A Household-Oriented Approach to The Benefits of Vehicle-To-Grid-Capable Electric Vehicles

Tobias Brandt, Stefan Feuerriegel, and Dirk Neumann

Albert-Ludwigs-University, Freiburg, Germany
{tobias.brandt,stefan.feuerriegel,dirk.neumann}@is.uni-freiburg.de

Abstract. In this paper we introduce a novel approach to exploring the benefits associated with Vehicle-to-Grid technology on an individual household level. We design an artifact that enables the implementation of different management strategies to utilize synergies between residential photovoltaic electricity generation and the energy storage provided by electric vehicles. The main advantage of this approach is that it does not rely on strong assumptions regarding the market penetration or social acceptance of electric vehicles. In a proof-of-concept case study we show that even a very simple management strategy derived from a household utility function provides additional revenues to the household, while simultaneously decreasing (peak) load on the distribution grid.

Keywords: Green IS, Energy Informatics, Electric Mobility, Energy Management, Sustainability

1 Introduction

The integration of intermittent renewable energy sources into the energy grid is one of the most pressing challenges many advanced nations face today. As the increasing scarcity of fossil fuels combined with a growing global demand for energy is likely to push resource prices upwards in the coming decades [1-2], societies are starting to embrace alternative means for generating electrical energy. This trend is reinforced by steadily decreasing production costs for solar panels and wind turbines and a growing awareness of man-made climate change.

The emergence of a new research frontier, Energy Informatics [3], caused scientists in information systems and computer science to consider their role in tackling the challenges associated with the power system of the 21st century. The central issue associated with an energy supply largely based on wind and solar power is its exogenously given intermittency, as energy is only generated when wind is blowing or the sun is shining. Out of several possible solutions to this problem, two stand out, both with their own inherent advantages and drawbacks, but both increasingly relying on information technology [4]. One is to align energy consumption with energy generation (demand-side management), thus flipping the traditional paradigm of adjusting energy generation to match demand. Often, this requires only small investments in infrastructure, mostly information technology for automation purposes, as it relies

11th International Conference on Wirtschaftsinformatik,
27th February – 01st March 2013, Leipzig, Germany

primarily on rescheduling specific tasks. However, its limits are also evident – there is only so much work (both, in its colloquial and physical sense) that can be rescheduled before significantly encroaching on people's lives. The second approach is the substantial expansion of energy storage systems. Most common methods of storing electrical energy rely on transforming it into other forms of energy that can be stored more easily, examples being chemical energy in the case of batteries and potential energy for pumped hydro storage. However, these systems have in common that they are to a varying degree quite expensive. Pumped hydro and any form of gas-based storage are also characterized by specific geologic requirements and, while they do not interfere with the day-to-day life of people, the former often requires significant alterations to landscapes and ecological habitats.

In recent years, electric vehicles (EVs) have been proposed as a possible – at least partial – solution to the problem of energy storage. While they do require electrical energy to function, creating their very own challenges for energy supply systems in the case of mass distribution, each one of them is supplied with its own battery. When equipped with technology that enables a two-way power flow – grid-to-vehicle and vehicle-to-grid (V2G) – they can serve as a swarm of small energy storage devices. The benefits and risks associated with V2G-capable EVs have since been the subject of several publications, which will be explored in Section 2. Most of them focus on large-scale utilization of EV fleets. Possible benefits of V2G-technology in the residential sector have been largely overlooked, since a single EV only offers a comparatively small amount of energy storage and is primarily used for mobility purposes.

This paper presents a novel perspective on the benefits of V2G-capable EVs in the residential housing sector. We introduce an energy management artifact that implements different strategies for coordinating energy generation from residential photovoltaic (PV) panels, household energy consumption, EV battery storage and mobility needs to derive additional benefits for the residents. We show that even the simplest management strategy can provide financial incentives for employing V2G-technology, while simultaneously decreasing peak demand and PV load on the distribution grid. This is especially relevant, since there are no assumptions about a widespread acquisition of EVs required – even a single household employing this management artifact can reap the benefit and take some burden off the power grid. Finally, we also shift a common approach in smart grid research: Instead of asking what is optimal from a technological point of view and subsequently analyzing how to "sell" this to the public, we first derive the optimum on an individual level and consider the aggregated effect on the grid following that.

