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Agents Cut Emissions On how a Multi-Agent System Contributes to a more Sustainable Energy Consumption[☆]

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Abstract

The *Vehicle-to-Grid* technology allows electric vehicles to not only procure electric energy, but also to feed energy back into the grid network. However, by using Vehicle-to-Grid, energy literally degenerates into an article of merchandise and becomes of interest to several stakeholders. In this paper, we describe a multi-agent system, which embraces this exact view and maximises the interest of several stakeholders in using *Vehicle-to-Grid* capable electric vehicles. In order to emphasise the applicability of our approach we performed a field test with real electric vehicles and charging stations. We describe both, implementational details as well as the results of our field test in this paper.

Keywords: electric vehicles, regulatory energy, vehicle-to-grid, smart charging

1. Introduction

Electric Vehicles — A term that received growing media coverage, lately. Yet, coverage in general raises expectations and, as a matter of fact, the expectations in the electric powertrain are high. Not only are electric vehicles (EV) supposed to constitute CO_2 efficient alternatives to conventional vehicles, but also to open entirely new business perspectives, where electric vehicles are –strangely enough– no longer considered as such, but rather as 'batteries on wheels'. This metaphor is only supported by the so called *Vehicle-to-Grid* (*V2G*) technology, which allows electric vehicles to not only procure electric energy, but also to feed energy back into the grid network.

The application spectrum which evolves from V2G capable EVs is fairly extensive. Energy literally degenerates into an article of merchandise and becomes of interest to several stakeholders. As an example for a stakeholder, consider domestic energy providers, which consider electric vehicles as an economic

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alternative to the operation of regulatory power plants. As a matter of fact, energy providers examine approaches [1, 2] in which charging periods with either a low grid-sided demand, or an increased availability of energy (as for instance caused by a wrong prediction of energy from renewable energy sources, e.g. wind- or solar energy), are incentivised to their customers — the drivers of electric vehicles.

Recently, we developed a distributed system in which we express the intentions of several stakeholders by means of software agents. We designed the agents to negotiate with one another in order to maximise their profit. Our work is based on a joint project in which industry partners as well as research institutes tried to lay the foundation for *Gesteuertes Laden*, the sustainable utilisation of V2G capable EVs. We evaluated our joint approach by means of simulation, but also in a field test in which we actually deployed our system to three *MINI E* vehicles.

In this paper we describe our distributed software system in detail. We start with a stakeholder analysis (see Section 2) from which we motivate our system architecture. We proceed by describing implementational details (see Section 3). Finally, we present collected results, from our field test (see Section 4) and wrap up with a conclusion (see Section 5).

2. Concept

In our system, we accounted for five different stakeholders which try to exploit V2G capable electric vehicles in order to maximise their –partially conflicting– interests. In the following we explain each stakeholder in detail.

The first stakeholder in our scenario is the ***driver***. Above all, the driver requires unrestricted mobility. Further, the driver is interested in maximising his profit with respect to the incentives, given by the energy provider. Currently, we use a time dependent *Priority Signal* which is delivered by the energy provider and which reflects both, the forecasted availability of renewable energy (namely wind energy) and the expected grid-sided demand.[1] The second stakeholder in our scenario is the ***vehicle manufacturer***. We consider his intention to maximise the lifetime of the vehicle's battery and also to produce CO_2 efficient vehicles. As such, charging or discharging processes have to comply to battery-friendly patterns and account for the energy sources (or their CO_2, respectively) which are used to generate the grid electricity. The third stakeholder in our scenario is the ***charging infrastructure provider***. It is his intention to maximise the utilisation of his charging stations and to maximise his profit. In order to do so, several grid-sided constraints have to be considered, to prevent from system collapses. The ***distribution system operator*** (DSO) is the the fourth stakeholder in our scenario. It is the DSO's intention to ensure the reliability of the distribution grid. Further, the DSO is interested in minimising his investments. The fifth stakeholder is the ***transmission system operator*** (TSO). The TSO controls the transmission grid and ensures the availability of regulatory energy. He is interested in a cost efficient storage of energy, but also, in a balanced energy demand from the grid and a loss free utilisation of energy from renewable energy sources.

The different nature of the above mentioned stakeholders indicates that we are dealing with a distributed system. We applied *Agent Oriented Software Engineering* (AOSE) [3] and implemented several software agents, which we deployed on the hardware of each stakeholder respectively.

