© EVS-25 Shenzhen, China, Nov. 5-9, 2010
The 25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition

Perspectives of electric vehicles: customer suitability and renewable energy integration

Bernd Propfe[1], Diego Luca de Tena[2]

[1]Institute of Vehicle Concepts, German Aerospace Center (DLR)
Pfaffenwaldring 38-40, 70569 Stuttgart, Germany
E-mail: Bernd.Propfe@dlr.de

[2]Institute of Technical Thermodynamics, German Aerospace Center (DLR)
Pfaffenwaldring 38-40, 70569 Stuttgart, Germany
E-mail: Diego.LucadeTena@dlr.de

Abstract— Nowadays most car makers are about to start the production of battery electric vehicles and range-extended vehicles in series. Two crucial questions arise, one concerning the customer suitability of these vehicles, and other concerning the integration in the power system. For this purpose daily trips from an extensive survey of passenger transportation were simulated with electric vehicles (based on real world models) to analyze suitability of the electric vehicles and to identify the boundaries for load management of the electric vehicle fleet. The impact on the future power system, in terms of generation capacity requirements and utilization as well as of generator start-ups, has been analyzed using the optimization tool REMix considering both uncontrolled and controlled charging.

Keywords— Plug-in Electric Vehicle, Customer Suitability, Renewable Energy, Load Management

1. Introduction

The main objective of this paper is to give answers to current questions regarding the future of e-mobility, such as customer suitability, as well as those concerning the power supply infrastructure.

The National Renewable Energy Action Plan, adopted by the Federal German Cabinet stipulates a renewable share in electricity of 38,6% by 2020. This share is expected to further increase after 2020. Wind power generation, which is of intermittent nature, is expected to be the main renewable source for electricity production. Hence, the integration of renewable energy sources into the existing power system is a crucial question which needs to be answered.

In this paper, technical specifications of EVs have been matched with real-world customer driving patterns. Total market penetration of alternative vehicle concepts has been derived utilizing the state-of-the-art simulation tool *VECTOR21*. The interdependency of EVs and RES has been examined regarding the crucial topic of the integration of EVs and of renewable power generation using a linear optimization approach with geo-referenced hourly potentials from RES with the program *REMix*.

2. User Behavior

The objective of the first research step presented in this paper was to link real world driving patterns to newly emerging vehicle concepts. Eventually, the aim was to identify charging opportunities for the integration of plug-in electric vehicles into the power grid.

At first, individual driving profiles with an hourly resolution regarding their driving status have been derived. These driving profiles have then been matched with specific alternative vehicle concepts and their technical characteristics. Consequently, charging boundaries for each vehicle have been calculated. In a last step, with this comprehensive data and by applying confidence intervals to the individual profiles, the load management potential of the electric vehicle fleet has been estimated from the point of view of the electric power system.

2.1 Daily Driving Profiles

In order to quantify user behavior, a new approach has been developed. Based on the comprehensive survey "Mobilität in Deutschland (Mobility in Germany, MiD) 2008" with over 34,000 surveyed vehicles and more than 193,000 trips, driving profiles have been analyzed in detail [1]. The data included in the derived daily driving profiles consists of the vehicle type, the driving distance, and the driving purposes (for each trip), differentiated into 8 specific purposes, ranging from 'getting to work' to 'leisure activities'. Subsequently, probabilities for finding an unoccupied charging spot at the end of a trip have been linked to each driving purpose. Table 1 summarizes the assumed probabilities for each driving purpose. Based on this information, driving patterns for every single surveyed vehicle have been deducted. Both, the driving distance as well as the probability-dependent charging possibility have been calculated hourly, resulting in two binary functions: one indicating whether a vehicle has been driven during any given hour, and the other one showing whether this specific vehicle could have been charged during its idle times. The assumptions made regarding the probability for finding an unoccupied charging spot at the end of each trip, depending on the purpose of the trip, are shown in table 1.

Purpose of trip	Work	Education	Business	Escort	Private Business	Shopping	Leisure	Other	Home
P(x) [%]	50	40	10	10	10	30	30	10	70

Table 1: Probabilities of finding an unoccupied charging spot at the end of a trip, depending on the purpose x of the trip.

2.2 Electric Vehicles considered

For the research presented in this paper, only plug-in electric vehicles are of interest. Hence, 4 vehicles have been specified: small and medium battery electric vehicles (BEV), and medium and large extended-range electric vehicles (EREV). Currently, due to their battery sizes, these 4 vehicles are the only ones relevant for power-grid integration issues. So far, neither a large BEV nor a small EREV has been introduced into the market, worldwide.
The battery sizes have been determined based on EVs currently being commercialized as well as recent publications. Table 2 depicts the technical characteristics of the 4 vehicles. In order to achieve highly practical outcomes, assumptions regarding the usable battery capacity have been made. For BEVs, states of charge (SOC) ranging from 10% to 95% of the actual battery capacity are allowed to be used for propulsion. EREVs are limited to a usable capacity ranging from 35% to 90%. These constraints have been implemented due to the fact that the batteries' life time very much depends on the depth of discharge and hence stronger restrictions regarding the usable battery capacity directly result in longer life times. The assumed ranges represent current usable SOCs [2] [3] [4].

