The impact of vehicle-to-grid on the distribution grid

Kristien Clement-Nyns*, Edwin Haesen, Johan Driesen

K.U.Leuven, Electrical Engineering Department ESAT-ELECTA, Kasteelpark Arenberg 10 box 2445, B-3001 Heverlee, Belgium

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ABSTRACT

Plug-in hybrid electric vehicles (PHEVs) can be connected to the power grid. The power flow of this connection can be bidirectional, so vehicles can charge and discharge. This vehicle-to-grid option can aid to improve grid efficiency and reliability. A simulation covering an entire day is essential to obtain an accurate assessment of the impact of PHEVs. It is important to know when, statistically, vehicles are available for charging or discharging. In this work is shown that uncoordinated charging of PHEVs in distribution grid can lead to local grid problems. Therefore, coordinated charging and discharging is investigated and a voltage constraint is implemented. These vehicles can support the grid in terms of voltage control and congestion management. In that way, the distribution grid can handle more PHEVs without reinforcements. Distributed generation units are more common nowadays in the distribution grid with some of these generation units based on intermittent renewable resources. This paper shows that there could be a good combination with PHEVs as they can provide storage to take care of the excess of produced energy and use it for driving or release it into the grid at a later time. In that way, consumption and generation are more efficiently matched.

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1. Introduction

Plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) have an advantage compared to hybrid electric vehicles (HEVs), i.e. a connection to the electric power grid allowing more opportunities. The vehicle can not only charge, but also discharge and thus inject energy into the grid. In that way, PHEVs can support the grid. This is indicated as vehicle-to-grid (V2G) operation. The electrical consumption for charging PHEVs amount to 5% of the total electrical consumption in Belgium by 2030 [1].

Currently, there is little storage available in the power grid so demand and generation must be perfectly matched and continuously managed to avoid frequency instabilities. PHEVs have an energy storage capacity which is rather small for each individual vehicle, but the number of vehicles will be large, yielding a significant energy storage capacity. At any given time, at least 90% of the vehicles are theoretically available for V2G [2,3]. These vehicles must be connected to the grid when idle. There must be enough vehicles plugged in during the day to provide grid services therefore it could be beneficial to give incentives to vehicle owners to stay plugged in. Most of the weekdays, vehicles follow a schedule which does not vary much from week to week [4]. The electrical storage of PHEVs could provide grid services via V2G concept and add a surplus value to the vehicle owner [5]. The vehicle owners need energy for driving at more or less predictable times and the grid operator needs power to match demand and consumption [2]. PHEVs can handle large and frequent power fluctuations because they are designed that way for driving needs [6].

When uncoordinated charging of PHEVs is applied, the vehicles will immediately start to charge at full power, e.g. 4 kW, when they are plugged in until they are fully charged or leave earlier. Uncoordinated charging will cause local grid problems in terms of extra power losses, which can be regarded as an economic concern, and voltage deviations, affecting power quality. This decreases the efficiency of the distribution grid. Therefore, coordinated charging is introduced in this article, where the objective function is to minimize the power losses. In previous work [7,8], vehicles were only able to charge and could not discharge and therefore supporting the grid was not possible.

The idea of this research is to support the grid by using a bidirectional power flow. A voltage control is implemented as a constraint in the optimization problem to increase the power quality of the grid by using coordinated charging and discharging. A smart meter or an embedded controller is therefore essential [9]. A full day simulation is also considered to achieve a more global overview of the impact of charging PHEVs on the distribution grid. The research fits in a more global context where also other new technologies, such as combined heat and power systems and photovoltaic cells, are implemented in the distribution grid in combination with PHEVs. The proposed methodology can help evaluating planned grid reinforcements versus PHEV ancillary services to achieve the most efficient grid operation. It allows to determine a maximum hosting capacity of the grid for PHEVs. The coordination of the charging...
and the implementing of voltage control can postpone the rein-
forcements of the grid.

