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Modelling the plug-in availability and calculation of energy storage potential of electric vehicles in Germany

Hartmann, N.[1, 2], Özdemir, E. D.[1], Goyns, P. H.[1], Eltrop, L.[1]
[1]*Institute of Energy Economics and Rational Use of Energy, University of Stuttgart*
Heßbrühlstraße 49a, D-70565 Stuttgart
[2]*Corresponding author*
nh@ier.uni-stuttgart.de
Tel: +49 711 685 87827

Abstract

Renewable energy production in Germany will grow immensely in the next twenty years. Wind energy generation capacity, in particular, is expected to be 65 GW by 2030 and will constitute a larger proportion of the total generated electricity than today. Storage facilities are required to compensate for the fluctuating character of renewable electricity generation. Stationary storage such as pumped hydro and compressed air are typical solutions so far. Electric vehicles and plug-in hybrid electric vehicles could also provide electrical storage capacity in the near future. This will lead to the possibility of balancing the fluctuating energy generation with mobile storage devices. A problem with mobile storage is the uncertainty in the availability of electrical vehicles connected to the grid and their spare storage capacity at any instant. In this study the availability of electric vehicles is simulated for Germany. The simulation determines the availability on an hourly basis for all days of an average week. The storage capacity for a defined scenario of electric vehicle uptake was also calculated. In conclusion the overall availability of plug-in electric passenger cars in Germany is high. A significant difference between the characteristics of weekdays, Saturdays and Sundays is evident. A high potential to use electric passenger cars for balancing the fluctuating renewable energy could be presumed, due to the large number of vehicles being plugged into the grid during in the evening hours for which charging could be delayed into the night.

Keywords: plug-in availability, vehicle-to-grid, V2G, electrical storage, electric passenger car, renewable energy

1 Introduction

Renewable energies (especially wind and solar) are intermittent. The related challenges increase with higher installed capacities of renewable energies. In Germany installed wind energy capacity is expected to grow from 22 GW in 2007 to 65 GW in 2030 (Wind Energy Study, 2008). A reason for the expected increase is that grid operators are obliged to accept power generated from renewable energy sources at a feed-in-tariff prescribed by the "Erneuerbaren Energien Gesetz" (EEG).

One method to overcome problems related to the fluctuating character of renewable energies is to use energy storage systems. Such systems compensate for the variable nature of renewable electricity generation making it more reliable.

Until now, only storage technologies with stationary applications (e.g. pumped hydro energy storage) are used commercially. However, mobile storage systems will be available in the near future provided plug-in hybrid and electric vehicles are available and have a large enough market share.
One of the differences between stationary and mobile storage is their availability. Stationary storage is available basically throughout the day whereas mobile storage systems are only available when they are connected to the grid (Figure 1).

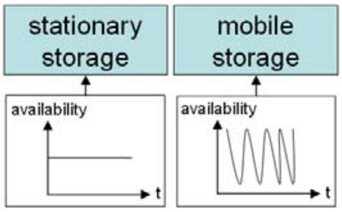

Figure 1: Difference in availability of stationary and mobile storage systems

To be able to model the storage of renewable electricity, e.g. by a wind energy converter (WEC), the availability of the mobile storage units has to be defined at any instant.
Existing research in this field has focused on electric vehicles (EV), hybrid vehicles (HEV) or vehicle-to-grid (V2G) issues. In 1997 Kempton et al. published their work on vehicle-to-grid and battery storage for electric vehicles [1]. Other work on battery technologies and a comparison of electric drive vehicles, hybrid electric vehicles, especially plug-in hybrids (PHEV), have been published in [3][5][6][10][11]. Other publications have focused on the grid stabilisation [4][6][13]. More general summaries about the topic vehicle-to-grid are given in [2][7][8][9][12]. There have been numerous publications on research about driving cycles and travel patterns, e.g. [3][14][15][16][21]. Also the comparison between the available power plant capacity and charging need of electric vehicles in Germany was published in [22]. However the analysis of the availability of mobile storage systems (electric and hybrid vehicles) has not been investigated in much detail.

2 Objectives

The aim of this study is to determine the possible capacity of mobile storage systems by calculating the number of electric vehicles plugged into the grid and with the potential to act as a storage device at any instant. The temporal resolution is set to an hourly basis for each day of an average week. The total mobile electric storage capacity as well as the power of the mobile storage system in Germany can then be determined for the described scenario of electric vehicle market share.

