IMPACT OF BEHAVIOR ON USING PHOTOVOLTAICS TO CHARGE ELECTRIC VEHICLES: SYSTEMATIC ANALYSIS

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ABSTRACT: Electric vehicles will be one of the major drivers of future electricity demand. Due to their large storage they are a very attractive energy consumer for photovoltaic energy and a good energy sink to increase self-consumption. But for most of the working population, the car is frequently not at home at times of optimal solar radiation and thus cannot be charged. In the last years a new, behavior-based residential load profile generator has developed that models the individual people as independent software agents. This makes it possible model very diverse behavior patterns, for example singles and families, office workers, shift workers and unemployed people. The tool has now been extended to also model electromobility. The aim of this paper is to do a systematic analysis of when and with how much power and energy people can charge their cars considering real energy use, behavior and absences and how much of this energy can be covered by PV in each case.
Keywords: see enclosed list of keywords

1 INTRODUCTION

Electromobility will be one of the major future demand drivers. Photovoltaics (PV) is predicted to become one the biggest producers of energy. Therefore, it would make intuitive sense to charge electric cars using solar cells.
The challenge is the temporal match of solar energy with the demand from typical living patterns. If the car is at the parking lot of the office during the day, it can't be charged at the same time at home from the home PV system.
In the last years a very detailed load profile generator was developed that has now been extended to include mobility. In this paper selected load profiles have been used to quantify how much self-consumption, autarky and solar charging is possible with different PV sizes, different behavior patterns and different commuting distances. The tool used in this paper is freely available for download at [1]

2 STATE OF THE ART

There have been other studies that looked at electromobility charging before. [2] created a charging profile generator and analyzed the results. They showed very similar averaged charging profiles to the single office worker used as example in this paper.

Another study was [3]. Here they showed among other things that a large percent of people plugs their car in in the evening when they get home and that about 25% of the cars are plugged in longer than 24h. Both of these findings are replicated in the synthetic load profiles generated for this paper. Especially on the weekends the cars tend to be connected a very long time. To the best knowledge of the authors there has not been any detailed analysis of the mismatch of PV-electricity to charging demand for different living styles and behavior patterns.

3 MODEL

The paper uses the behavior-based load profile generator developed in [4]. It models the people in the household as independent software agents that are driven by their desires. For example, they get hungry every 4-6 hours and will then try to get food at the next opportunity.

The basic idea is shown in Figure 1.

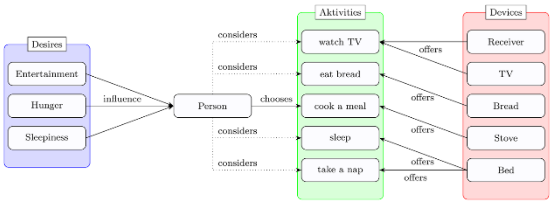

Figure 1: Basic idea behind the load profile generator [4]

The model has been extended a lot from this basic idea and includes, among other things:

- Sicknesses that makes people stop going to work for a few days
- Vacations
- Bridge days around holidays
- Shift workers
- Temperature dependent activities such as gardening
- Weekly routines such as going to a fitness studio once a week
- Autonomous devices such as fridges, standby devices, freezers and other things
- Automatic tracking of dirty laundry or dirty dishes to run the washing machine and dishwasher on appropriate intervals

The resulting activity profiles are very detailed and have been validated with statistics in [4]. The load profiles are the generated from the activity profiles and from measured device profiles. The generated activity profiles are very realistic, but frequently slightly idealized versions because the behavior stays constant over the year, compared with reality where people tend to change their behavior over time. For example, during the first year after a child's birth, the behavior shifts constantly due to the child growing.

