional electricity demand as optimally as possible into the existing load pattern. However, advanced information systems are a prerequisite for the realization of controlled charging processes. An implementation requires the ability to communicate between the EV and charging station, as well as the charging station and energy supplier (Parry and Redfern, 2010).

RESEARCH DESIGN

The research design is based on an approach to evaluate the energetic impacts on current power plant capacities that result from a higher market penetration of electric vehicles by 2030. The structure consists of two parts. The first part includes the calculation of various load profiles of EVs on a given day, based on a simulation. This simulation was developed with the simulation tool "Matlab/Simulink" for the reference years 2020 and 2030 considering different assumptions of the future development of key model parameters. For this, the main factors influencing the demand for electricity from EVs were combined to simulate whole-day load profiles resulting from the charging process of EV-batteries on a given day. This model-based approach also facilitates the demonstration and evaluation of a chosen load management system.

In the second part of the approach, whole-day residual load reserves were calculated. These can be defined as unused power plant capacities after electricity demand, which are thus available for current and future charging processes of EVs without expanding the power plant capacities. Through combining the whole-day residual load reserves with the predicted load profiles of the EVs one can make reliable predications about potential capacity bottlenecks. Moreover, it is possible to calculate the exact amount of capacity adjustments necessary to ensure the security of energy supply, despite the additional demand for electricity, depending on various scenarios. The energetic results were then used to analyze the economic impacts on the electricity industry by 2030. To achieve this, additional revenues from the increased electricity demand were compared with the investments necessary to avoid a possible capacity bottleneck, analyzing two alternatives. Finally, the energetic potentials of load management systems were converted into financial saving potentials. The following figure illustrates the above described model's approach.

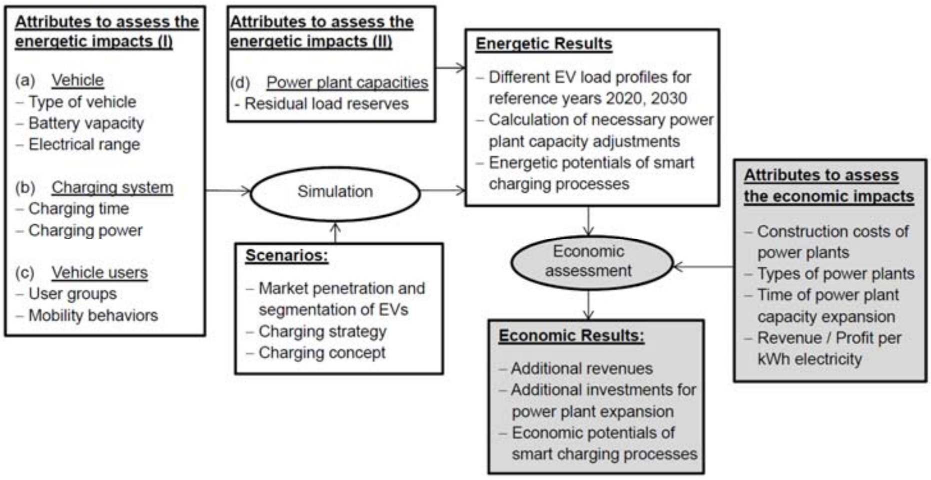

Figure 1. Approach of the Simulation and Economic Appraisal (shaded grey)

The central objective of the model is the quantification of the benefits of smart charging processes, as part of demand side management, from energetic and economic perspectives. It is assumed that the implementation of a proper load management system could significantly reduce the required investments of possible power plant capacity expansions. Thus it could be an alternative solution to conventional investment strategies.