3 Approach

The approach is structured into two sections. First the simulation model and simulation procedure is described. Second the scenario, which is used to calculate the storage power and capacity potential in Germany, is presented.

3.1 Simulation model to calculate the plug-in availability

The number of passenger cars being used at any moment of time in Germany was analysed based on data from "Mobilität in Deutschland" [17]. The basic design of the spreadsheet simulation model is displayed in Figure 2.

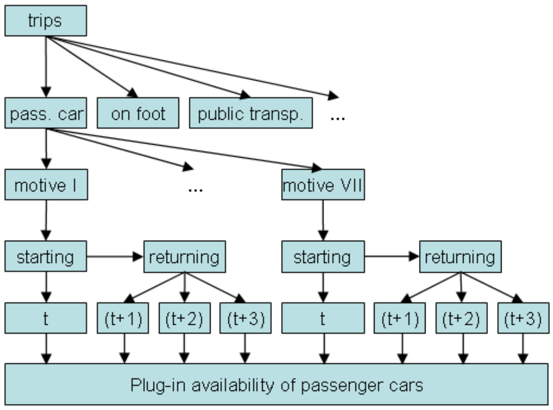

Figure 2: Procedure of the simulation

The calculations are based on the number of trips travelled each day in Germany. Each trip is further divided into motives to travel. On weekdays the average citizen in Germany covers 3.6 trips [17]. These trips are separated into different motives for travelling and each motive into six different modes of transport: a passenger car driver, a car passenger, per bike, on foot and with public transportation.
Seven different types of motives for travelling were identified, namely:

1. Leisure (trips for leisure, e.g. meeting friends)
2. Shopping (daily needs)
3. Private errands (e.g. consultation or bureaucratic affairs)
4. Accompanying (bringing and picking up people)

5. Business trip (each trip which can be accounted to business reasons, except trips with the motivation of "Work")
6. Education (each trip to reach the training post or school)
7. Work (each trip from and to work)

The distinction between the different types of motives was needed to classify the vehicles en route to the different travel motives as well as for subsequent research to analyse the driven distances of the vehicles which vary for every type of motive.

For each motive, the percentage of trips which was performed as a passenger car driver, was calculated separately and taken as input data for the simulation. To calculate the time needed for each trip the average speed for several distances was calculated. The distances were partitioned into 3 groups: The first from 0 to 16 km, the second from 16 to 49 km and the last for distances greater than 49 km. This classification resulted out of average speed of 32.8 km/h for passenger cars in Germany [17]. The average speed was calculated including stops e.g. at traffic lights. Although this value is slightly lower than those proposed in other studies, e.g. average speed of 36 km/h in [18], which however is calculated out of a value dispersion between 20 – 52 km/h, it was assumed suitable for this study, because the source of the average speed value was consistent with the input data for the simulation. Hence the first group accounts for a travel time from 0 to 30 min, the second one from 30 to 1 h 30 min and the third one for travel times longer than 1 h 30 min. The beginnings of the trips were taken as an input file into the simulation. Again these values were revised to get the hourly values of passenger car drivers, who begin their trips with different motives.

With the combination of average speeds, length of trips and the starting times a simulation was performed which determined, in several iterations, the number of passenger cars used during each hour of the day. The simulation was carried out for workdays, Saturdays and Sundays (Sundays include public holidays). The simulation procedure is described below.

The simulation is performed by calculating the number of passenger cars starting a trip each hour of the day. A basic assumption for the simulation was that if a car is not being driven it is connected to the grid. The calculating point is defined as the midway of specified hour e.g. a trip specified as starting in the hour between 1 pm and 2 pm is assumed to have started at 1:30 pm. This leads to the basic assumption for the simulation that a trip ending after one hour would count towards the subsequent hour too. The calculations were performed for every hour with the following equations:

$$Y(t) = \left(X(0) - X(t)\right) \tag{1}$$

with

Y(t) : passenger cars en route
X(t) : passenger cars connected to the grid
X(0) : total number of passenger cars
t : time step in hours

The passenger cars en route are subsequently calculated by the difference of the vehicle population and passenger cars connected to the grid X(0)-X(t). In Germany the total amount of passenger cars X(0) for 2007 was 46.6 million [19].