This paper is structured as follows: In Section two we present publications related to our research and position our paper in this context. In Section three the requirements for the management artifact are analyzed, while the artifact itself is introduced within a case study in Section four. In Section five we discuss other possible management strategies and possible extensions to the underlying model. Section six concludes.

2 Related Work

Watson et al. [3] have stressed the importance of information systems and computer science in achieving sustainable solutions for a global economy. They emphasize that sustainable development supported by information technology goes beyond concepts like Green IS and Green IT and must include the role of these disciplines of shaping the power supply, transmission, and consumption systems of the future. Kossahl et al. [5] have since shown that Energy Informatics has gathered significant traction within the research community.

However, the steady rise of electric mobility as an alternative to traditional combustion engines has also caused research on energy and on mobility to become more and more intertwined. Battery-only Electric Vehicles (BEVs) and Plugin-Hybrid Electric Vehicles (PHEVs) pose a promising option to address the problem of energy storage associated with the rise of intermittent renewable energy sources like wind and solar power. While a single vehicle can only store a comparatively small amount of energy (e.g. 16 kWh for the Mitsubishi i-MiEV or the Chevrolet Volt), the aggregated effect of a widespread adoption of EVs can provide substantial storage capabilities to the power grid. Beyond charging their batteries using the power grid, EVs require the ability to feed energy back into the grid – V2G-technology – to function as effective storage devices.

The engineering challenge associated with this technology has been addressed in several papers. Kempton and Tomic [6-7] summarize the technical and economic fundamentals related to V2G, while Cvetkovic et al. [8] extend this approach to include residential photovoltaic panels into the system design. The resulting energy system allows for smooth, uninterrupted transitions from grid-supplied to V2G-supplied energy provision for the households. Gurkaynak and Khaligh [9] design a residential photovoltaic control system to coordinate PHEV charging and regular residential requirements. On a larger scale, Lopes et al. [10] analyze grid-EV-interfaces to evaluate the effect of V2G-capable vehicles on the integration of wind power, showing that EVs can provide assistance in frequency control problems caused by intermittent energy sources.

The effects of a large number of EVs on the power grid have been the subject of a range of further publications, particularly in terms of adopted charging strategy. Lopes et al. [11] define a “dumb” strategy (charging whenever the vehicle owner desires to do so), a dual tariff strategy (lower energy price provides incentives to charge during night hours), and a “smart” strategy (charging centrally-controlled and grid-optimized), showing that the grid can only sustain a certain number of “dumb” EVs, but requires additional measures once the number of EVs increases. However, the financial incentives for vehicle owners to switch to a smart strategy are assumed to be given and not justified in detail. Similarly, Clement-Nyns et al. [12-13] illustrate the effect of an uncoordinated and a coordinated (dis)charging strategy of V2G-capable EVs on the power grid. However, these strategies are not examined on their popular incentive compatibility. Additionally, Flath et al. [14] have characterized protocols for smart charging from an Energy Informatics perspective.

A striking similarity in the literature on V2G-based business models is the reliance on EV-fleets or a widespread acquisition of EVs. This is justified in Guille and Gross [15], as well as Kempton and Tomic [7], with the superior revenues from entering the markets for ancillary services like frequency control. Most of these markets can only be entered when a certain amount of energy or power can be reliably provided, necessitating the aggregation of numerous EVs. Consequently, Kempton and Tomic [7] propose three business models distinguished by the aggregating player: (1) aggregation by the vehicle fleet owner, (2) aggregation by an electricity retail company, and (3) aggregation by a third party. The authors also identify the essential conflict between EVs as storage devices and their primary purpose, i.e. reliable mobility. White and Zhang [16] analyze the feasibility of an aggregated V2G program entering the markets for frequency regulation and peak-load reduction simultaneously. The authors conclude that there are additional payoffs for the individual participants of such a program, but do not propose a concrete contracting scheme to distribute these payoffs among the players in this scenario, thus not addressing the aforementioned essential conflict and the incentive compatibility of such a program. In a case study of PHEVs as providers of regulatory power in Germany and Sweden, Andersson et al. [17] simulate individual EVs as bidders in the regulatory power market in the respective countries. While this approach is one of the few to address individual vehicle owners, the authors mention a specific problem the implementation of such a project in a real-world setting would face. As the transmission system operators, who run the market for regulatory power, would be able to collect a massive amount of data on individual mobility, concerns about data protection could create substantial social resistance to such a V2G-program.