The core functionalities of our system, namely the *Mobility Management* and the *EV Energy managment*, are realised by the so called *User Agent* and by the so called *EV Planning Agent*. Both agents operate on information from further agents, as for instance from the *EV Control Agent* and the *GPS Agents*, which possesses information on the vehicle's current state and its position. Other agents (e.g. the *Charging Station Agent*) or online-services (e.g. the *Grid Service* or the *Charging Station Service*) are accessed for further information (e.g. the availability of charging stations or grid load- and wind energy forecasts), while the user interface is provided by the *Semantic Apps Server* and the *V2G App Client*. The overall architecture of our distributed agent-based system, including agents, their physical grouping and their communicative relations is illustrated in Figure 1.

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[1] We assume that dynamic pricing behaves in a matter congruent to this priority signal and assume that drivers aspire to maximise their profit with respect to this priority signal.

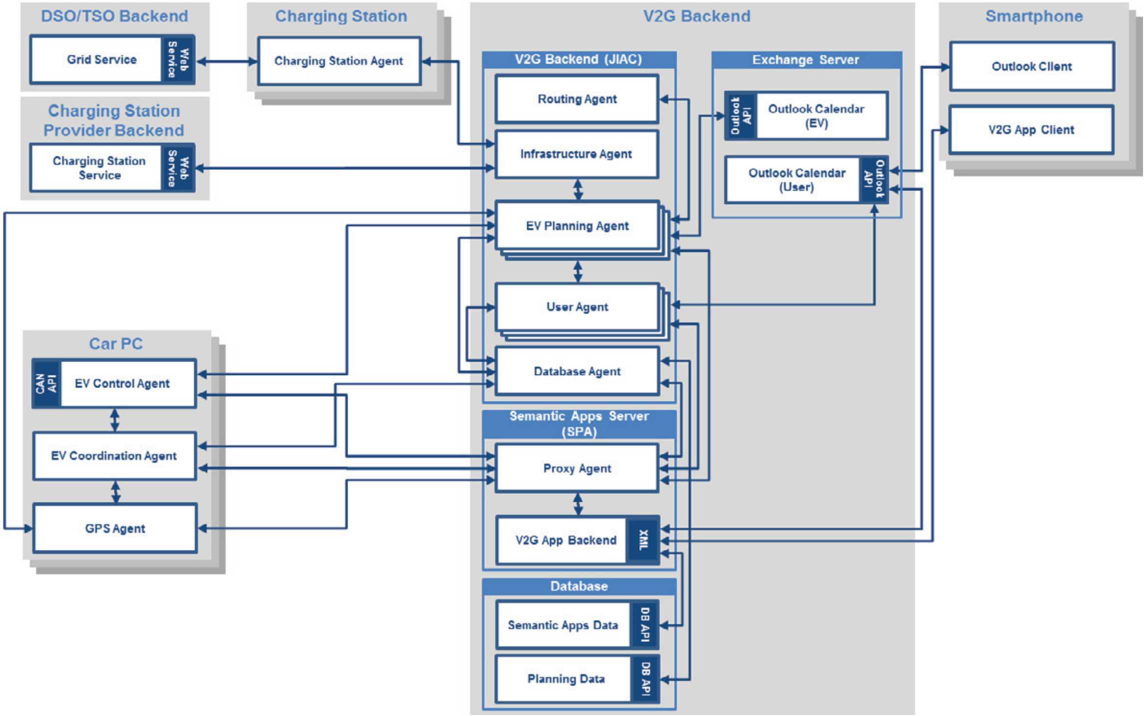

Fig. 1. The agent-based system architecture

In order to facilitate the effective utilisation of V2G capable EV's (in the interest of all stakeholders), we developed an anticipatory approach in which –for a given amount of time– software agents negotiate a charging and discharging profile. This profile reflects the interests of the involved stakeholders. For the driver, we derive an estimated trajectory from his personal calendar. Using this information, we estimate an energy progression curve for the battery of the electric vehicle and additionally identify potential charging- or feeding intervals. Also, our assistance system allows for the specification of an individual level of risk tolerance. This factor determines the driver's willingness to exploit profitable charging- and feeding intervals on the expenses of his mobility. Further, drivers are able to specify a comfortability factor, which determines the tolerated distance from a charging station to an appointment location. In addition to the information on the driver himself, we take infrastructural information into account. As such, our system is aware of detailed characteristics of *Berlin*'s charging infrastructure, including the location of each charging station, the available charging rates as well as information on the availability of charging stations. The interests of both, the DSO and the TSO are represented by the priority signal, which reflects the forecasted availability of renewable energy and the expected grid-sided demand. Further, the DSO intentions are represented by a so called "load management signal", which reflects the limitations of local area grid-networks and whose interpretation prevents from regional grid failures. Finally, we account for the interest of the vehicle manufacturer by using optimised charging- and feeding patterns, and also by considering the priority signal (as incentivised periods imply CO_2 efficiency).