The passenger cars connected to the grid X(t) are determined by the grid-connected vehicles of the previous hour X(t-1) plus the difference between the number of vehicles ending their trips W(t) and the number of vehicles starting their trips V(t).

$$X(t) = X(t-1) + W(t) - V(t) \tag{2}$$

with

W(t) : passenger cars ending their trips
V(t) : passenger cars starting their trips

The number of passenger cars ending their trips is calculated from:

$$W(t) = W_1(t-1) + W_2(t-2) + W_3(t-3) \tag{3}$$

Due to the fact that the data of returning passenger cars, which end their trips after more than three hours, was marginal or not present, the arriving passenger cars are divided into three groups concerning their time of trip termination.

The values for the different trip termination times are assessed with the multiplication of the starting passenger cars and the percentage of vehicles f_b ending their trips.

$$W_b(t) = V(t) \cdot f_b \tag{4}$$

with

f_b : percentage of passenger cars ending their trips

The index b can be a value from 1 to 3. This index describes the different percentages of passenger cars returning from one trip in the above described time groups. The index varies for the various days of the week and motives for travelling. In contrast, the hourly values of one day and inside one motive the factor remains at a constant value. The share of passenger cars en route was calculated by:

$$u(t) = \frac{Y(t)}{X(0)} \qquad (5)$$

with

u(t) : share of passenger cars en route

By these equations the plug-in availability of the passenger cars in Germany could be determined for every hour of the week. In addition a distinction for every trip with different motives could be calculated.

3.2 Scenario

The scenario of the electric vehicle market share, which was used for the simulation, shall lead to conclusions about the storage capacity of 100,000 electric passenger vehicles which is available to the grid. In the above described simulation the longest trip duration is defined as 2.5 h. Having an average travel velocity of 32.8 km/h the greatest distance, which one electric vehicle will drive during one trip is about 82 km. The maximum storage capacity is determined so that the needed capacity of the batteries is multiplied by the safety factor of 1.5 to provide enough energy even after several years of use. The compensation of the depth of discharge (DoD), which is assumed to be 80 % is also included in this safety factor. Therefore in the scenario the storage capacity of the battery must be capable to provide enough power to the electric vehicles to drive the maximum trip distance equivalent to 123 km. The electricity consumption is set to 0.51 MJ/vkm [20] and the storage density to 160 Wh/kg. With these input values and the above described simulation model, the electricity consumption for the passenger cars for different trip distances and different motives were calculated.

The results of the above simulation are displayed and analysed in the following.

4 Simulation results

The presentation of the simulation results is split into two sections. The analysis of the usage of passenger cars in Germany results in the availability of plug-in electric vehicles to store energy. Secondly, the storage potential for the above described scenario will be analysed in the ensuing section.

4.1 Analysis of availability

The availability of plug-in electric passenger cars (which can be plugged into the grid) in Germany was calculated for an average weekday. This allowed the different levels of availability of electric vehicle energy storage capacity for the various days of the week.

In Figure 3 the number of vehicles en route is displayed as a percentage of the total vehicle population in Germany. The total energy storage potential can be determined from this number. For weekdays the total percentages of vehicles en route varies between nearly zero at night up to about 10.6 % between 3 pm and 5 pm. The highest number of passenger cars en route can be perceived with 10.8 % on Fridays at 3 pm. The difference between the vehicles en route concerning the different motives is analysed later and not discussed further at this point.

For an average weekday the number of vehicles en route follows a similar daily characteristic. Beginning from about 4 am an intense increase of the percentage of vehicles en route is evident. At about 7 am the increase in activity stops and the percentage of vehicles en route fluctuates between 0.2 % and 0.4% at these levels until about 1 pm. From 1 pm until about 4 pm the percentages of passenger cars en route rises to the daily maximum. For weekdays this lies between 9.7 % and 10.8 %. From Monday to Thursday the maximum is reached between 4 pm and 5 pm. On Fridays the maximum is reached earlier at about 3 pm. From the daily maximum number of passenger cars en route the percentage decreases sharply until about 9 pm, which accounts for a percentage of vehicles of less than 2 %.

From 9 pm vehicle activity declines and flattens out to a minimum at around 2 am. In general the total amount of passenger cars en route follows a similar curve during weekdays. On weekends the curve of vehicles en route differs. On Saturdays the amount of non available passenger cars increases from 3 am until 10 am to the daily maximum of about 10.3 % and then decreases over the time of 10 hours until it drops below 2 % at 9 pm. The decrease declines afterwards and reaches its minimum value at about 1 am.

The percentage of vehicles en route on Sundays deviates significantly from those on the other weekdays.