A broader analysis of barriers to a transition towards PHEVs and V2G is provided in Sovacool and Hirsh [18]. The authors argue that not only technical barriers are to be overcome, but also social, cultural and political hurdles. They highlight the basic acceptance problem of BEVs and PHEVs, the cultural aversion towards technological change and the interests of stakeholders in the current paradigm of mobility. Nevertheless, in an analysis on the long-term potential of V2G technology, Turton and Moura [19] conclude that V2G may cause a paradigm shift in both energy systems and transportation.

Summarizing, we conclude that V2G-technology offers an interesting perspective on managing future power systems in light of the rise of renewable energies. It would, however, also implicitly change the way we think about mobility and transportation. The majority of recent publications has analyzed the grid stabilizing effect of V2G-capable EVs. This approach relies heavily on a widespread adoption of electric mobility and only marginally considers popular acceptance of the coordination mechanisms, if at all. In this paper we present a novel approach to V2G research. Instead of optimizing on the aggregated level without regards to individual incentive structures, a control artifact implements different strategies to manage energy supply from residential PV installations and V2G-capable EVs on the household level. These strategies are derived from an individual utility function, thus addressing the incentive compatibility problem. While the aggregated effect on grid stability of such a household-level optimization may be inferior to other approaches in related works, it does not rely on ambitious assumptions concerning the total number of EVs, popular acceptance or data security.

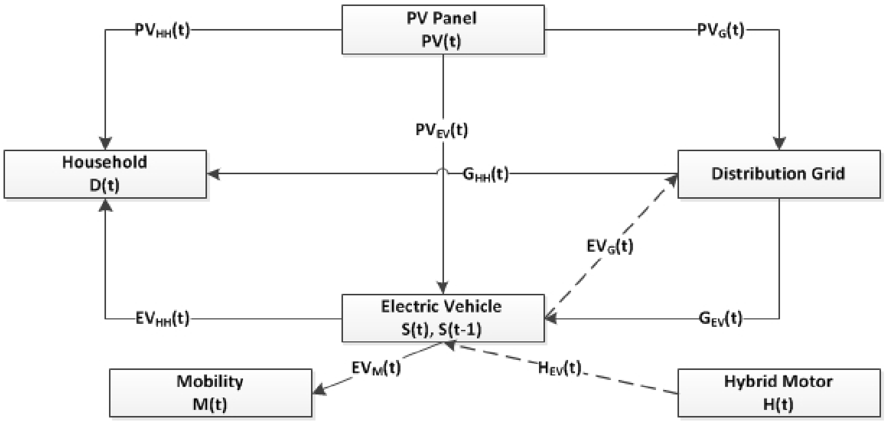
3 Requirements Analysis

The fundamental tradeoff associated with V2G for an individual car owner is between possible financial gains from using V2G-capabilities and unconstrained mobility. Subsequently, when constructing charging strategies, this tradeoff must be considered. In this paper we approach V2G in its fundamental sense as a technology complementary to renewable energy sources, and not primarily as a way to stabilize the power grid. The baseline scenario we analyze includes a single household, a residential photovoltaic panel and an EV. While houses with rooftop-PV panels have become common sights in many industrialized countries, there is still a low market penetration of EVs. Consequently, the notion of EV-fleets in the residential sector is still a long way off for the next years, perhaps even decades. Yet, the number of households that own both, a PV installation and an EV, is likely to steadily increase during that time, since both are currently targeted at the same type of customer (middle to upper income class, ecologically aware). By intelligently using V2G-technology, the owner can receive additional financial benefits from home-produced PV electricity without depending on a widespread adoption of EVs. This scenario is illustrated in Figure 1.