2010		**BEV**		**EREV**	
		S	**M**	**M**	**L**
Battery capacity	[kWh]	21.6	43.2	18.9	21.6
Upper limit usable capacity	[%]	95		90	
	[kWh]	20.5	41.0	17.0	19.4
All electrical range	[km]	124.1	193.3	58.1	53.5
Lower limit usable capacity	[%]	10		35	
	[kWh]	2.2	4.3	6.6	7.6
	[km]	14.6	22.7	37.0	34.1
Energy consumption	[kWh/ 100km]	14.8	19.0	17.9	22.2
Charging power	[kW]	3.7			

Table 2: Specification of relevant electric vehicles.

Overall, small and medium BEVs have been dimensioned for an all electric range of 124 km and 193 km, respectively. Additionally, it has been assumed that EREVs are driven in a charge-depleting mode; in other words, the vehicle is driven fully electrically as long as possible The batteries have been dimensioned for an all electric range of 50-60 km.. The energy consumption per km for each type of vehicle as been assessed based on OEM indications and recent publications [5] [6] [7] [8] [9]. Again, in order to achieve results close to reality, the depicted consumptions represent energy usages in real world driving cycles such as the Artemis driving cycles and are not based on generic driving cycles such as the New European Driving Cycle (NEDC) [13] Regarding the maximal available charging power, the power outlet of a standard German household serves as reference; the available power is assumed to be 3.7 kW.

2.3 State-of-charge boundaries of individual profiles

In the next step, the daily driving profiles and the relevant vehicle concepts have been combined. The objective of this step was to assess the possible boundaries of the SOC of a vehicles' battery with feasible daily driving routes. In other words, the aim was to identify both the maximum possible SOC at any given time assuming that the vehicle is charged with full power as soon as it is plugged-in, and the minimal possible SOC which will allow the vehicle to complete its last trip of the day and then be fully discharged, down to the minimal usable SOC. The difference between these two extremes represents the bandwidth of the possible SOCs.
In order to calculate the two SOC boundaries, two different algorithms have been implemented. Both algorithms are based on the derived individual driving profiles. The calculation of the maximum SOC assumes that the vehicle is being charged at the maximum available power as soon it is plugged-in. While the vehicle is driving, the SOC is reduced depending on the driving distance as well as on the given energy consumption, which depends on the type of vehicle. In other words, this function represents the case of uncontrolled charging.
The function for the minimum SOC is based on the ex-ante information of the database: The surveyed user behavior could be seen as deterministic and hence the algorithm is able to start at the end of the last trip of the day. At this time, the SOC is set to be the minimal (usable) SOC of the specific battery. Going backwards, the last point in time at which loading has to start in order to ensure that the last trip will still be feasible is calculated. This logic continues until the moment before the first trip of the day. This lower boundary for battery usage represents the technical limit and hence can be seen as the absolute minimum. This limit is entirely based on the technical restrictions of the battery.
In case one or both SOC functions exceed the usable SOC boundaries, or in case the two functions cross, the surveyed vehicle will no longer be regarded as suitable for the considered daily profile and will be eliminated from the statistic.

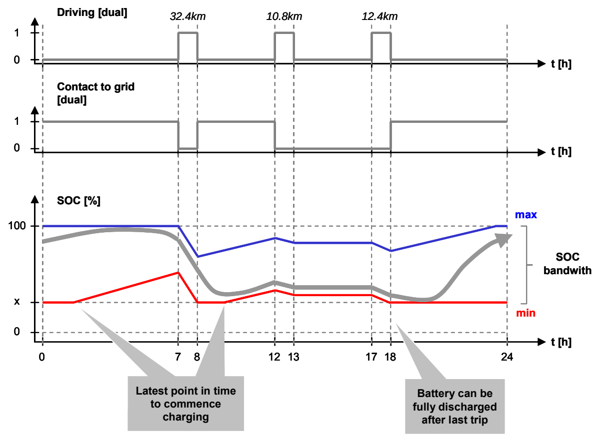

Figure 1: Methodology of calculation of SOC boundaries

The methodology for an exemplary vehicle is summarized in Figure 1. In the upper half of the chart, the two binary profiles are depicted. Based on these two functions, the minimal (red line) and the maximal (blue line) SOC at any given time are derived.

2.4 Charging Boundaries of the vehicle fleet. Evaluation

In this step, the charging boundaries of the vehicle fleet have been calculated. Due to the high diversity of the daily profiles a clustering into a reduced number of users has not been feasible. Instead, a statistical approach based on confidence intervals has been chosen to summarize the more than 17.000 individual profiles. These intervals are based on the SOC boundaries of each individual daily driving profile. Due to the high significance level assumed when evaluating the charging boundaries of the vehicle fleet (99%), the usability is ensured.

The calculated boundaries are based on ex-ante information and do not include any uncertainties regarding risk-aversions of the actual users. However, this will not constrain the outcomes and findings of the calculated SOC boundaries, since high significance levels are used to describe the vehicle fleet.