ASSUMPTIONS FOR AN ASSESSMENT OF THE ENERGETIC IMPACTS ON POWER PLANT CAPACITIES

The analysis of the energetic impacts by 2030 was based upon data for the basis year 2008 (aggregated German energy data: Federal Association of the German Energy and Water Industries, 2013**)**. Based on several studies, for all calculations it was assumed that electricity demand (excluded additional electricity demand of EVs) and supply remain at a constant level throughout the period examined (Matthes and Ziesing, 2008; Klaus et al., 2010). Furthermore the model incorporates values of a medium-sized BEV (Volkswagen Golf blue-e-motion) and PHEV (Toyota Prius plug-in-hybrid) as reference EVs. For the simulation, private charging with two different current levels was considered. As we specifically want to assess a worst case scenario, it was assumed that the users have no possibility to recharge the EV during the day and connect their vehicles after the last trip has ended. For this purpose, all EVs plug in at 6:00 p.m., as previous analyses have shown that the majority of trips (89.6%) are finished by this time. Certain impact factors that influence the demand for electricity due to the charging processes of EVs can be varied within the framework of the simulation. This is intended to develop different load curve scenarios of EVs on a given day. For this reason, two different charging strategies were examined. "Daily charging after the last trip" describes the strategy in which all vehicle owners recharge their vehicles each day after finishing their last journey. In contrast, the "adjusted charging after the last trip" strategy compares the range of one battery charge with the average daily driving distance. From this, one can calculate the actual frequency with which the cars must be charged.

For this paper, two different charging concepts were examined. The first concept is uncontrolled charging, in which the charging process of the EVs starts immediately after the vehicle is connected to the grid. The second and more sophisticated charging strategy is the implementation of smartly controlled charging processes. We examine the simplest smart charging strategy in which the initial charge of the EVs is delayed to avoid the evening demand peak and realize load shifting (Parks, Denholm and Markel, 2007). Since the number of EVs has a considerable influence on electricity demand, two market penetration scenarios are generated. The "expected" scenario (a) assumes a moderate market penetration, for which the federal government's goals of introducing one million EVs by 2020 and six million by 2030 is used (German Federal Government, 2009). Currently, these goals seem difficult to achieve. However, purchase price incentives, rising oil prices and low energy costs for EV are still assumed to stimulate the market for electric vehicles and thus lead to a significant increase in future sales (Propfe et al., 2013). The "optimistic" scenario (b) assumes a considerably higher market penetration of EVs. Moreover, the ratio of PHEVs to BEVs is changed during the observation period. An overview of the relevant impact factors and their respective parameters is illustrated in Table 2.

Impact Factor	Parameter	Modifiable in simulation?
Technical Data	$Capacity_{Bev}$ = 26.5 kilowatt hours (kWh) / $Capacity_{PHEV}$ = 5.2 kWh	x
Market penetration of electric vehicles	2020 (a): 500.000_{BEV}, 500.000_{PHEV}; (b) 750.000_{BEV} / 750.000_{PHEV} 2030 (a): $4.000.000_{BEV}$, $1.000.000_{PHEV}$; (b) $6.000.000_{BEV}$, $1.500.000_{PHEV}$	✓
Time of battery charge	Plug-In of EV = 6 p.m. Load Shifting = Depending on load concept; latest end of charging 4:30 a.m.	✓
Charging power	$Charging\ Power_{Normal}$ = 3,7 kilowatts (kW); $Charging\ Power_{Fast}$ = 11 kW	x
Average electric distance driven daily	$Electric\ Driven\ Daily\ Distance_{BEV}$ = 39 km $Electric\ Driven\ Daily\ Distance_{PHEV}$ = 31.2 km (80 % of average driven distance)	x
Charging concept	Uncontrolled and smart charging	✓
Charging strategy (I)	EV_{daily} = Daily Charging; $BEV_{adjusted}$ = Every 3.85 days; $PHEV_{adjusted}$ = Daily	✓
Charging strategy (II)	Fast charging = 20 % of all BEV owners	x

Table 2. Impact Factors and Parameters of the Model

The calculation of residual load reserves was based on the day with the maximum peak load from the basis year 2008; the additional demand must not cause a power outage even on this day with an already very high electricity demand. By combining the simulated "load profiles of EVs on a given day" with the "residual load reserves on a given day" it is possible to make exact statements about the impacts of a higher market penetration of EVs on power plant capacities; if the power producers can cover the additional demand even on the day with the maximum peak load, it seems plausible that the electricity demand can also be covered on all other days of the year. For this, the key performance indicator of the "maximum electricity deficit" is introduced. This measure can be used to calculate the necessary amount of power plant capacity adjustments, to secure energy supplies. We denote the total load of all electric vehicles in gigawatt (GW) by P_{max}^{*} and the residual load reserves of the power plants in GW by $C_{Power\ Plants}^{\sim}$.