The basic idea is that the EV stores excess photovoltaic energy during times of low demand D, which would normally be fed into the grid (PV_G) and uses this energy to supply the household (EV_{HH}) during times of high demand, when otherwise energy would need to be procured from the distribution grid (G_{HH}). The often substantial price difference between energy fed into the grid and energy procured from the grid would then provide monetary incentives to the vehicle owner, as long as this gain is not offset by additional constraints on mobility. This allows us to formulate the fundamental tradeoff associated with V2G as follows:

$$U(t, M(t), s) = -C_E(t, s) + \phi(t, M(t), s) \tag{1}$$

The utility U of the household at time t with the mobility requirements $M(t)$ and under the V2G-strategy s is thus defined in Equation 1 as the degree to which $M(t)$ is satisfied under s, computed and translated into monetary terms by the satisfaction function ϕ, minus the total cost of energy procurement C_E in t under strategy s. While there are



PV(t)	Energy generated by PV panel in period *t*
D(t)	Household energy demand in period *t*
S(t)	Energy stored in battery of EV at the end of period *t*
M(t)	Energy required for mobility in period *t*
H(t)	Energy generated by the Hybrid Motor in period *t*

Energy supplied in period *t* ...

$PV_{HH}(t)$	... by PV installation to household
$PV_{EV}(t)$	... by PV installation to EV
$PV_G(t)$	... by PV installation to distribution grid
$G_{HH}(t)$	... by distribution grid to household
$G_{EV}(t)$	... by distribution grid to EV
$EV_{HH}(t)$	... by EV to household
$EV_G(t)$	... by EV to distribution grid (not considered)
$EV_M(t)$	... by the EV for mobility purposes
$H_{EV}(t)$	... by the Hybrid Motor to the EV

Fig. 1. Illustration of basic scenario

other variables that influence utility, they are assumed to be not affected by the V2G strategy and subsequently not considered.

The requirements the management artifact and the V2G strategies implemented need to fulfill are derived directly from the scenario and Equation 1. The requirements are as follows:

Requirement 1: Monitor and reflect the energy flows in the system and mobility behavior in the calculations

The reasoning behind this requirement should be evident, as the management artifact needs to observe the actual system to make informed decisions. This is even more important for management strategies that depend on predictions of future behavior (energy consumption or generation, mobility), since a historic data set of a higher quality is likely to improve forecasts.

Requirement 2: $\phi(t, M(t), s)$ *must be computable for strategy s*

This requirement addresses the problem of translating constraints on mobility into a value that can be compared to energy costs. Solving this problem is, however, essential for addressing the fundamental tradeoff of V2G.

Requirement 3: $\int_{t=0}^{T} U(t, M(t), s)\, dt$ *of a strategy that includes V2G must be higher than the utility without V2G within a reasonable time interval [0,T]*

This determines that any strategy that includes V2G must provide a higher utility than without this technology. What constitutes a reasonable time interval is largely in the eye of the beholder, but should at least span more than 24 hours (up to several weeks or months), since the EV energy storage takes advantage of daily cycles in PV-generation and mobility behavior.

Requirement 4: The distribution grid should not be adversely affected in terms of demand and feed-ins from PV

Although our approach aims primarily at the synergies between V2G and residential renewable energy sources, the distribution grid should at least not be negatively affected by the management artifact. We do not only consider a decrease in demand to be beneficial for the grid, but also a decrease in feed-ins from PV generation, since a large number of residential PV installations could pose challenges to the distribution grid in the future [20].

4 Strategy Modeling and Evaluation

In this section we present a simulation-based evaluation to illustrate the possible benefits that can be gained from managing synergies between residential renewable energy generation and a V2G-capable EV. As this study intends to serve as a proof-of-concept, we use a very simple management strategy to show that even with this simple strategy there are benefits for an individual household.