2.4.1 Charging Boundaries of Battery Electric Vehicles

Figure 2 shows the minimal and the maximal SOC boundaries for different significance levels for small BEVs. The 99%-line for the minimum SOC indicates that the SOC of 99% of all small BEVs can be below this line at any given time. Only 1% of the small BEVs require an SOC above this boundary. Accordingly, the 99%-line for the maximum SOC indicates that 99% of the vehicles can be charged at least up to this boundary and only 1% of the vehicles lie below the line and can't reach this charging level.

The 99% SOC boundaries represent a very high confidence level for the following analyses. At this significance level, the small bandwidth indicates that from a power network point of view the possible amount of energy transfer for controlled load management has to be assessed very carefully. The narrowest gap occurs at 9 a.m., when the difference between the minimal and the maximal SOC boundary comes down to 3.1 kWh per vehicle. Shortly prior to this time (at around 7 a.m.) many vehicles require a high SOC in order to fulfill their remaining driving routines. The highest point of the red SOC-line at a 99% significance level lies at 13.8 kWh, which is equivalent to over 60% of the usable battery capacity.

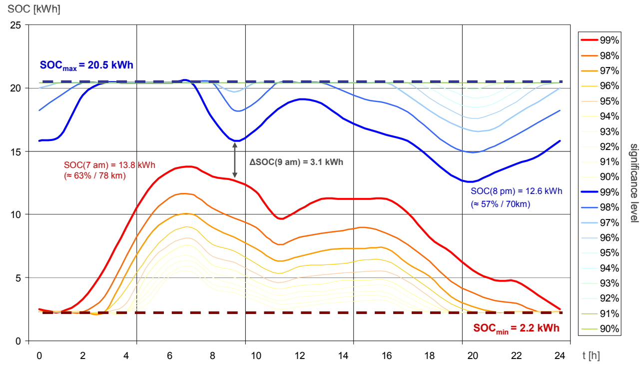

Figure 2: Confidence intervals for state-of-charge boundaries of small battery electric vehicles.

A second interesting observation is the course of the upper (blue) limit. The usable energy storage capacity of the battery is not always fully available. The global minimum of the blue SOC function is reached at 8 p.m., when the maximal feasible SOC at a 99% significance level lies at 12.6 kWh per vehicle, which is equivalent to about only 3 fifths of the usable battery capacity. This SOC even lies below the minimal SOC that has to be achieved at 7 a.m. in order to fulfill all of the remaining trips of the day.

The third key learning is that charging during the night has to commence at about 2 a.m., again, at a 99% significance level. Before this time almost all batteries could be discharged completely (within the allowed usable SOC range). If a significance level of only 95% is assumed, this latest time to commence charging even moves forward to around 4 a.m. On the other hand, the maximum available battery capacity cannot be used until around 2 a.m.

Under the assumed conditions regarding the considered vehicle characteristics and the plug-in probabilities, only 74.7% of the surveyed daily profiles could be driven with a small BEV.

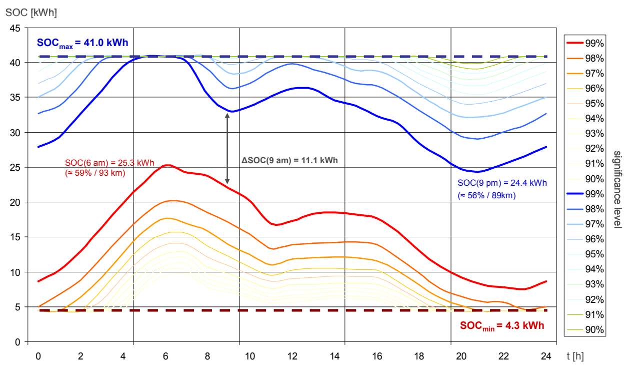

Figure 3: Confidence intervals for state-of-charge boundaries of medium battery electric vehicles.

Figure 3 shows the calculation results for the medium BEV. Although this vehicle type has a bigger battery, the minimal SOC-line for the 99% significance level does never drop to the overall minimal usable SOC. Nevertheless, the load leveling potential is slightly larger than for small BEVs. However, similar learnings can be made: Many vehicles require a high SOC in the early morning, the narrowest gap occurs at around 9 a.m., and the blue SOC function reaches its minimum in the evening. For medium BEVs, the suitability rate lies marginally higher than for the small BEVs. Under the assumptions made, 75.9% of all surveyed daily profiles could be driven with medium electric vehicles; the remaining daily profiles are not suitable for these vehicles, due to the battery size or due to the insufficient charging infrastructure.

With the assumptions made for battery capacity and plug-in possibilities around 75% of today's driving profiles can be driven with BEVs. However, this percentage is highly dependant on the probability of finding an unoccupied charging spot.