3. Implementation

In this section we describe the implementation of our distributed multi-agent system in detail. For the realisation we used the JIAC V agent framework (or JIAC) [4].[2] JIAC supports the development of multi-

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[2] JIAC V being short for *Java Intelligent Agent Componentware Version 5*

agent systems from the initial design to the runtime monitoring and comprises a methodology as well as several development tools. In the following we describe the implemented system in detail.

For the reason of comprehensibility, we explain the system's five main functionalities — namely the *Mobility Management*, the *EV Energy Management*, the *V2G User Application*, the *Car Computer* and the *Charging Station Infrastructure Provider* — and respectively emphasise underlying agents as well as implementational details.

3.1. Mobility Management

As our system follows a prospective approach in scheduling ecological effective charging and discharging events one huge challenge is to estimate the future attributes of relevant influencing factors. One of them is the grid with its internal constraints. Another one is the driver's mobility behaviour which affects many different parameters. It defines at which time the vehicle is parked at which place, when it is driven, and it impacts the state of charge (SOC) over time. Without the knowledge of these information it would not be possible to seriously propose energy intervals to the user, as most of them would be controversial to the user's intention. Contrariwise we cannot expect the driver to support the system with all these information manually.

Therefore we decided to develop a mobility management which relies upon a typical user appointment calendar. Doing so the user only has to set up its mobility preferences within the system and to manage its daily appointments defining when and where they will be taking place, which is quite usual in business scenarios. In our approach the mobility management has been implemented within the *User Agent* and *EV Planning Agent*. In order to provide the agents with the user's calendar attributes we further developed a Outlook Calendar service. Doing so, the *User Agent* regularly checks for new appointments and, as needed, triggers the planning process. It computes all relevant journey routes (by requesting the *Routing Agent*) with the help of the appointment locations and the user preferences.

The results of the mobility management process are used twofold. On the one hand the evaluated journeys are persisted within the user's calendar and with the help of a *User Application* the driver is able to see the details of the proposed journeys. On the other hand the prediction of the future driving behaviour allows us to set up an estimated progression curve of the vehicle batterie's SOC. This information is relevant as an input parameter for the *EV Energy Management*.

3.2. EV Energy Management

The energy progression curve derived by the mobility management together with the knowledge at what times the vehicle is parked at what place are the most important information for the EV Energy Management. Taking these information into account the energy management system is able to recognise at which time in the future the vehicle has to be charged at latest. This computation is implemented within the *EV Planning Agent*. Further the algorithm is not just looking at the SOC over time but also whether there are charging stations nearby the targeted locations. Therefore the *Infrastructure Agent* provides access to external charging station information, which was in our use case the public charging station infrastructure of Berlin provided by Vattenfall. Further for the decision of when to charge additional grid related preferences are integrated. So the algorithm to compute optimal charging events relies upon the user's behaviour, the provided charging station infrastructure and grid preferences, which in our case represented the amount of renewable energy within the grid. Further the EV Management additionally computes discharging events for the vehicle which enables the driver to act as a stabilisator to the energy network. In this case the algorithm always considers the user's mobility guarantee first. For more detailed information about the charging and discharging algorithms we refer to [5]. The results of the energy management will be stored persistently via the *Database Agent* and will be provided to the *Car-PC* and the *User Application*.

3.3. V2G User Application

The smartphone application enables the user to interact with the distributed V2G system in terms of graphical user interfaces. This application is based on the *SPA framework*[3], which allows the easy devel-

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[3] Smart Personal Assistant: http://smartassistantsolutions.de

opment of mobile applications for different platforms, e.g. iOS and Android. The application consists of three parts: an application client on each smart phone, the application backend as well as a *Proxy Agent* on the application server. This agent connects the SPA-based smart phone application with the JIAC-based multi-agent system.