The simulation architecture has been implemented in MATLAB and enables the execution of different management strategies. In a real-world setting requirement 1, the monitoring of energy flows, would be addressed by using smart meters that supply the management artifact with data on the current system state. Within the simulation we use the profiles and parameters as specified and explained in Table 1. While we refer to the German market and German prices for electricity, which are heavily distorted by subsidies for renewable energies, this does not invalidate the applicability of our results to other countries without these subsidies. In fact, the spread between c_P and c_F (cost of procuring 1 kWh from the grid and cost of feeding 1 kWh into the grid, respectively) may be less than in an unsubsidized case. For example, an energy retail company may only be willing to voluntarily pay 4 or 5 cents per kWh, whereas the average retail price would only drop by about 2 cents, the current price effect of the solar subsidies. Finally, as recommended in Kempton and Tomic [6], we use a factor of 0.93 for AC/DC-inversion and vice versa. Battery degradation is not considered in our model, because its effect is likely to be negligible [21].

There are two possible ways to address requirement 2, evaluating mobility satisfaction in monetary terms. One is using a PHEV and computing the financial cost in regards to additional fuel required. The underlying assumption is that mobility needs can always be satisfied, it might just be more expensive to do so. In our simple proof-of-concept strategy we use a different approach by assuming that the driver will never need the full battery capacity between charging cycles. More precisely, we define two decision strategies s_0 and s_{V2G} as the benchmark scenario and the V2G scenario as illustrated in Table 2.

Essentially, the EV owner determines a battery level S^{MIN} deemed necessary to fulfill all mobility needs. Up to this level all excess PV power (i.e. power exceeding household demand, Equations 2a and 3a in Table 2, respectively), and the distribution grid is used to charge the vehicle (subject to maximum charging power constraint, Equations 2e, 2f, 3e, 3f). In the benchmark case, once S^{MIN} is reached, only excess PV power is used to charge the EV (Equation 2e). All remaining PV power is fed into the grid (Equation 2g), which also supplies any additional power needed to satisfy demand (Equation 2d). Under the V2G-strategy, the EV uses any energy above S^{MIN} to power the household if the power generated from PV is not sufficient (Equation 3c). Hence, the central difference between the strategies and the potential for cost savings is how each strategy deals with stored energy above S^{MIN}.

Current BEV models still have a quite limited driving range and thus cannot fully replace cars powered by combustion engine. Hence, in our benchmark scenario we assume the EV to be the second car in the household. Specifically, we consider a four-person household in rural Germany with a household demand and PV generation as illustrated in Figure 2 for a sample day. This household consists of one full-time working parent (using the primary car), one stay/work-at-home parent (using the EV), a schoolchild and a toddler. While this seems to be a very strict selection, the artifact is not solely aimed at this small subset of the population. Basically, any household where one car is parked at home for a significant part of the day would achieve similar results. We use this very specific selection only to generate realistic patterns for driving behavior. Hence, our sample household and a household with a stay-at-home senior may both have a car being parked at home during the day, but they would undertake trips for completely different reasons.

We analyze the effects of our management artifact during one week of August with the following mobility requirements for the EV derived from our data set:

- **06.30 AM – 07.00 AM** Driving child to school and returning home (16 km)
- **12.30 PM – 02.00 PM** Shopping, picking child up from school and returning home (22 km)
- **05.30 PM – 05.45 PM** Short additional shopping trip (3 km)