2.4.2 Charging Boundaries of Extended-range Electric Vehicles

Since the minimal SOC boundary is no criterion for exclusion for range-extended vehicles, only the maximal SOC function is relevant for the work presented in this paper. Figure 4 shows the maximal SOC boundary for medium EREVs[1] and different significance levels. Due to the fact that none of the surveyed vehicles is excluded, the overall SOC-line lies somewhat lower than for the BEVs. Since the 99% significance level is the highest shown, the blue SOC line never drops to the minimal usable SOC level. However, it becomes clear that the load management potential is significantly different from the one for BEVs. At around 9 a.m. and after 4 p.m., only about 2 fifths of the usable battery capacity could be used is available for load management. During the night and in the early morning, EREVs behave similar to BEVs. Again, from a power network integration point of view, carefully assessing the charging behavior of range-extended vehicles is essential.

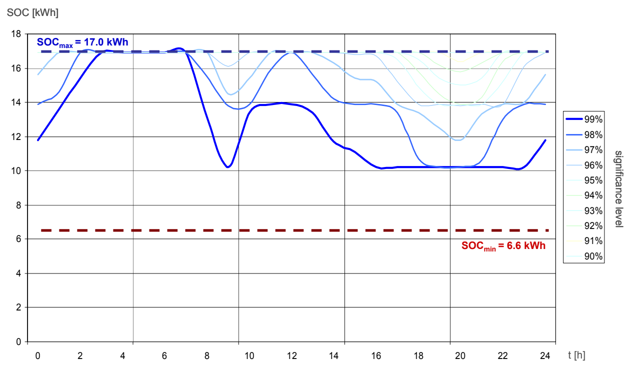

Figure 4: Confidence intervals for state-of-charge boundaries of medium extended-range electric vehicles.

In summary, it can be stated that the developed methodology in combination with extensive primary data can provide detailed information regarding charging characteristics of plug-in electric vehicles. Based on realistic assumptions, user suitability of different electric vehicles has been examined. Regarding the question to which extent future vehicles could impact on the power grid considering their load management potential, this data can now be utilized.

3. Future Market Penetration

In a second research step, in order to quantify the future electric vehicle sales, the scenario based simulation model *VECTOR21* has been utilized. The aim was calculate a total number of vehicles with which the previous results could be weighted. The model at hand is capable of calculating such a figure.

The model has been internally developed at the DLR Institute of Vehicle Concepts and is capable of simulating the competition between conventional and alternative propulsion concepts on the German new vehicle market. Based on several scenario characteristics, such as oil and platinum prices, taxes and subsidies, sources of electricity etc., 900 different types of customers are simulated. These customer types choose future vehicle technologies on a least cost basis, taking into account technical developments and their impact on the vehicle fleet. The model has been verified using historical data for the German market. For further information on the model itself, see [10] [11] [12].

For the work presented in this paper - the analysis of the impact of electric vehicles on the power system - an optimistic scenario for alternative vehicle concepts has been defined. This scenario assumes electric energy used for propulsion to be entirely produced by renewable energy sources. The oil price develops according to the IEA reference scenario. Starting in 2017, an additional tax on electricity used for propulsion will be introduced stepwise. Furthermore, the today planned CO_2-penalties will be considered. Theses penalties are based on EU-legislation and have in accordance with the current legislation been adjusted to historical German fleet characteristics, i.e. the 130 g CO_2/km target for 2015 has been increased to 140 g CO_2/km for German vehicles. For 2030, the targets are assumed to be lowered to 76 g CO_2/km. The monetary CO_2-penalties are also based on current EU-legislation and are assumed to start at 95 € / (g CO_2/km) in 2015. For 2030 the penalties are assumed to be increased to 120 € / (g CO_2/km).[2] Subsidies will be paid in varying rates for BEVs, EREVs as well as FCV in the total amount of about 1.6 bn €, distributed over 5 years. In comparison to the German "cash for clunkers"-program which accounted for 5 bn € and had been distributed over one single year, these subsidies appear reasonable. The subsidies will only be paid for the first 5 years after market introduction of the new vehicle concept; by 2018, no subsidies will be paid anymore.

Figure 5 depicts the composition of the German new vehicle market under these conditions. The chart shows the aggregated German new vehicle fleet. For the following analyses, however, differentiations into the different vehicle sizes will be used.

[1] Please note that the calculation results for large EREVs look very similar to those for medium EREVs and are hence not depicted.

[2] Please note, the current EU-legislation assumes a one time payment for exceeding the mass-based CO_2-targets. The individual target for each European fleet is calculated annually, based on the average mass of the particular fleet. Hence, due to the historically heavier fleet, the German CO_2-target has been slightly increased.

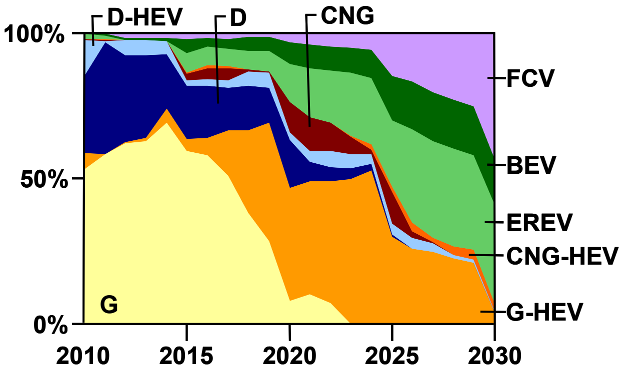

Figure 5: Market penetrations of the German new vehicles fleet up to 2030.