The whole application was realised by the modular integration of smaller applications, which are explained in the following:

User profile : Additional to the general settings like home address and email address, the user can influence the planning process by different settings, e.g. working time, minimum duration of stay or maximum walkway to/from a charging station.

Calendar : The calendar view is synchronised with the user's Exchange calendar and contains his appointments, journeys as well as the charging and discharging plans of the used vehicle.

Vehicle state : It contains information about the current SOC, charging rate and connection state. If the vehicle is connected to a charging station, the user has the possibility to temporary ignore the charging plan by manually setting the charging rate. The risk tolerance of the user can be specificied by a minimum range which has to be ensured by the planning system when considering charging and especially discharging events.

Charging stations : The user can search for compatible charging stations provided by charging station providers. The result is ordered by the distance to the actual position of the user.

Charge history : Presents an overview about the amount of energy used for driving, charging and discharging within a day, week or month. A visualised priority function illustrates the quality of the evaluated charging and discharging events to the user.

3.4. Car Computer

The vehicle manufacturer has to equip the vehicles with an bidirectional charge controller and to provide functionalities and interfaces for getting information about the vehicle's state and for controlling the charging and discharging behaviour according to the input of the energy management plan. In this prototype with MINI E we have deployed three agents on an embedded computer[4], which we have integrated under the co-driver's seat and equipped with additional modules for the *Controller Area Network* (CAN bus), *Powerline Communication* (PLC), the *Universal Mobile Telecommunications System* (UMTS), the *Global Positioning System* (GPS) and the access to the vehicle's wakeup line. PLC enables the authentication of the vehicle's user by applying standards from the telecommunication area and the communication with remote agents if UMTS is not available during the charging process.

The *GPS Agent* provides location information from the GPS sensor and calculates speed and kilometrage of the vehicle whereas the *EV Control Agent* uses the CAN bus to provide battery information[5] and to set the desired charging or discharging rate. The real charging rate can be lower than the desired rate, because it is controlled by the vehicle's battery management system to increase the lifetime of the battery. The *EV Coordination Agent* cooperates with both agents to follow the calculated charging and discharging plans with consideration of the limitation of the actual used charging station and to initiate a re-planning process in case of significant variations in SOC, location or time.

3.5. Charging Station Infrastructure Provider

As mentioned in our analysis, it is the intention of this stakeholder to maximise both, the utilisation of his charging stations and his profit. Additionally, grid-sided constraints have to be considered in order to prevent from system collapses. In order to reflect the interests of the charging station infrastructure provider in our system, we implemented the charging station agent. The charging station agent manages available charging stations by means of an advanced booking system. As electric mobility is no established business concept so far, the role of a private infrastructure providers is somewhat hypothetic. It is by all means

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[4] For a series launch the functionality should be integrated into the bord computer of the future vehicles

[5] In this prototype the voltage, current, state of charge (SOC) and temperature are available

possible, that in the near future charging infrastructure will be provided by private parties. Nevertheless, today, every existing charging station in the capital region of Berlin is operated by an energy provider [6]. As such, in our project *Vattenfall Europe* emerged not only as DSO, but also as charging infrastructure provider. We designed his representative, the charging station agent, to manage reservations of his charging stations, and additionally, to request current and expected limitations of the energy grid from the web service of DSO/TSO Backend. Based on this information, the charging station agent is able to determine whether proposed charging- or feeding intervals are either feasible or compromise the energy grid's integrity. In the former case the request is granted whereas in the latter case, the request is rejected with a respective error indication.[6] In addition to knowledge on the energy grid's integrity and a booking schedule, the charging station agent is aware of the characteristics of each charging station, such as supported current ratings, V2G capability, serviceability, or its location, to name but a few.

4. Evaluation

In total, we evaluated our assistance system in two different ways. The main evaluation was done in a three-week field experiment for which we deployed our multi-agent system on real hardware components (e.g. charging stations, vehicles, cell phones, etc.) and had selected test drivers evaluate the reliability and suitability of our system. Yet, in order to receive quick results and to draw large-scale implications on future eco systems, we also developed a simulation framework [7]. As a matter of fact, we initially used our simulation framework to ensure the multi-agent system's reliability for the field test. However, we also re-adjusted assumed information (e.g. consumption- and charging characteristics, vehicle ranges, etc.) based on data we collected from our field test, and finally used this real input data for our large-scale, simulation based evaluation. In the following we describe both evaluations in detail.