Maximum electricity deficit (P^{*}_{max}): The highest positive difference between total load of EVs and residual load reserves (in GW) occurs at the same time on a given day, per day and scenario.

$$P_{max}^{*} = max\{P_{EV} - C_{Power\ Plants}^{\sim}\}\ ;\ P_{max}^{*} > 0 \qquad (1)$$

ASSUMPTIONS FOR AN ASSESSMENT OF THE ECONOMIC IMPACTS

An increasing number of EVs creates a sales potential for the electricity industry due to the higher demand for electricity. Corresponding calculations start from 2009, when the first marketable EVs were launched. The forecast of the additional revenues requires knowledge of the 2008 to 2010 statistically recorded (electric sales data: Federal Statistical Office, 2013) and predicted (2011-2030) average price per kWh, as well as the additional electricity demand per year by 2030. For the calculation of the additional electricity demand from 2009 to 2030 (cumulative total load of EVs in terawatt hours [TWh] = $E_{EV,cumulative}$), let n be the number of electric vehicles in units and $\overline{\pi}$ the average yearly electric driven distance in km.

Moreover, we denote the actual average energy consumption of the EVs (in consideration of charge losses) in TWh per km by $\Phi_{\text{Real,EV}}$. Finally, we use the following formula to calculate the additional electricity demand:

$$E_{EV,cumulative} = n_{PHEV} \times \Phi_{Real,PHEV} \times \bar{\pi}_{Electric,PHEV} + n_{BEV} \times \Phi_{Real,BEV} \times \bar{\pi}_{Electric,BEV} \qquad (2)$$

For the calculation of the additional profits for the electricity producers, a calculated margin derived from the electricity production costs is used. The profit per kWh of electricity is assumed to be constant during the observation period. The expected investments by 2030 for the electricity industry focus on the measurements required to sufficiently cover the additional demand for electricity by EVs, and thus prevent a blackout. Investments can either be made by expanding existing power plant capacities or by implementing a DSM system.

Additional investments: a necessary increase of the power-plant capacities

We suppose that investments increasing power plant capacities depend solely upon the construction costs of building new or expanding existing peaking power plants. Focusing on peaking power plants is reasonable although the share of renewable energies is around 25 % in Germany and shall increase to even 50 % by 2035. In this regard, peaking power plants generally run when there is a high demand for electricity, such as in the early evening. This is suitable due to the previous assumption that EVs are connected to the grid in the early evening. Moreover, in contrast to renewable energies, these types of power plants entirely belong to the secured power plant capacities. The forecast of the composition of the peak load power for the reference years is based on existing studies (Schlesinger, Lindenberger and Lutz, 2011). The same applies for the determination of the construction costs for the basis year 2008 (Panos, 2009; Groscurth and Bode, 2009). Capital expenditures for run-of-the-river power plants and pumped-storage plants can differ considerably. For this reason, a distinction is made between new and modernized plants, as well as location conditions. The average construction time was determined to be five years. By multiplying the respective shares of the power plants in the total peak power generation with the construction costs, it is possible to calculate the average capital expenditures for the construction of a peaking power plant with an output of one GW for the reference years. The estimation for the remaining years is based on a regression analysis. For the calculation of overall additional investments, the previously calculated “maximum electricity deficit” was used; the existing stock of power plants has to be increased by this amount of electricity to prevent a power outage. For simplification, it was assumed that the entire capacity expansion necessary is conducted by the year the first bottlenecks are expected.

Additional investments: implementation of a load management system

Investments in smart charging technologies and therefore in advanced information systems realizing controlled charging processes are a potential substitute for investments in power plant capacity as described above. Through this alternative, an increase of power plant capacities can be either reduced or prevented. The cost analysis was based on data from the power company RWE (eMobility products RWE: RWE eMobility, 2013). It was found that static charging processes can now be realized without extensive capital investments, but with only a simple home charging station connected with the respective electricity supplier. The costs of this charging station range from 500 to 2000 Euros. However, users must bear the purchasing costs of the charging stations. Not considered here are operation costs for load management systems (e.g., permanent control of the load profiles).