Table 1. Variables and Parameters

Variable / Parameter	Value	Unit	Comment
$D(t)$	N/A	kW	This is simulated according to the standardized household demand profile of the German Association of Energy and Water Industries [22] for 2011 (15 minute intervals) with an annual demand of 3880 kWh. While this load trace is averaged over all households and flattens peaks, this does not present an issue for the proof-of-concept, since the flexible discharging of EVs would allow for a better management of demand spikes than provided by PV. The beneficial effect of our management artifact is thus at most underestimated.
$PV(t)$	N/A	kW	PV generation is based on the trace of a rooftop PV installation on a single-family home in eastern Bavaria, Germany (5.58 kWp installed).
$M(t)$	N/A	N/A	Mobility needs are constructed on the basis of the study "Mobility in Germany, 2008" [23], which documents several tens of thousands of trips in passenger cars taken in 2008 and links them to households and individuals. As mobility behavior is very persistent, there should arise no problem from linking these requirements with PV and demand data from 2011.
S^{MAX} OUT^{MAX} IN^{MAX} EV_M	16 1.5 2.4 0.187	kWh kW kW kWh / km	The technical parameters for the EV are based on the Mitsubishi i-MiEV electric car, as Mitsubishi is one of the first producers planning to introduce V2G-capable vehicles at least for emergency support [24] Additional parameters are taken from the "Fuel Economy Guide" [25]. They represent the maximum energy that can be stored in the battery, the maximum power the vehicle can feed into the household, the maximum power the vehicle can be charged with and the average energy required for 1 km of driving distance, respectively.
c_G c_P c_P	0.2495 –0.1243 –0.2443	€ / kWh € / kWh € / kWh	These parameters represent the cost of a single kWh procured from the distribution grid, PV-generated and used for private consumption, and PV-generated and fed into the grid, respectively. Values are according to the German subsidy scheme [26] and the average retail price in Germany in 2011 [27].

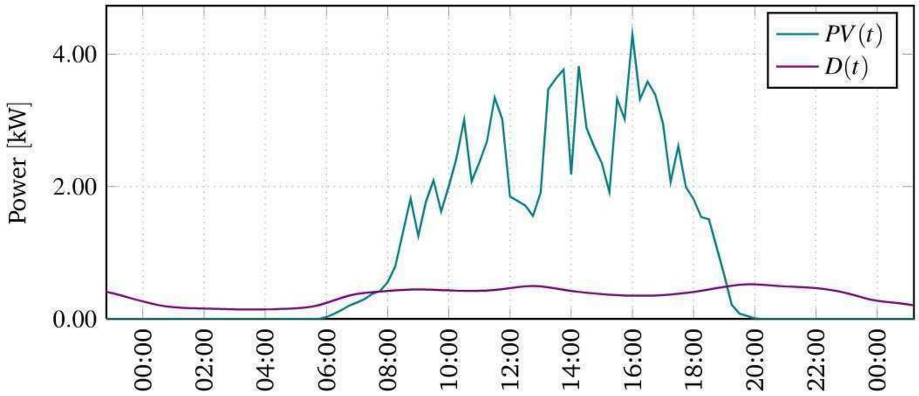


Fig. 2. Household demand and PV generation as on August 5, 2011

Table 2. Strategies

s_0:	$PV_{HH}(t) = \min[D(t),PV(t)]$		(2a)
	$y = \begin{cases}1 \\ 0\end{cases}$	*if EV plugged in* *otherwise*	(2b)
	$EV_{HH}(t) = 0$		(2c)
	$G_{HH}(t) = D(t) - PV_{HH}(t)$		(2d)
	$PV_{EV}(t) = \begin{cases}\min[PV(t) - PV_{HH}(t), IN^{MAX}] \\ 0\end{cases}$	*if* $y = 1$ *and* $S(t) < S^{MAX}$ *otherwise*	(2e)
	$G_{EV}(t) = \begin{cases}IN^{MAX} - PV_{EV}(t) \\ 0\end{cases}$	*if* $y = 1$ *and* $S(t) < S^{MIN}$ *otherwise*	(2f)
	$PV_G(t) = PV(t) - PV_{HH}(t) - PV_{EV}(t)$		(2g)
s_{V2G}:	$PV_{HH}(t) = \min[D(t),PV(t)]$		(3a)
	$y = \begin{cases}1 \\ 0\end{cases}$	*if EV plugged in* *otherwise*	(3b)
	$EV_{HH}(t) = \begin{cases}\min[\max[D(t) - PV_{HH}(t), 0], OUT^{MAX}] \\ 0\end{cases}$	*if* $y = 1$ *and* $S(t) > S^{MIN}$ *otherwise*	(3c)
	$G_{HH}(t) = D(t) - PV_{HH}(t) - EV_{HH}(t)$		(3d)
	$PV_{EV}(t) = \begin{cases}\min[PV(t) - PV_{HH}(t), IN^{MAX}] \\ 0\end{cases}$	*if* $y = 1$ *and* $S(t) < S^{MAX}$ *otherwise*	(3e)
	$G_{EV}(t) = \begin{cases}IN^{MAX} - PV_{EV}(t) \\ 0\end{cases}$	*if* $y = 1$ *and* $S(t) < S^{MIN}$ *otherwise*	(3f)
	$PV_G(t) = PV(t) - PV_{HH}(t) - PV_{EV}(t)$		(3g)