2. Vehicle-to-grid concept

2.1. Connection to the grid

The connection to the electric power grid offers opportunities for PHEVs for charging the vehicle but also for discharging and thus injecting energy into the grid. In the ideal case, the electricity con-
sumption should match perfectly with wind and solar energy and the generation of conventional power plants. Because of forecasting errors and the intermittent behavior of renewable resources, imbal-
ances occur and generation and demand do not perfectly match. The vehicles can help to match consumption and generation by charging and discharging 'on the right moment'. The combustion engine can also deliver electricity during peak hours, though this is not realistic for several reasons. The emissions, emitted locally, in this case will rise because of the local generation and the effi-
ciency will be lower compared to large power plants. There is also a cooling problem for vehicles which remain stationary while deliver-
ing significant amounts of power. Emptying their fuel tank will also reduce their driving range and increase the noise level.

The management, i.e. dispatching, of the PHEVs is crucial. Com-
unication is needed between the vehicles and the utility grid, by sending signals to request energy from the PHEVs [2]. For the vehicle-to-grid concept, three elements are required. First, a power connection to the grid must be available, second, a control con-
nection is essential for communication with the grid operator and third, there must be an on-board precision metering for knowing the battery content [4]. The vehicles can be represented in three ways. First, the signal can be sent to each vehicle separately or to a central controller supervising the PHEVs in a single facility, e.g. a parking lot. The third possibility is a third-party aggregator who is responsible for separately located vehicles.

2.2. Ancillary services

PHEVs are for the moment more expensive compared to con-
ventional vehicles. In [2], it is concluded that selling energy could be beneficial for these vehicles. The batteries can act as a source of stored energy to provide a number of grid services. The most promising market for these vehicles is probably that of the ancillary services [3]. Possible services for V2G are: supply of peak power, supply of primary, secondary and tertiary control (for frequency regulation and balancing), load leveling, and voltage regulation. PHEVs are able to respond quickly and thus serving for high value electrical services. It is unlikely that each vehicle will be contracted separately because the maximum power output of each vehicle is too low. But a fleet manager or aggregator could conclude a contract for a fleet of PHEVs. The advantage of dealing with an aggregator or fleet manager is that a single party represents a more significant amount of power, that is the accumulated power of the vehicles in the fleet. Moreover, the availability profile of a larger group of vehicles is much smoother. A single vehicle owner could conclude a contract with the aggregator without being concerned about the interface with the electricity markets.

2.2.1. Frequency regulation

One aspect of grid management is to provide power reserves to maintain frequency and voltage and facilitate the efficient handling of imbalances or congestion. So it is essential to keep the frequency at appropriate levels, i.e. between 49.99 and 50.01 Hz according to the ENTSO-E, the former UCTE [10]. Frequency regulation has several levels of control: primary, secondary and tertiary control. The primary reserves regulate the frequency and stabilize the European grid to avoid blackouts. The frequency control is acti-

vated automatically and continually. Primary control can only be activated if primary reserves are available. The primary reserves are about 100 MW for Belgium. The response time is smaller than 1 s.

Secondary reserves are allocated a day ahead to balance the grid and are adjusted automatically and continually, both upward and downward on a 15 min time base. If the frequency is lower than 50 Hz, the batteries could be discharged (regulation up) and if the frequency is above 50 Hz, the batteries could be charged (regula-
tion down). On average, the regulation up and down are equal. The impact on the battery is a small discharge due to charge and dis-
charge efficiency. The reaction time is a few seconds. These reserves are used for imbalances between nominated and measured power injections and to restore the frequency.

There are two types of tertiary reserves: tertiary production and tertiary offtake reserves. These reserves are used for major imbalances and congestions. In contrast to primary and secondary reserves, these are activated manually and only a few times per year. These reserves must deliver their power within 15 min [11].

It is not clear which types of ancillary services are economically profitable for PHEVs. According to [6], secondary and tertiary control are assumed to be competitive and primary control is supposed to be highly competitive. In [12] primary control is expected to have the highest value for V2G. According to [13], peak power control could be the most economical solution in Japan. The power that must be delivered by tertiary reserves would be too high and the duration too long for the vehicles [14]. Thus only primary and secondary control could be interesting from a technological point of view.

2.2.2. Voltage regulation

In a low-voltage grid, cables are common and the resistance R is large compared to reactance X. Adjusting the flow of active power in this grid will influence the voltage amplitude. The voltage reg-
ulation maintains the voltage between the limits defined by the mandatory standard ENS0160 [15]. This voltage control can be embedded in the charger. The charging of the vehicles will stop when the voltage at the grid connection becomes too low. In a fur-
ther step, discharging of an unit of active power can also be taken into account to increase the grid voltage.