4.1. Traffic Simulation

We compared three different vehicle usage patterns by means of our traffic simulation system [7], namely unplanned vehicles, W2V vehicles, and W2V2G vehicles.[7] We designed unplanned vehicles to have knowledge neither of the priority signal nor of the local load management signal which is broadcasted by the DSO/TSO. It is the highest intention of unplanned vehicles to remain mobile. For this purpose, we developed a comprehensive driver conceptualisation model [8]. W2V Vehicles apply the driver assistance system and are aware of the priority curve and local load management signals. As such, charging intervals are optimised with respect to both. However, W2V Vehicles are not capable of the V2G technology. As opposed to that, W2V2G are capable of the V2G technology. They act exactly as W2V Vehicles, only that both, charging- and feeding intervals are optimised with respect to the priority- and load management signals.

For the simulation we selected a time period of three days and specified a static priority function. This function is illustrated in Figure 2. In total we specified three future scenarios, one for the year 2015, one for the year 2020 and one for the year 2030). Following the report of the NPE [6], we adjusted characteristics of the charging infrastructure as well as the expected amount of registered electric vehicles from scenario to scenario. For each future scenario, we respectively simulated three different driver types: a typical commuter, a field worker and a deliverer. In order to assess the effect of the W2V and the W2V2G efficiency, we calculated the average amount of wind energy that was effectively charged by the simulated vehicles. The simulation result emphasised, that for each scenario, the W2V algorithm was able to increase the amount of wind energy, compared to unplanned driver behaviour. The additional appliance of V2G was able to increase the average amount of charged wind energy even more. We explain this result with the fact that any V2G process would have an impact on this curve. In our simulation, we were not able to account for this

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[6] Currently, we extend the charging station agent to distinguish not only between feasible and not feasible, but to –in case of a violation– return an alternative (and feasible) suggestion to the applicant.

[7] With W2V being short for *Wind-to-Vehicle*, the capability of electric vehicles to procure energy from the grid network, and W2V2G being short for *Wind-to-Vehicle-to-Grid*, the capability of electric vehicles to procure energy from- and to feed energy back into the energy grid.

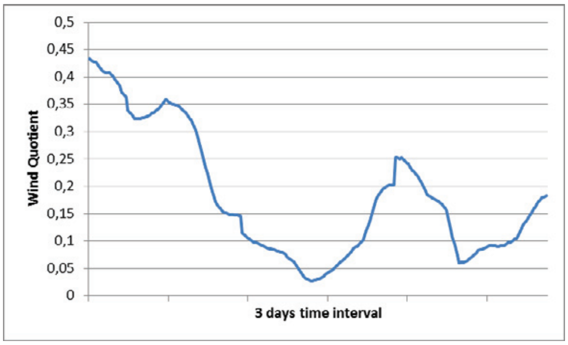

Fig. 2. Contribution (in 10^2 per cent) of wind energy to the total electricity requirements (also referred to as ‘Wind Quotient’) over three days in the north-eastern region of Germany.

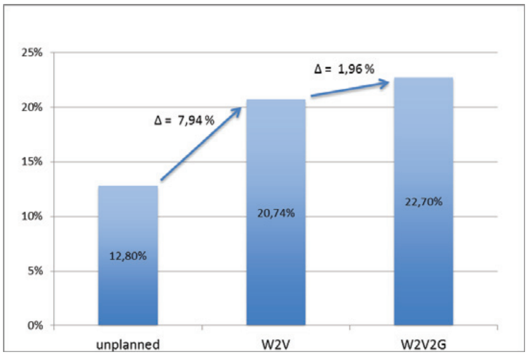

Fig. 3. Average amount of wind energy (in per cent), which was charged by electric vehicles during the simulation of the 2020 commuter scenario.

dynamic feedback. Yet, discharging of energy can be considered as charging a negative amount of energy in mathematical terms. As such, we directly credited discharging vehicles with the positive effect of the V2G procedure and argue that this additional, CO_2 effective energy is directly used to charge other vehicles in our simulation. Average amounts of charged wind energy for the 2020 commuter scenario are illustrated in Figure 3.