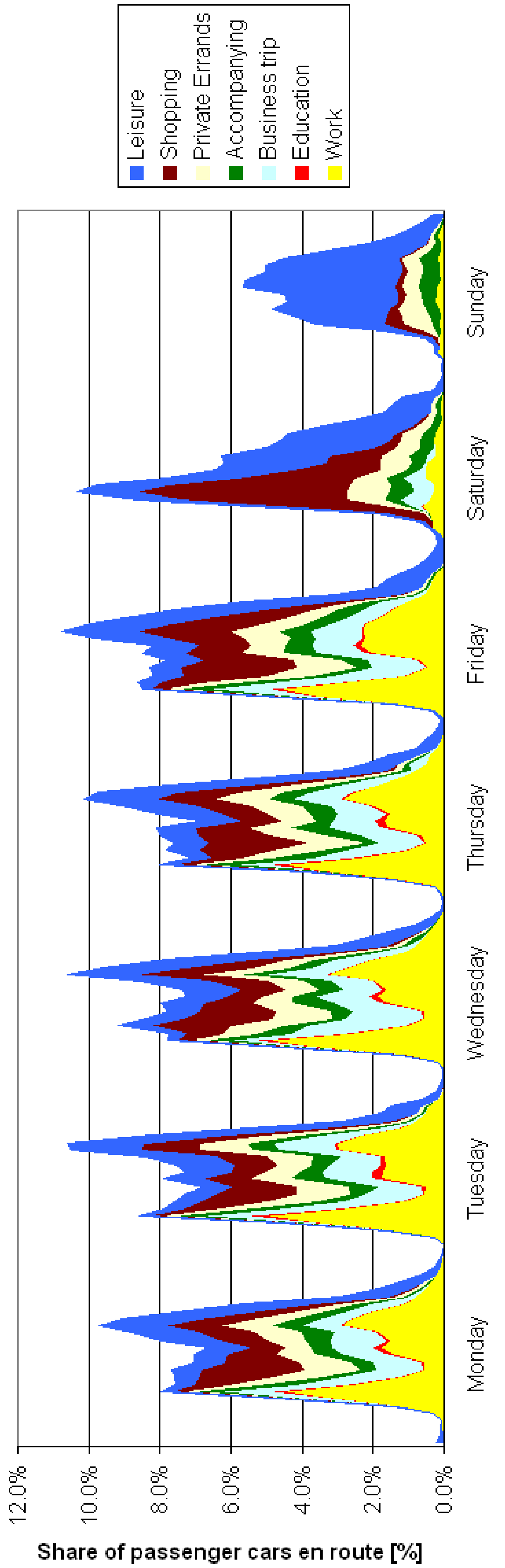

Figure 3: Cumulated share of passenger cars en route in Germany

The maximum number of passenger cars en route is reached in the early afternoon at 2 pm with the value of 5.7 %. The percentage of vehicles en route increases steadily, beginning from 0.05 % at 4 am in the morning and after its maximum decreases steadily until its default value in the afternoon and night.

To summarise the allocation of the values of passenger cars en route in percentage underlies no big differentiations during weekdays. The highest amount of vehicles en route is always reached in the early afternoon. However, it can be noticed that the maximum of vehicles en route on Mondays is slightly lower than on the other weekdays. Also the maximum is reached at an earlier stage on Fridays than on the other weekdays.

In the following a more detailed analysis of the percentage of passenger cars en route over one day will be provided. The share over an average weekday is presented in Figure 4, whereas the cumulated numbers of vehicles en route regarding the different motives for the trip are displayed in Figure 5.

In the following the difference in number of vehicles en route regarding their motive is first analysed. Afterwards the number of passenger cars (Figure 5) of an average weekday is compared to those during Saturdays and Sundays (Figure 3).

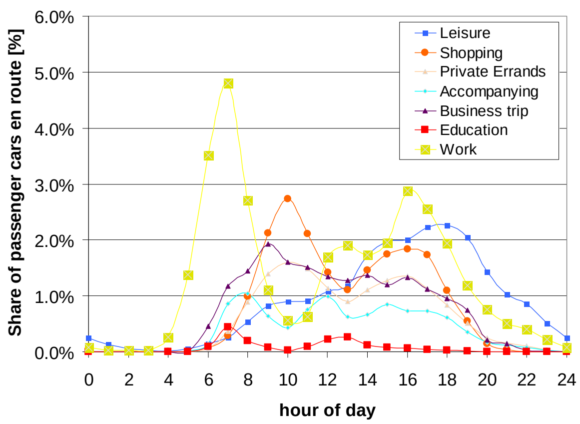

Figure 4: Share of passenger cars en route in Germany (average weekday)

The values for an average weekday show that in the morning hours between 4 am and 7 am the highest percentage of passenger cars en route can be appointed to the motive “work”. This means that at 7 am about 4.8 % of the passenger cars are en route between the working place and home of the driver.