2.2.3. Load leveling and peak power

For load leveling, the demand is shifted from peak hours to off-peak hours. Therefore, dispatching is necessary. PHEVs could discharge during the daily peak loads, replacing the peak capacity generators that are only used during peak demand hours. If these vehicles want to discharge during the peak hours, they will have to charge during the off-peak hours. In the case the energy which is stored during off-peak hours, is released during peak hours to relieve congestion in the grid infrastructure, supplying peak power and load leveling are the same. Supposing peak power is possibly difficult for PHEVs because of the relatively long duration and the storage limitations. Thus, supplying peak power is generally not profitable as the largest cost is the wear of the batteries [14]. Load leveling is more likely because the vehicle does not necessary need to discharge during peak hours. The total consumption of electricity will not be lowered but shifted to the hours of low electricity con-
sumption which are the off-peak hours to minimize the power losses and to increase grid efficiency. The implementation of smart meters or real-time pricing and coordinated charging is essential.

2.3. Opportunities for PHEVs

PHEVs have the potential to support a residential distribution grid but are technically and economically unsuitable for all kind of
3.2. Specifications of PHEVs

Some nodes, which are chosen randomly, PHEVs will be charging. Power losses are adapted to achieve tolerable voltage deviations and impedances are adapted to achieve tolerable voltage deviations and power losses. At each node, a residential load is connected and at some nodes, which are chosen randomly, PHEVs will be charging.

3.1. Grid topology

The radial network used for this analysis is the IEEE 34 node test feeder [16] shown in Fig. 1. This network is downscaled to 230 V so this grid topology represents a residential radial network. The line impedances are adapted to achieve tolerable voltage deviations and power losses. At each node, a residential load is connected and at some nodes, which are chosen randomly, PHEVs will be charging.

3.2. Specifications of PHEVs

Each of the PHEVs has a battery with a maximum storage capacity of 11 kWh [17]. Only 80% of the capacity of the battery can be used in order to optimize life expectancy. This gives an available capacity of 8.8 kWh. In a full charging cycle, 10 kWh is required from the grid, assuming an 88% energy conversion efficiency from AC energy absorbed from the utility grid to DC energy stored in the battery of the vehicle [18]. The energy flow is bidirectional, meaning that the batteries can charge and discharge. The charger has a maximum output power of 4 kW. The charger of 4 kW is chosen because the maximum power output of a standard single-phase 230 V outlet, with a maximum current of 20 A, is 4.6 kW. Therefore, this is the largest charger that can be used for a standard outlet at home without reinforcing the wiring. Fast charging is not considered because it requires a higher power rating which is not available at standard electrical outlets in houses. For fast charging, connections at a higher voltage level are indispensable. A higher voltage connection could be installed, but this is an extra investment for the PHEV owner. The maximum penetration level of PHEVs is 30% by 2030 for Belgium as forecasted by the Tremove model [19].

3.3. Charging periods

It is not realistic to assume that PHEVs could be charged anywhere a standard outlet is present. Therefore in this article, the batteries of the vehicles are assumed to be charged at home in distribution grids. Fig. 2 shows the percentage of all trips by vehicle each hour. At that moment, they are not available for charging. Based on this figure, one important charging period is proposed which is during the evening and night. Most of the vehicles are at home from 21h00 until 06h00 in the morning. However, the proposed methods are also valid for other periods and scenarios.

3.4. Availability analysis

The charging period of the previous section is determined as a fixed part of the day. These charging periods will be extended to charging between 00h00 and 23h45, i.e. a full day. For a more accurate assessment, it is essential to know when vehicles are available for charging during a full day. The knowledge of the amount of energy that is left in the battery and the presence of a network connection for charging is important. A simulation of a full day would give more information about the vehicles, in particular if discharging is implemented, because vehicles which have energy left in their battery when they arrive during the evening could support the grid during peak hours. For the simulation of a full day, the time slots the vehicles are present for charging must be exactly known. To make the simulation more realistic, these time slots are based on the behavior of the drivers and on stochastic data [20] representing the vehicles leaving and arriving at different moments to and from work. For the sake of convenience, it is assumed that the vehicle owner is a full-time employee. The probability is the highest that the vehicle owner leaves to work during the morning between 07h00 and 10h00 and arrives from work during the evening between 16h00 and 19h00 [14]. It is also possible that a vehicle performs another trip during the day or evening for reasons of family visits, shopping, education etc. The average number of trips is 2.23 per day.