4.2. Field Test

Within the field test, six selected users used three V2G-capable MINI E, three smart phones, three V2G-enabled charging stations and 24 regular, public available charging stations. Prior to our field test, an opinion survey [1, p.563-598] was performed in order to verify that users generally agree to use a prospective planning system in order to make a personal contribution to a sustainable energy utilisation. This survey provided valuable suggestions on how to improve our assistance system — although this was not the main intention of the opinion survey. We used the results of the field test to re-adjust model and parameters (e.g. user behaviour, consumption- and charging characteristics, vehicle ranges, etc.) of our traffic simulation in order to receive better simulation results. The preparation of the field test was done by psychologists from the *Technical University Chemnitz*, which selected the most suitable users. The same psychologists also used different instruments (preliminary and follow-up questionnaires, interviews, task scenarios, diaries, and log analysis, to name but a few) for a comprehensive evaluation. Special tasks were assigned to the users, as for instance to add meetings near to a public charging station, to perform immediate and self-controlled charging, to add or to postpone a meeting and thus to trigger the re-scheduling functionality, to remove a meeting and change the location of a meeting. During the field test selected test drivers performed an average of five journeys per day, covering an average daily distance of 39km. In total, 31 charging- or discharging processes were done within 28 days of usage. In ten cases a public charging station was used. The self-controlled charging was initialised 12 times (mostly by one particular user). The users added an average 2.4 appointments per day and selected a minimal tolerated SOC between 40 and 80 km, meaning that the EV Energy Management avoided SOCs below 25 to 50%. Only two out of 143 ways failed due to an unsufficient state of charge. The questionnaires and interviews showed that the users generally assign predicates like usefulness, efficiency and effectiveness to our the system. The use of a smart phone was widely favoured, yet, additional improvements –especially regarding the usability of our system– were suggested as well. Users demanded easier handling of appointments, a more flexible selection of mobility scenarios (e.g. working and non-working days), an improved address lookup function, a push mechanism capable of reminding on updated plans as well as communicating conflicting dates, significant error messages and hints, and an improved offline capability of the smart phone application. Some users also indicated interest in advanced (financial) incentives and feedback on performed charging processes. Also, an increased number of public charging stations as well as a private one at home and a transfer of the battery warranty to the electricity provider were suggested.

5. Conclusion

In this paper we presented an assistance system which optimises the use of V2G capable electric vehicles for different stakeholders. In order to do so, we analysed the interests of the involved stakeholders, namely the driver, the vehicle manufacturer, the charging infrastructure provider, the DSO and the TSO. Based on this analysis, we motivated the use of AOSE for the development and for the implementation of our system. We decided to apply agent technology for several reasons. Firstly, it was our idea to avoid communication bottlenecks and to ensure the system's reliability. Secondly, it was our intention to foster information privacy and to deploy autonomous and proactive software instances on the hardware of the respective stakeholder. Further, we aspired a certain offline capability in order to cope with temporary communication problems, and finally, the agent-oriented approach facilitated an easy integration of additional agents with redundant or additional features — even at runtime — and allowed for an easy extension of the system's computational power. We described our agent system in more detail and introduced our agents, their tasks and their capabilities. We also explained on which hardware the agent types were deployed. Subsequently, we presented collected evaluation results. In total, we performed two evaluations. Firstly, we evaluated our approach by means of a computer aided simulation. Secondly, we deployed our multi-agent system to real hardware and performed a long-term field test in which we had the system evaluated by selected human test drivers. We used the results from the field test to re-adjust initial simulation parameters, such as driver profiles and consumption-, charging- and range characteristics of the simulated vehicles. Based on both evaluations we can state, that our assistance system was able to increase the utilisation of CO_2 efficient energy by electric vehicles. Compared to vehicles without any assistance system, the W2V algorithm was able to increase the average amount of charged wind energy by 7.94%. The additional application of the V2G technology was able to further this efficiency by another 1.96%, such that the efficiency of the W2V2G was able to increase the utilisation of renewable energy by 9.9% compared to electric vehicles without any assistance system. Based on an opinion survey [1, p.563-598] we can argue that users generally agree to use a prospective planning system in order to make a personal contribution to a sustainable energy utilisation. As an additional result of this survey, we also received valuable suggestions on how to improve our assistance system. To conclude — based on our evaluation we can state, that the W2V2G algorithm is able to facilitate a more effective utilisation of renewable energy sources. Futher, we demonstrated that a distributed agent system is able to account not only for individuals but to support the interests of many stakeholders. Based on an opinion survey we can argue that a respective system is well appreciated and able to contribute to a more sustainable utilisation of energy resources.

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