The results show a clear success of alternative propulsion concepts due to the relatively favorable assumptions made; by 2030, plug-in electric vehicles would gain a significant market share.

Under the described scenario assumptions, by 2020 especially range-extended electric vehicles start to gain market share. They are joined around 2025 by fuel cell vehicles (FCV), which themselves achieve a significant market share by 2030. Conventional combustion engines will be successively pushed out of the market. Already by 2025, all ICE-based vehicles will have been replaced by some sort of electric powertrain vehicle concept, ranging from non-plug-in full hybrids to the all electric BEVs. Due to the expensive EURO 5 & 6 norms, Diesel-vehicles lose market shares year over year. Conventional gasoline vehicles will be at first replaced by full-gasoline-hybrids, before they are entirely pushed out of the market by alternative vehicle concepts. Interestingly, this result is fairly consistent throughout all three vehicle sizes.

In order to assess the impact of the future vehicle fleet on the power system, the total vehicle stock is crucial. *VECTOR21* is capable of calculating the vehicle fleet from the simulated new vehicle sales in combination with surviving rates for each type of vehicle. Figure 6 shows the development of the German vehicle stock up to 2030. Even in this optimistic scenario regarding alternative propulsion concepts, the entire vehicle stock shifts only slowly. In 2030, FCVs, BEVs and EREVs account for around 40% of the entire vehicle stock.

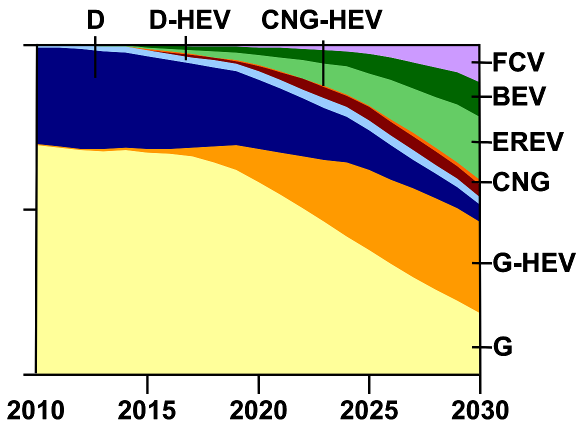

Figure 6: Development of the German vehicle stock up to 2030.

Combining these absolute figures for the vehicle fleet and the calculated SOC-boundaries for the four types of electric vehicles, the available potential of the entire future German vehicle fleet for load management can be derived. In the following, the impact of electrical cars on the power system as well as their possible contribution to renewable power integration has been studied.

4. Integration of renewable power and EVs

Within the next years a strong development of renewable energy sources (RES) for power generation is expected. This is motivated by global warming, increasing scarcity of fossil resources and by means of political independence. Electrical cars can contribute to reduce the emissions of greenhouse gases (GHG), but this depends to a large extent on how electricity is produced. Thus, the more efficient a power system is, and the higher the penetration of RES, the lesser the GHG emissions of the electrical car fleet. Most RES, such as wind and solar photovoltaic, depend on weather conditions and are therefore neither predictable nor controllable. Due to their expected growth the volatility of the residual power demand will increase.

The residual load can be covered by controllable generators, like fossil power plants, but also from controllable renewable plants like biomass or solar thermal plants with heat storage. Storage power plants, like pumped storage, compressed air energy storage (CAES), hydrogen storage, or batteries, can be used to adapt power generation to variations in generation and demand. Another possibility is to increase the transmission capacities of the electricity network, so that in periods of low generation from RES power can be imported from abroad. The so called Demand Side Management (DSM) entails actions to adapt electricity demand to energy availability (using price signals), and can therefore contribute to renewable power integration by reducing or raising power consumption depending on wind power or on power demand; this results in less volatility in the residual load to be covered by controllable generators, hence achieving a higher utilization.

Electric vehicles are well suited for DSM as cars remain parked most of the time – time in which it can be decided whether and when charging takes place. This load management will not affect customers as long as the battery level does not compromise following trips. Nevertheless, battery loading in the first generation of electric vehicles will be uncontrolled, i.e. loading starts just after plugging in.

Furthermore, DSM can contribute to renewable power integration by charging the batteries of EVs during wind surpluses and by avoiding charging when wind power is low. In this context, vehicle-to-grid (V2G) is an interesting technology. It allows for bidirectional power transmission between EVs and the electric power grid and can thus be adopted to deliver electricity back into the grid when the residual demand is highest and most costly, or to provide balancing power.

It becomes clear that electrical vehicles and renewable energies present a high degree of interdependence: on the one hand a higher penetration of RES makes EVs more attractive compared to conventional automobiles, due to the significantly lower carbon emissions. On the other hand EVs can contribute to the integration of RES through load management and by providing system services.