The percentage drops again to about 0.6 % between 10 am and 11 am. Later until 4 pm, the percentage of passenger cars en route increases again until an amount of about 2.9 %. The trips motivated by education will not be analysed here, due to its low impact on the overall percentage of vehicles en route. Trips motivated by business and private errands fluctuate between 8 am and 4 pm around their mean of 1.3 %. Company trips fluctuate slightly lower at around 0.8 %.

Different characteristics concerning the percentage of vehicles en route can be observed for shopping and leisure. The patterns of travel motivated by shopping are similar to those for work. However the first peak is only reached at 10 am with a value of about 2.7 %. By 1 pm the percentage drops to about 1.1 % and rises again until 4 pm to the value of about 1.8 %. The percentage of passenger vehicles, which are en route with the motivation of leisure rise slowly from the value of 0.02 % at 4 am to the value of about 2.3 % at 6 pm. Afterwards it decreases slowly again until a value of less than 0.3 % at 0 am.

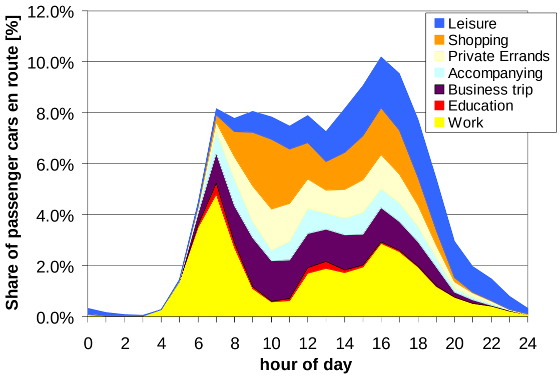

Figure 5: Cumulated share of passenger cars en route in Germany (average weekday)

Without these two purposes of travel, which create a strong demand for vehicles use in the late afternoon and evening hours, the majority of passenger cars would be parked between 6 am and 8 am. However, the percentage of passenger vehicles en route does not exceed about 10.6 % of the total amount of passenger cars in Germany for weekdays.

As already mentioned, the total amount of vehicles en route does not change significantly compared to Saturdays, however, the time when the total amount is reached changes from afternoon (4 pm) to morning (10 am). This is due mainly to the lack of trips to work and business trips. On the one hand travel for these purposes largely decrease but on the other hand the percentage of trips for shopping and leisure strongly increase. Shopping accounts for more than 50 % of all vehicle trips on Saturdays (at 10 am). This is more than twice as much compared to passenger car trips for shopping reasons at 10 am on Mondays. Also the trips with the motive leisure increase (from about 2.3 % on weekdays to about 3.1 % at Saturday). On Sundays and holidays all trips decrease except the leisure trips. This leads to the distribution, that at the time of the maximum use of passenger cars on Sundays (3 pm) 75 % of the vehicles are motivated by leisure. More exactly, at 2 pm 4.3 % of the overall passenger cars en route (5.6 %) are motivated by leisure.

In total the plug-in availability of the passenger cars in Germany does not decrease below 89 %. On Sundays and holidays the availability is even higher with about 94 %. During the day however the plug-in availability underlies fluctuations, which arise from the different travel motives and their different amount of vehicles use over the day. The usage of passenger cars also varies over one day and one motive. Though, the cumulated amount of passenger cars en route shows similar characteristics over the weekdays. These differ clearly from the daily characteristics of passenger cars en route on Saturdays and Sundays. In the following the results of the plug-in availability of passenger cars in Germany are analysed for the above described scenario.

4.2 Analysis of storage potential

The results of an example scenario with 100,000 electric vehicles in Germany is analysed below. Needing to travel a maximum distance of 123 km, the battery storage capacity of 62.8 MJ per EV is required. In combination with the above defined storage density of 160 Wh/kg this results in a battery weight of about 110 kg per EV. The overall maximum storage capacity of the scenario is calculated as 6.275 GJ.

In Figure 6 the storage capacity of the 100,000 electric passenger vehicles in Germany is displayed for one average weekday. It is evident, that the storage capacity falls between 4 am and 7 am sharply. Then until 1 pm the capacity keeps at a constant value and decreases again until 4 pm. Between 4 pm and 8 pm the storage capacity increases sharply again and levels out at its maximum value by 3 am. The storage capacity remains at a high level throughout the whole day. It must be said that the storage capacity in Figure 6 is only based on the plug-in availability of the passenger cars. Therefore the state of charge of the battery during driving is not considered in the analysis.