In the first instance, the vehicles charge at home. One sample of the availability analysis gives information about one vehicle during a full day on a 15 min base as shown in Fig. 3. The number of trips and the consumption per trip can be deduced from that sample. A database of 1000 samples is collected. If the PHEV consumes more than available in the battery, the vehicle is using its combustion engine to complete the trip.
3.5. Load scenarios

From an available set of residential load measurements, a day with a high peak load is selected. The load profile covers 24 h and the instantaneous power consumption is given on a 15 min time base.

3.6. Assumptions

The exact advantage of coordinated charging depends on the assumptions made in this section. The household load profiles are typical for Belgium. Other regions may have other load profiles because of different weather conditions, such as an air conditioning peak in the afternoon for warm regions. Some regions will also have other grid voltages, for instance 120 V. The IEEE grid is an example of a distribution grid, so the obtained results are only valid for this grid. The maximum power of the charger is determined by the maximum power of a standard electric outlet. Fast charging and discharging is not considered because it can have a negative impact on the battery life time [3]. Other parameters which have an impact on the distribution grid are the utility load cycle of the base-load power plants, incentives and the use of smart meters. The results of the availability analysis are only valid for full-time employees.

4. Optimization problem

In this section, the applied methodology for the optimization problem is described. This methodology is used to indicate the significance of the coordination of charging and discharging. The objective function of the optimization problem is the minimization of the cost. The charger can also determine the optimal charging profile by voltage, power losses or owner preferences.

4.1. Uncoordinated charging

When no smart meter or embedded controller is available, the vehicles will immediately start to charge at full power when they are plugged in until they are fully charged or are disconnected. The vehicle owners do not have the incentives nor the essential information to schedule the charging of the batteries to optimize the grid stability.

The vehicles are placed randomly in the IEEE test grid. A load flow analysis is performed to assess the voltage deviations in the selected distribution grid. This analysis is based on the backward–forward sweep method to calculate the nodal currents, line currents and nodal voltages [21]. At the initialization step, a flat profile is taken for the nodal voltages. A constant power load model is used at all connections at each time step. In the backward step, the currents are computed based on the voltages of the previous iteration. In the forward step, the voltages are computed based on the voltage at the root node and the voltage drops of the lines between the nodes. The currents and voltages are updated iteratively until the stopping criterion, based on nodal voltages, is reached.

4.2. Coordinated charging and discharging

The owners of PHEVs will not be able to change their charging profile at any time, meaning that the only realistic degree of freedom left for the owners is to postulate a point in time when the vehicles must be fully charged. The power output of the charger varies and can also be bidirectional, meaning that the vehicle can charge (consumption energy) and discharge (injection energy into the grid). The penetration level is between 0% and 75%.

The objective function is a cost function which reflects the charging cost and must be minimized as shown in (1). This function has only two constants: one constant represents the tariff during the day, \( C_{\text{day}} \), and one constant is the tariff overnight, \( C_{\text{night}} \). The ratio of the day constant to the night constant is estimated to be about 1.6 [22]. A night tariff starts between 21h00 and 23h00 and ends between 06h00 and 08h00. In this paper, the night tariff starts at 22h00 and ends at 07h00. The constraints are shown in (2). These are linear functions so the linear programming technique (LP) can be used. The vehicles are able to charge and discharge so the charger output varies between –4000 and 4000 W. The charge and discharge efficiency are taken into account, which is 88% for each. The content of the batteries, \( C_{n,t} \), must be between zero and \( C_{\text{max}} \) for each time step and equals \( C_{\text{max}} \) at the end of the charging period. The voltage must satisfy the EN50160 standard so the nodal voltages \( U_{n,t} \) at each time step must be higher than 90% of 230 V and lower then 110% of 230 V, which is respectively \( U_{\text{lower limit}} \) and \( U_{\text{upper limit}} \). \( x_n \) indicates whether a PHEV is connected or not and is not a variable.