4.1 Power system modeling

In order to analyse grid-integration issues of EVs the program *REMix* will be used. The program, internally developed at the DLR Institute of Technical Thermodynamics, combines the (in the field of energy economics) well established approach of the linear optimization with a Geographic Information System (GIS), that provides spatial and temporal information of the potentials of RES. The GIS-based database is partly derived from satellite data in high dimensional (10 x 10 km) and temporal (hourly) resolution. This facilitates the incorporation of specific conditions of a power system with a high share of fluctuating RES into an optimization model. Figure 7 illustrates the model structure of *REMix*. *REMix* makes use of GIS-based renewable energy potentials as input. Under specified conditions (such as 85% renewable energy share) *REMix* calculates the optimal system expansion and operation of the different generation and storage technologies considering the temporal and spatial availability of the renewable energy sources for one given year.

The fundamental behavior of the conventional power plant park was modeled taking into account technical availability, fuel consumption, different operating costs, cost of carbon certificates, as well as date of construction for the technologies brown coal, hard coal, Combined Cycle Gas Turbine (CCGT) and Gas Turbine. In this work the power plants of the same technology and with similar date of construction have been summarized.

Storage technologies, such as hydroelectric plants with reservoir, pumped storage, and CAES are included in the model, taking into account information such as charging and discharging efficiency, as well as their storage capacity.

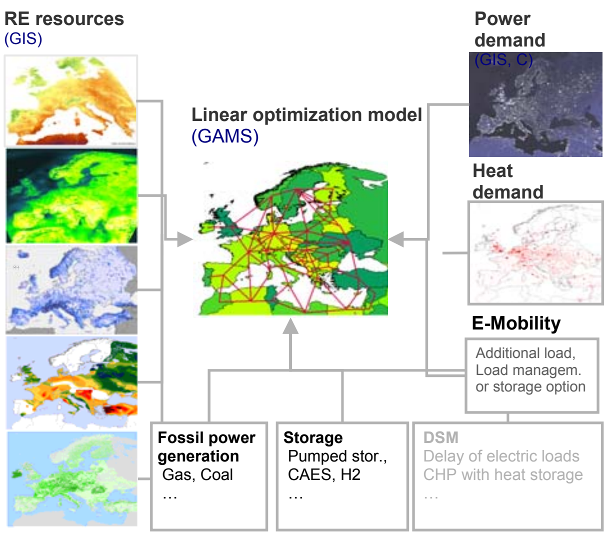

Figure 7: *REMix* structure (light grey, field under development).

The hourly power generation from photovoltaic has been calculated as described in [14] [15]. The wind power generation profiles have been calculated using the ‚Lokalmodell Europa’ (now “Cosmo-EU”) from the German Weather Service [16]. For runoff river plants daily measured data from the Global Runoff River Database [17] has been used.

Combined Heat and Power (CHP) can contribute to renewable power integration by decoupling power generation from heat demand, e.g. by storing the heat produced. This field is currently under development; as an approach generation from CHP plants has been assumed as constant in this work.

Other power generation such as geothermal, or generation from gases used as a by-product, such as those produced in steel production, are assumed to be constant. The annual generation scenarios from these plants are obtained from published reports published by the German Federal Environment Ministry and the Federal Environment Agency [18] [19].

The conventional power plants are modeled based on an extended version of a database including power plants over 100 MW in Germany [20], under consideration of the power plants approved and in approval process. The scenario of renewable power generation, of generation from plants using combined-heat and power (CHP), as well as of the electricity demand is obtained from the Leitszenario 2009 [19]. The power demand profiles have been calculated based on the hourly consumption data published by ENTSO-E [21] and adjusted by the annual demand scenario for the given year.

Electric vehicles are modeled as controllable loads, taking into account the minimal and maximal charging boundaries and market penetration previously presented in this paper, as well as the power connection, and the amount of vehicles plugged-in, according to the results computed with *VECTOR21*.

The decisions for the expansion of the power system are based on installation costs, amortization time, as well as on the interest rates.

REMix calculates the optimal system expansion and operation for a given year that meets the power demand on a least cost basis. Annuity costs of the installed plants as well as, operating and maintenance costs of both existing and installed plants are considered. In this work REMix was used to examined the possible impact of a large EV fleet on the German power system in 2030, here the transport and distribution network have not been considered.

4.2 Demand coverage with controlled loading

In order to examine the possible contribution of EVs with CL to integration of intermittent energy power sources, electricity demand coverage has been analyzed during three days with significant variations in wind generation,.

In this first analysis system operation has been optimized over three days with a temporal resolution of one hour using CL. Figure 8 depicts power demand coverage in a three-day period with an increasing share of wind power generation in the first day, which is strongly reduced during the second day. The areas above the abscissa represent power generation classified by technology, whereas the areas below the axis represent power storage in pumped storage plants (purple) and in EVs (light purple); the black line represent the electricity demand excluding EVs and storage.