While this behavior is unlikely to repeat every day for the entire week (usually there is no school on the weekend), it still constitutes a reasonable benchmark case (the child might go to sports practice, instead). We set S^{MIN} to 70% of the maximum, i.e. 11.2 kWh. This guarantees that all trips can be realized and leaves some leeway for additional unplanned trips.

As our assumption is that this decrease of the effective battery capacity does not limit mobility behavior, $\phi(t, M(t), s_0)$ and $\phi(t, M(t), s_{V2G})$ would be equal, thus eliminating each other when calculating the difference in the total utilities of each strategy.

The difference in utilities reduces to the purely monetary difference in the electricity costs, resulting in the following equation:

$$\Delta U = -C_E(t,s_{V2G}) + C_E(t,s_0) \tag{4}$$

with

$$C_E(t,s_i) = \int_{t=0}^{T} [c_G(G_{HH}(t,s_i) + G_{EV}(t,s_i)) + c_P(PV_{HH}(t,s_i) + PV_{EV}(t,s_i)) + c_F PV_g(t,s_i)]dt\,. \tag{5}$$

Since the demand and PV data is divided in intervals of 15 minutes, we used a discrete approximation of these functions. Figure 3 illustrates the daily costs for electrical energy associated with each strategy, which were obtained through a computational experiment. The variance between the days is largely caused by the volatility of PV generation, but also by daily differences in the household demand. Negative costs implicate a profit for the household, resulting in an increase in profits of 9.15% over the week (27.17€ compared to 24.89€) from employing the V2G-strategy.

The actual impact of the V2G-strategy for a specific day is depicted in Figure 4. While the left graph shows which sources supply the electricity demand of the household given s_0, the right graph illustrates this for s_{V2G}. With the latter strategy the EV relieves the distribution grid during the evening hours and at night, thus even dampening the load peak between 6 and 8 PM. Over the entire week the feed-ins from PV on the grid have been reduced by 14.02 kWh (14.07%), while the energy procured from the grid has been reduced by 15.87 kWh (55.83%, difference in absolute terms largely due to losses from inversion). This shows that our management artifact can provide additional revenues for the household and simultaneously reduce (peak) load on the distribution grid – even with a very simple management strategy.