\[
\min \sum_{n=1}^{\text{nodes}} \left( t_{\text{night}} \cdot P_{n,t} + \sum_{t=1}^{t_{\text{max}}} C_{\text{day}} \cdot P_{n,t} \right) \quad (1)
\]

\[
\begin{align*}
&\forall t, \forall n \in \text{[nodes]} : -P_{\text{max}} \leq P_{n,t} \leq P_{\text{max}} \\
&\forall t, \forall n \in \text{[nodes]} : 0 \leq C_{n,t} \leq C_{\text{max}} \\
&\forall t, \forall n \in \text{[nodes]} : U_{\text{lower limit}} \leq U_{n,t} \leq U_{\text{upper limit}} \\
&\forall n \in \text{[nodes]} : \sum_{t=1}^{t_{\text{max}}} P_{n,t} \cdot \Delta t \cdot x_n = C_{\text{max}} \\
x_n \in \{0, 1\}
\end{align*} \quad (2)
\]

The vehicles are placed randomly after the selection of the number of PHEVs. A flat voltage profile is assumed and the nodal voltages are computed with the backward–forward sweep method assuming that there are no PHEVs. The backward and forward sweep are formulated as a matrix multiplication. The linear program technique is performed in order to determine the optimal charge profile. Then, the nodal voltages are computed again. This process is repeated until the cost based stopping criterion is reached.

5. Voltage control of PHEVs overnight

This sections emphasizes the importance to implement a voltage controller to support the grid. This support is not consid-
ered as an ancillary service, but is a first step in the direction of supporting the grid by PHEVs. The voltage support, by injection of active power, can be embedded in the charger. This could even be made compulsory because grid reliability must be assured. The computations are performed for charging during the night which occurs between 19h00 and 06h00. For the sake of convenience, at the end of the charging period, the vehicles must be fully charged. In the test grid of this paper, no voltage deviations occur if no PHEVs are present. The results are presented for a day of the winter season with high peak loads. The voltage constraints and the discharging are added separately to distinguish their impacts.

In the first scenario, the vehicles are unable to discharge and no voltage constraint is implemented. The objective function is simplified and a single tariff is used, making no distinction between night and day. Voltage profiles for a node at the end of the IEEE test grid are shown in Fig. 4 for three different penetration levels. Because no voltage constraint is implemented, the voltage goes well below the voltage limit for a penetration level of 50% and more. Therefore, voltage constraints are implemented in the optimization case. The charge profile for a node at the end of the test grid is shown in Fig. 5. The vehicles are not allowed to charge when the voltage is already low due to the household loads. The cost function stays the same so the vehicles charge randomly between 19h00 and 06h00, satisfying an extra constraint, i.e. the voltage constraint. Fig. 6 shows the voltage profiles if the voltage constraint is implemented. The voltage stays well above the voltage limit.

For the next scenario, the discharging of the vehicles is implemented and the objective function has two tariffs. However, in this case the vehicles will never discharge as can be seen in Fig. 7. The charging period starts at 19h00 and thus there is only 1 h left to discharge at peak tariff. This is not happening because the batteries of the PHEVs are assumed to be empty at the start of the charging period and charging and discharging at the same price of electricity will be uneconomical because of the charge and discharge efficiencies. Because there is no other objective, and there are only two electricity prices, the vehicles are further charged randomly at night tariff. There is no incentive to reduce the power losses.

For the last scenario, there is still energy left in the batteries at the start of the charging period. This energy is determined stochastically based on a Gaussian with an average of zero and a standard deviation, $\sigma$, of 1000 W. Only the positive values of this curve are used. Fig. 8 shows the charge profiles of a node at the end of the test grid for different penetration levels. The night tariff starts at 22h00, therefore the vehicles discharge between 19h00 and 22h00 depending on the energy left in the battery. The batteries still must be fully charged at the end of the period.

The impact of the energy left in the battery at the beginning of the charging period is shown in Fig. 9. The more energy left in the battery, the more the PHEVs discharge between 19h00 and 22h00, when the peak tariff is valid. The amount of discharging is

![Fig. 4. Voltage profile for different penetration levels and no voltage constraint.](image1)

![Fig. 5. Charge profile for different penetration levels with voltage constraint.](image2)

![Fig. 6. Voltage profile for different penetration levels with voltage constraint.](image3)

![Fig. 7. Charge profile for different penetration levels for two tariffs in the cost function.](image4)
directly related to the energy left in the battery. This is shown for a penetration level of 50%.