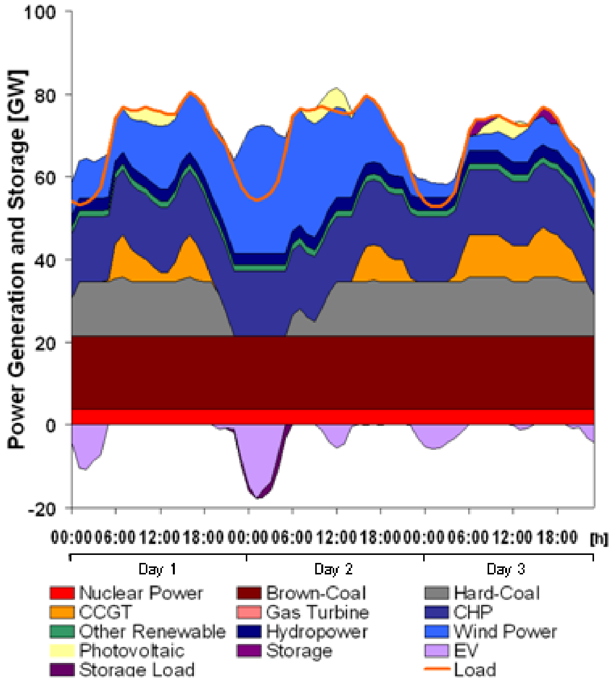

Figure 8: Demand coverage with controlled loading.

It can be first seen that EVs with CL are mostly charged during the nighttime (around midnight). Therefore they can contribute to reduce load variations between day and night, as charging takes place mainly at night when demand is lower. Furthermore, EVs present higher charging rates at times with higher power generation from wind and photovoltaic, namely during the night from the first to the second day and during the second day, it can be seen that wind power as well as loading of EVs present the highest values. Thus, as charging rates are higher when generation from these sources is higher, EVs can contribute to a better integration of these RES, by reducing peaks in generation from these sources.

4.3 System integration of electric vehicles

With the purpose of first determining with a higher detail to which extent EV can contribute to compensate the increasing volatility in residual demand, as well as which advantages it would have, three *REMix* runs are conducted; the first without EVs (NEV), the second with uncontrolled loading (UL) and the third with controlled loading (CL). In this analysis, the expansion of conventional generators and of storage capacities is optimized over one year with a resolution of three hours.

4.3.1 Impact on generation capacity utilization and requirements

In 4.2 it was seen that EVs with CL will be charged mainly at night, when demand is low and intermittent renewable generation high, so as to analyze this with a higher level of detail, the impact of EVs on the residual load has been calculated[3] over a larger period of time. Figure 9 illustrates capacity utilization depending on the level of the residual load.

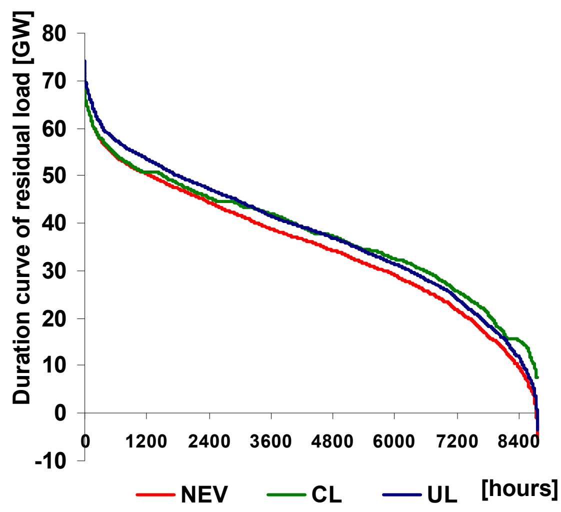

Figure 9: Duration curve of the residual load in the 3 scenarios

It can first be seen that in both scenarios incorporating EVs (UL, CL) the residual demand is higher than in the scenario without EVs. This is due to the higher power consumption in the scenarios with EVs. Secondly, it can be observed that with CL the maximum residual demand is lower than with UL and that the minimal is higher, as in this scenario EVs are charged when residual load is low and avoid charging when it is higher.

This compensation has many advantages for the power system; one of them is the lower requirements of power generation capacity to meet power demand. The results show that, with the assumptions made, 3713 MW additional capacity is needed with UL, while no additional capacity is required with CL compared to NEV. This capacity corresponds to the capacity of 10 modern CCGT plants or 5 new coal power plants.

Another advantage concerns capacity utilization. Since in the CL scenario generation capacity requirements are lower a higher utilization of the existing power plants can be achieved. The *REMix* results show, that with the assumptions made in the NEV scenario an annual capacity utilization of 3175 full-load-hours (flh) is achieved, with UL utilization increases up to 3382 flh, and with CL utilization is highest with 3514 flh[4].

If power demand during periods with high wind power generation can not react to variations in supply, i.e. changing the charging rates of electrical vehicles, wind turbines will not be able to feed-in all the electrical energy

[3] The residual load was calculated as the power demand (including electric vehicles) minus renewable power generation (excluding CHP).
[4] An availability of 92% has been assumed for the power plants.

they could produce, due to the lack of demand. Model results show that power surpluses over the analyzed period sum up to 2,99 TWh for NEV. In the UL scenario, due to the additional power demand of EV surplus is lowered to 1,84 TWh. The results show that with CL surplus can be reduced up to 1,04 TWh. The differences are very significant, the improvement of the CL-scenario compared to those of the UL-scenario represents the annual power generation of around 150 wind turbines in Germany[5].