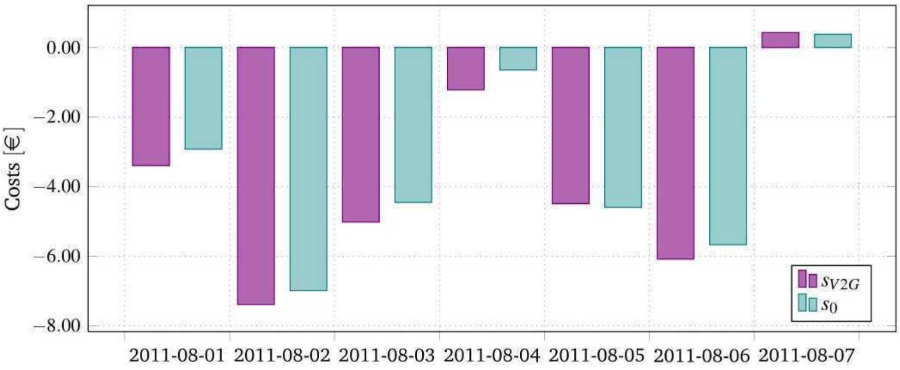


Fig. 3. Daily costs for electrical energy

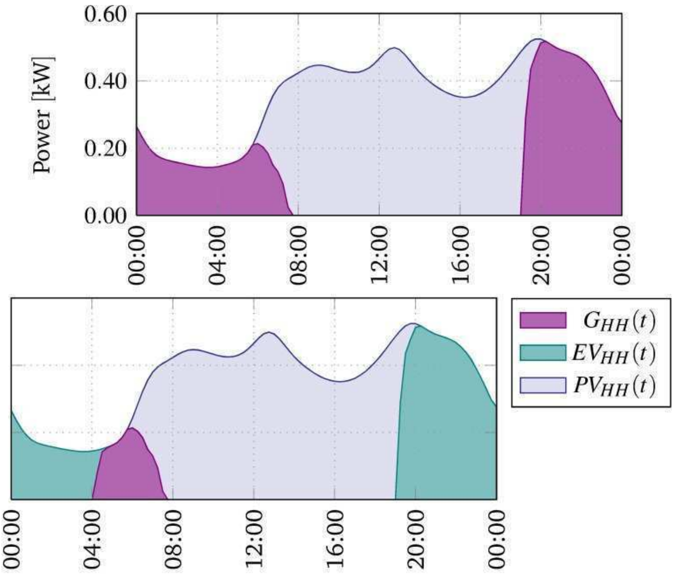


Fig. 4. Energy sources that supply household demand (top: s_0 / bottom: s_{V2G})

5 Discussion

It has been shown that using our management artifact households can realize monetary benefits through V2G without relying on (not yet existing) aggregation programs. While not every week is an August week, this sample household could gain revenues of around 60€ during a year, estimating that on average about 50% of the additional weekly income or savings is realistic for the entire year. This is almost an entire monthly rate of the average standardized three-person household in Germany [27].

However, this is just a lower boundary to the possible financial gains, as we used a very simple decision strategy that did not employ any optimization techniques and focused entirely on the synergies between residential PV and energy storage. In this section we briefly present three possible additions to our model that could substantially increase these revenues.

Strategies under Uncertainty (with or without Signaling)

In our case study, the mobility needs *M(t)* are assumed to be equally satisfied by the strategy with V2G and without V2G. Consequently, the satisfaction function Φ was eliminated when taking the difference of utilities. However, the choice of a fixed S^{MIN} severely limits the ability of the management artifact for intraday optimization. This problem could be alleviated by handling ϕ differently and considering a PHEV instead of a BEV. The full satisfaction of *M(t)* would be formulated as a constraint on the optimization problem, handling a low battery state by relying on the more expensive combustion engine. This would allow the management artifact to optimize V2G power supply over a future time interval, subject to forecasts on future demand, PV generation and mobility behavior. The results could additionally be improved by enabling the household to signal short-time mobility needs.

Non-uniform Energy Retail Pricing

Varying retail prices of electricity within a day could increase these revenues from intraday optimization even further. This does not necessarily require real-time pricing, as a dual-tariff structure (day / night) would suffice. Photovoltaic energy would then preferably be distributed during high price times, subject to mobility constraints.

Participation in V2G Program for Frequency Control

White and Zhang [24] explore the potential of V2G aggregation programs simultaneously entering the markets for peak-load reduction and frequency control and this concept should be adaptable to our approach, as well. Once such a program actually exists, it could be incorporated into the optimization calculus of the management artifact. The optimal strategy would then maximize the superior revenues from the V2G program and use any spare capacity for excess PV energy.

6 Conclusion

While most research focuses on the aggregated benefits of V2G-capable EVs, there exist potential revenues for individual households from synergies between residential renewable energy generation and EV energy storage. In this paper we introduced a management artifact that supports a household in realizing these revenues. The main advantage of this approach is that it does not rely on a high market penetration and social acceptance of EVs – even a single household with a PV installation and an EV can profit.

Our study showed how simple information systems open up new possibilities for integrating renewable energies and electric mobility. However, this work should serve as a basis for future research on the role of information systems in this context. Systems that allow for signaling or prediction of driving behavior could substantially enhance the results produced in this study.

The strategy we implemented as a proof-of-concept was a simple decision strategy, but, nevertheless, produced non-negligible revenue increases. In our future research we will further extend this concept to PHEVs, thus enabling the computation of intraday optimization strategies. We will also consider the effects of non-uniform energy retail pricing and the compatibility with V2G programs for frequency control.

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