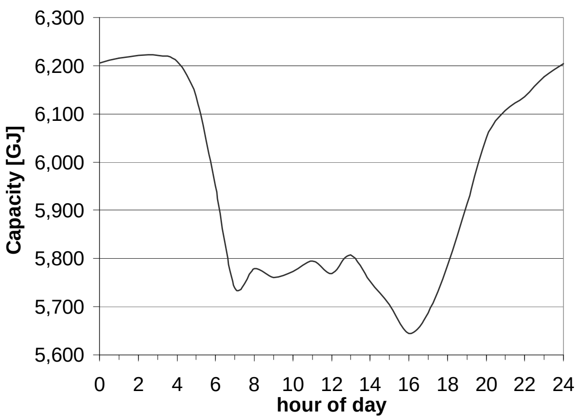

Figure 6: Storage capacity of 100,000 EV in Germany during the day (average weekday)

However it can be mentioned, that due to the high amount of passenger cars being connected to the grid (being plug-in available) in the late afternoon and evening (between 6 pm and 8 pm) the need for electricity to charge these batteries will be considerable, which will result in an additive increase of the daily demand peak in the late afternoon. In contrast, the potential for delaying the charging of the vehicles into the night and therefore providing grid service in the afternoon and night will be large as well. To make use of this potential an intelligent connection between electric vehicles and the grid will be inevitable.

5 Conclusion

The analysis of the availability of plug-in passenger cars in Germany and the storage capacity for an example scenario showed that the overall plug-in availability in Germany is high at any time over the day (> 89 %). A significant difference between the daily characteristics of the availability on weekdays, Saturdays and Sundays was recognized. The main reasons for travel were identified as trips to and from work, for shopping and for leisure. The maximum passenger cars en route on weekdays are reached in the afternoon at around 4 pm, on Saturdays this maximum shifts to around 10 am and on Sundays it moves to the early afternoon at around 3 pm.

The analysis of the scenario with 100,000 EV in Germany showed that the storage potential is large (about 6.2 TJ) and varies about 10 % over the day. This would result in an available storage power of about 1.7 GW for 100,000 EV which is about a quarter of the installed pumped hydro storage power (7 GW) in Germany today [22]. The potential of 1.7 GW hereby is calculated without the influence of any limitation concerning the charging point or the distribution network.

In the afternoon there is a sharp increase in the number of vehicles ending their trips and which will need power to recharge. Grid power to recharge will be the largest over the day at this time. Therefore having an intelligent charging management integrated would produce the opportunity to shift the charging into the night and use the batteries e.g. for compensating fluctuating renewable energies. Subsequent to this analysis different charging characteristics of electric vehicles in Germany will be analysed. The goal hereby is to determine the predicted capacity and power of passenger cars with account to different travel motives. This would lead to the knowledge of the needed storage capacity for one trip and therefore a more exact calculation of the potential of storage, which can be used to balance fluctuating renewable energy supply.

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Authors

Niklas Hartmann studied industrial engineering at the TU Kaiserslautern and finished his studies at the Fraunhofer ISE. Since 2008 he works as scientific assistant and PhD student at the IER at Stuttgart University. His key interests lie in the integration of wind and solar energy with storage technologies (stationary & mobile) into the grid. A special focus lies on electric vehicles and their potential for compensating fluctuating renewable energy production.

E. Doruk Özdemir studied mechanical engineering and sociology (double major program) at Middle East Technical University (Ankara, Turkey). He completed his masters degree in mechanical engineering in 2005 at the same university. In 2005 he commenced PhD studies at the University of Stuttgart. His interests are alternative fuels and powertrains for the transport sector, transport modelling and renewable energies.

Philip Goyns has an MSc in mechanical engineering and a DPhil in energy studies. His research has focussed on improving efficiency of and reducing emissions from internal combustion engines and modelling real-world driving, emissions and fuel consumption in the context of cities. Philip now works as a researcher in the EnerKey project for IER at the University of Stuttgart.

Ludger Eltrop is head of the department of "System analysis and renewable energies (SEE)" at the Institute of Energy economics and the rational use of energy (IER). He conducts work and projects on increasing the competitiveness and integration of renewable energies within the existing energy systems. This implies technical, economic and ecological analyses of the whole range of renewable energy technologies.