Economic appraisal: expand power plant capacities vs. invest in smart charging technologies

The associated economic appraisal compares the expected additional profits from the higher demand for electricity with the investments necessary to prevent a power outage by 2030. The focus regarding the expenditures is on two previously examined alternatives: (1) an increase in power plant capacities and (2) the implementation of smart charging processes. However, it must be noted that power plant capacities must be expanded in some scenarios, even if charging processes are controlled. The costs were calculated by straight-line depreciation from the first year of construction. The economic lifetime of the power plants considered is determined to be 35 years (Torres, 2011; Hannemann, Rukes and Kehlhoefer, 2009)

RESULTS

Energetic results

The table below displays the summarized model results, including the “first year a power outlet is expected due to a capacity bottleneck” and the “maximum electricity deficit” by 2030. The most important findings follow:

- The first capacity bottlenecks are expected around 2020 when using uncontrolled charging processes.
- Power producers must increase their capacities to around 30 GW to prevent a power outage in a worst-case scenario.

- Necessary power plant capacity adjustments can be reduced considerably or even prevented by the implementation of smart charging processes.

Scenario	Charging Strategy	Charging Concept	Expected date of capacity bottleneck	Maximum electricity deficit by 2030 in GW
a	Daily	Uncontrolled	2022	17.65
a	Adjusted	Uncontrolled	2023	2.37
b	Daily	Uncontrolled	2021	29.76
b	Adjusted	Uncontrolled	2022	6.9
a	Daily	Smart	2026	9.13
a	Adjusted	Smart	-	-
b	Daily	Smart	2023	21.25
b	Adjusted	Smart	-	-

Table 3. Energetic Results Depending on Market Penetration of EVs (a = expected scenario, b = optimistic scenario), Charging Strategy and Concept

Economic Results

Additional expected revenues and profits for the electricity industry

The following table shows the additional expected revenues and profits for the reference years resulting from a higher demand for electricity due to the charging processes of the EVs. The table also contains the forecasted cumulative additional revenue and profits by 2030. In total, this means that the revenue for the reference year 2030 (calculated revenues: 64.1 billion Euros) in the expected scenario will increase relative to the total revenue of the electric companies for the basis year 2008 (61.0 billion Euros: Federal Association of the German Energy and Water Industries, 2013) by just 1.02%. Even in the optimistic scenario (calculated revenues: 66.15 billion Euros), the revenues are only expected to increase up to 6.7%. According to these results, the electricity companies cannot expect a considerable increase in sales.

	Additional revenues (billions of Euros)		Additional profits (billions of Euros)	
Year	*Scenario (a)*	*Scenario (b)*	*Scenario (a)*	*Scenario (b)*
2008	0.00 (Basis Year)		0.00 (Basis Year)	
2020	0.62	0.94	0.05	0.08
2030	4.10	6.15	0.29	0.44
Cumulative by 2030	21.6	34.5	1.69	2.91

Table 4. Additional Revenue and Profit by 2030

Additional expected financial burden for the electricity companies

Table 5 shows the predicted additional expenditures for the power companies. As mentioned previously, these result solely from necessary investments in power plant capacity adjustments by 2030 (I_{2030}) to prevent a capacity bottleneck. Additionally, the average capital expenditures for the construction of a peaking power plant with a one-GW capacity in Euros ($I_{\emptyset}$) in the year construction commenced are illustrated.

Scenario	Charging strategy	Charging concept	Start of construction	P^{*}_{max} in GW	$I_{\emptyset,Start\ of\ Construction}$ (billions of Euros)	I_{2030} (billions of Euros)
a	Daily	Uncontrolled	2017	17.65	1.03	18.10
a	Adjusted	Uncontrolled	2018	2.37	1.03	2.45
b	Daily	Uncontrolled	2016	29.76	1.02	30.22
b	Adjusted	Uncontrolled	2017	6.9	1.03	7.07
a	Daily	Smart	2021	9.13	1.06	9.72
a	Adjusted	Smart	-	-	-	-
b	Daily	Smart	2018	21.25	1.03	21.99
b	Adjusted	Smart	-	-	-	-

Table 5. Additional Expenditures for the Power Companies by 2030

As seen this table, capacity expansions of the power plants can be reduced substantially by using smart charging processes. Regarding scenario (b), power producers have to invest 30.22 billion Euros by 2030 to prevent a capacity bottleneck if the EVs will be charged uncontrolled; the necessary investments by 2030 can be reduced substantially by the implementation of smart charging processes in the same scenario (necessary investment: 21.99 billion Euros) allowing a cost-saving potential of 8.23 billion Euros in this scenario. Therefore the utilization of IS, as precondition for the implementation of smart charging processes, creates significant saving potentials.