6. Simulations for 24 h

For a more accurate assessment, a full day of 24 h is simulated. In the case of overnight charging, it is assumed that the batteries of the vehicles are empty when they start to charge at 19h00 and that all the batteries must be fully charged at 06h00. A full day simulation gives more information about the moments vehicles can charge. This is in first instance at home. Not all vehicles must be fully charged at the same moment in the morning and not all vehicles will have an empty battery at the end of the work day. The energy left in the battery when arriving at home is also important. 1000 samples are taken, meaning that there are 1000 profiles of full-time employees that are ascribed to the nodes with a connected PHEV. The simulations are performed for a day with large peaks. In this section, the voltage deviations are important.

6.1. Uncoordinated charging

In the case of no PHEVs, no excessive voltage deviations, i.e. a voltage deviation larger than 10%, occur. 700 runs are performed for each penetration level and the average is taken. The fraction of instances when the voltage deviation is too large per node com-
deviations must stay within their limits. The batteries must be fully charged before the first trip and are filled for one third at the beginning of the program, i.e. at 00h00. At the end of the day, the batteries must be filled for one third.

The percentage of excessive voltage deviations for all penetration levels is practically zero, indicating that the problem is almost solved and the percentage of excessive voltage deviations is reduced to zero for 30% PHEVs. For 50% PHEVs or more, the percentage of excessive voltage deviations is significantly reduced. If the limit of the voltages is decreased to 89% of the grid voltage, then the excessive voltage deviations are reduced to zero. This is in contrast with uncoordinated charging where the percentage of excessive voltage deviations is still high when the voltage limit is decreased to 89%.

7. Renewable energy balancing

Plug-in hybrid electric vehicles have the opportunity to be combined with renewable energy. Renewable energy, for instance photovoltaic and wind energy, has the property to be intermittent. In the ideal case, the renewable energy and the generation by power plants should match the general consumption, which is the household and the PHEV demand.

Distributed generation (DG) units are becoming more important. Three kinds of distributed generation units are considered. A photovoltaic (PV) panel on the roof of the houses, a combined heat power unit (CHP) and a small-scale wind turbine. The generated electricity is injected locally in the distribution grid. The PV peak occurs a few hours before the peak hours of the households. Wind power is more complex and strongly intermittent. If the injected energy is too high, centralized power plants must decrease their electricity production to restore the balance in the grid or the distributed generator units must be curtailed. Decreasing their production is not always efficient. A better approach is to charge the vehicles with this excess of energy instead of decreasing the power output of the power plants or the distributed generators. The PHEVs will be a backup for the excess of renewable energy, if the number of PHEVs is large enough. This stored energy can be used for driving needs or to provide power at a later time [23].

These DG units are placed randomly and the number of DGs is depending on the penetration level. Maximum one DG unit is assumed to be connected to a household.

7.1. Uncoordinated charging

Fig. 14 shows the combination of several percentages of DG units and a low and high number of PHEVs. The DGs take care of the problems of excessive voltage deviations. An increase in the penetration level of DG units causes a decrease in the percentage of excessive voltage deviations. If the number of PHEVs is much larger, the percentage of excessive voltage deviations is also much larger.
7.2. Coordinated charging

The percentage of excessive voltage deviations is significantly reduced when coordinated charging is introduced as shown in Fig. 15.

8. Conclusion

Uncoordinated charging leads to voltage problems for both overnight charging and a simulation of 24h. These voltage problems can be handled by including a voltage constraint in the optimization problem and making the power flow of the charger bidirectional. Applying voltage control is a first step in the direction of supporting the grid by PHEVs. The implementation of a voltage controller embedded in the charger can solve the voltage problems partially. This control can postpone the grid reinforcements to a later moment. PHEVs can be matched with distributed generation units to take care of excess of energy and store it in the batteries. This stored energy can be used for driving needs or can be injected in the distribution grid at a later time. It is indicated that the percentage of excessive voltage deviations is decreased when the number of PHEVs is increased. To give a more accurate view of the intermittent properties of the DG units, a stochastic analysis is to be performed. The economical potential of the grid services is not considered in this paper.

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