4.3.2 Impact on start-ups of conventional generation

Start ups and stops of power plants are inherent to power systems. In Germany and in other countries these are expected to take place more often as installed capacity from wind power and photovoltaic expands. The start-up process depends on the plant type and on the time it has been offline, can take a long time and is expensive due to the high amounts of fuel needed. The start-up process of a coal power plant can take more than 10 hours and require the amount of fuel consumed during 3h at maximum generation. Conventional generators in partial load present a lower efficiency than those in full load conditions.

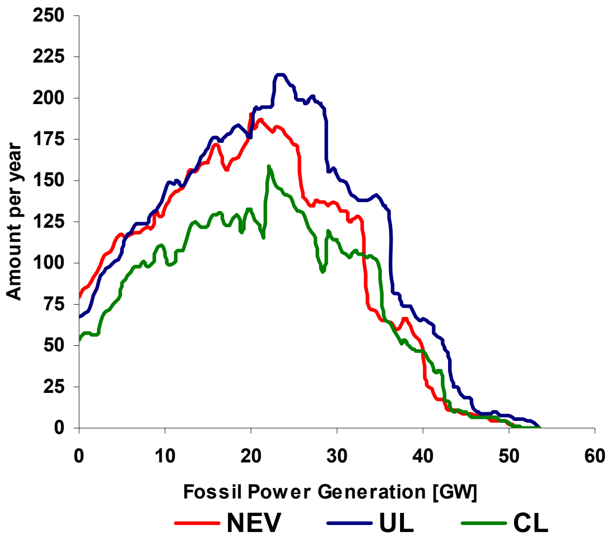

Figure 10: Shut down and ramping down processes of conventional generators in three electromobility scenarios.

Figure 10 shows the number of estimated shut down as well as ramping down processes required in the 3 scenarios depending on the level of conventional power generation. These were calculated based on differences on the level of the power demand covered by conventional generators assuming a block size of 500 MW, hence if power generation from conventional generators in one time step is 500 MW lower than in the previous time step it has been assumed that the generator is shut down – requiring a subsequent start up - or at least reduces its power generation and is operated in partial load. The results show that with CL significant reductions in generator start-ups or at partial load can be achieved if compared to both scenarios NEV or UL, thus controlling the EV's loading contributes to a higher efficiency of conventional generators.

5. Summary and Outlook

In this paper both customer suitability of plug-in electric vehicles as well as their possible contribution for the integration of renewable power sources have been analyzed.

For this purpose, a procedure for determining the suitability of electric vehicles based on individual driving profiles and technical characteristics has been developed. By applying confidence intervals to the individual results, the load balancing potential has been estimated for the entire German fleet.

In order to estimate the market penetration of electrical vehicles, the state of the art model *VECTOR21* has been utilized, simulating buying decisions on the new vehicle market of 900 customer types.

The model *REMix*, which combines GIS-based renewable energy potentials with an optimization model for power generation capacity expansion and power system operation, has been used to study the integration of renewable power generation and electric vehicles.

The results show that using controlled loading electric vehicles can contribute to both renewable power integration and to the compensation of daily load variations, adapting charging to the availability of wind generation or to power demand level. At the same time, this results in lower generation capacity requirements, in a higher capacity utilization and efficiency of conventional power plants

Moreover, a further advantage of controlled loading - neither analyzed in this work - is related to forecasting. Wind power generation present a certain forecasting error, which will increase in absolute terms with wind capacity expansion. Due to this uncertainty conventional power plants are operated at partial load causing lower efficiency. Additionally, changes in unit commitment are also expected to become more frequent, causing unnecessary and costly generator start-ups. This can be mitigated with load management by adapting EV's charging or feeding electricity back to the grid (see V2G) to compensate forecasting errors.

Another advantage of controlled loading - not analyzed in this work - is the possible reduction of power transmission and distribution capacity requirements.

It is clear that controlled loading presents many advantages for power system operation. However, other possibilities such as demand side management of conventional loads, a more flexible operation of CHP units, and increasing transmission capacities will also be important for the German power system as power generation of intermittent nature expands.

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7. Acknowledgments

We would like to thank the Federal Ministry of Economics and Technology in Germany for the funding of the research project “Perspectives of Electric Vehicles with high share of distributed and renewable energy sources” for which the work presented in this paper will be used.

8. Authors

Bernd Propfe received his diploma in Business Administration and Engineering with honors from the Karlsruhe Institute of Technology (KIT). Before joining the DLR, he worked on several projects for named players in the surface transportation industry in Europe and the US. Mr Propfe has extensive experience in market analysis and assessment as well as cost evaluation.

Diego Luca de Tena studied industrial engineering at the I.C.A.I. in Madrid, and in the University of Stuttgart. Mr. Luca de Tena analyzed in his final thesis the impact of wind power generation in the Iberian transport network. At the moment is conducting research in integration of electric vehicles and renewable power generation while preparing his doctoral thesis at DLR.