Economic appraisal

The summarized results for the economic appraisal can be seen in the following table. Here, the alternatives of "increasing the power plant capacities" and "implementation of a DSM system" are compared with regard to their economic benefits. To gauge this, the additional expected profits by 2030 (P_{2030}) are compared with the respective input costs, converted over straight-line depreciation by 2030 (Dep_{2030}).

Charging Type		Expected Scenario (a)			Optimistic Scenario (b)		
Strategy	Concept	*P_{2030} without capacity adjustments (billions of Euros)*	*Dep_{2030} (billions of Euros)*	*P_{2030} including capacity adjustments (billions of Euros)*	*P_{2030} without capacity adjustments (billions of Euros)*	*Def_{2030} (billions of Euros)*	*P_{2030} including capacity adjustments (billions of Euros)*
Daily	Uncontrolled	1.69	6.72	-5.03	2.91	12.09	-9.18
Adjusted	Uncontrolled	1.69	0.84	0.85	2.91	2.6	0.28
Daily	Smart	1.69	2.50	-0.81	2.91	7.54	-4.63
Adjusted	Smart	1.69	-	1.69	2.91	-	2.91

Table 6. Economic Appraisal

As a result, the electric companies must expect additional costs of 9.19 billion Euros in the worst-case scenario. On the other hand, the "best case" results in additional profits of 2.91 billion Euros by using smart charging processes. Moreover, one can see that the estimated costs exceed the profits in all scenarios when considering the "daily charging strategy". In summation, it can be concluded that, from the perspective of the electric industry, increasing electric mobility in combination with uncontrolled charging processes tend to have negative consequences by 2030. Hence, the value of IS lies in setting free cost-saving potentials, resulting from a reduced expansion of the power plant system by using smart charging processes.

CONCLUSION

In this paper we have presented the economic and energetic effects of an increasing share of electric vehicles on the German market on existing power plant capacities. The question - whether and to what extent the existing power plant capacities must be adjusted to prevent a power outage by 2030 - was one focus of the energetic analysis. Moreover, one kind of smart charging processes for an optimal integration of the additional demand for electricity into the existing load pattern was examined. The most important findings were:

- The first capacity bottlenecks are expected around 2020 when using uncontrolled charging processes.
- A necessary extension of power plant capacities by 2030 is made considerably smaller by using smart charging processes.

The focus of the economic analysis was an economic appraisal that compared the necessary capital expenditures to prevent a blackout by 2030 with the additional profits due to the increased electricity demand. For this assessment, two alternatives to ensure the security of energy supplies were examined: (1) power plant capacity adjustments and (2) implementation of a demand side management system to realize smart charging processes. The following conclusions can be made:

- Electric companies cannot expect a considerable increase in revenue and profits by 2030.
- Using uncontrolled charging processes from EV users may lead to significant additional costs for the electricity industry due to a considerable necessary increase of power plant capacities.
- The implementation of smart charging processes has cost-cutting potentials up to 8.2 billion Euros by 2030 because of an improved integration of the additional electricity demand.

In summation it was concluded that the investments in a demand side management system, and therefore in information systems as precondition for the implementation, would have positive effects due to the arising saving potentials. Therefore we recommend focusing on measures to realize smart charging strategies instead of power plant capacity expansions. This would also offer ecological benefits as a result of a reduced use of peaking power plants. Hence smart charging processes would also indirectly promote the development of renewable energies. However, further research is required to calculate the costs for the implementation more precisely. Associated economic analysis should also include the operational costs and consider further smart charging strategies. One of the major challenges for power producers is to find a solution how users can be convinced to invest in smart charging technologies. Since power producers' profit considerable by the implementation of smart charging processes, it appears appropriate that they also bear a share of the costs. For example, power producers could offer reduced electricity tariffs, if EV users give them the possibility to postpone the charging process. Further study is needed to answer this question. Moreover, it could also be examined if renewable energies are suitable to cover the additional demand. Finally, future studies should also employ driving patters in the model to perform a stochastic simulation for the determination of the probable “time of battery charge”.

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