The model has now been extended with mobility modelling. The mobility model has three major components:

- Travel routes between sites
- Transportation devices
- Charging stations

3.1 Travel Routes

The travel routes model all the steps the person has to go through to get from their source to their destination. An example for a travel route might be:

- Take the elevator 10 m with a speed of 1 m/s
- Walk to the car 200 m with a speed of 3km/h
- Drive 30 km with a speed of 30 km/h
- Walk 300 m to the office with a speed of 4 km/h

Such travel routes are defined between all locations that are used when modelling the behavior of the people in the load profile generator.

Travel routes are then combined into a travel route set that can be assigned to a household to make it easier to combine different household and different travel route sets.

3.2 Transportation devices

Transportation devices are for example cars, feet, busses or elevators. Every step in a travel route is assigned a transportation device category and only transportation devices that match the category can be used to travel the step. So, you can’t use a car to travel in the elevator for example. Transportation devices have among other things age limits that make sure that the children will not drive the cars by themselves and they are split into devices that are only at a single location at a time such as a car or a bicycle or devices that are always available at a certain spot such as buses.

The transportation devices are then combined again into a set that can be combined with any household.

3.3 Charging stations

Any site can have one or more charging stations. The charging stations are limited to a transportation device category and to a maximum charging power.

3.4 Implementation

The LPG is implemented as Windows program in C# with currently around 50.000 lines of code. It is scriptable to make it possible to integrate the software into other projects.

4 SELECTED TEST CASES

To study how well electric vehicles can be charged with PV, a number of different cases was selected to show the impact of the individual variables. The cases are shown in Table 1. The criteria for the selection was showing the effects are clearly as possible, thus the strong focus on the single person household.

Table 1: Selected Cases to study

Househol d	**PV Size Ratio***	**Distance to Work**	**Charging Place and Power**
Single, Office Worker	100%	5 km	Home, 3.7 kW
Single, Office Worker	100%	30 km	Home, 3.7 kW
Single, Office Worker	100%	30 km	Home, 22 kW
Single, Office Worker	500%	30 km	Home, 3.7 kW
Single, Office Worker	100%	30 km	Work, 3.7 kW
Shift Workers	100%	30 km	Home, 3.7 kW
Shift Workers	100%	30 km	Work, 3.7 kW
Retirees	100%	-	Home, 3.7 kW

As a solar profile weather data from the software Meteonorm from the company Meteotest [5] was used with a 1-minute resolution. A PV profile was calculated from that using the NREL System Advisory Model [6]. All calculations are done with a time resolution of 1 minute.

4.1 Single Office Worker

Figure 3 shows a carpet plot of the activities of the person in the household. It is a carpet plot showing the time of the day on the Y-axis and the days of the year on the Y-axis. The picture shows most of the effects from section 3 and should give a good impression of the typical living pattern of the person.

Additionally, Figure 2 shows a carpet plot of the electricity demand over the year for the household. It is visible that the main electricity consumption happens on the weekends and during the evenings and that the consumption during the two vacations, during the weekdays and at night is very low.

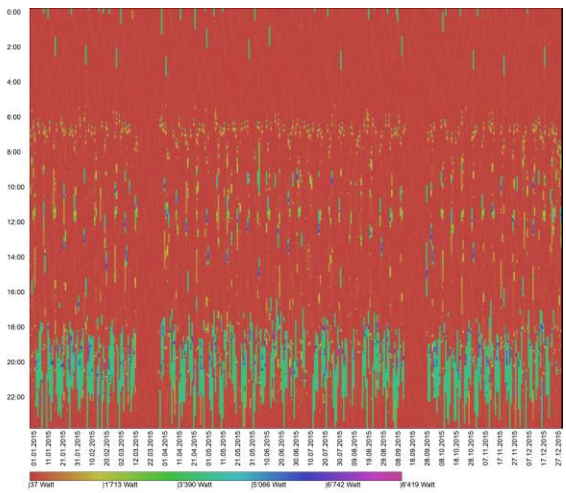

Figure 2: Carpet plot of the electric energy consumption for the single office worker

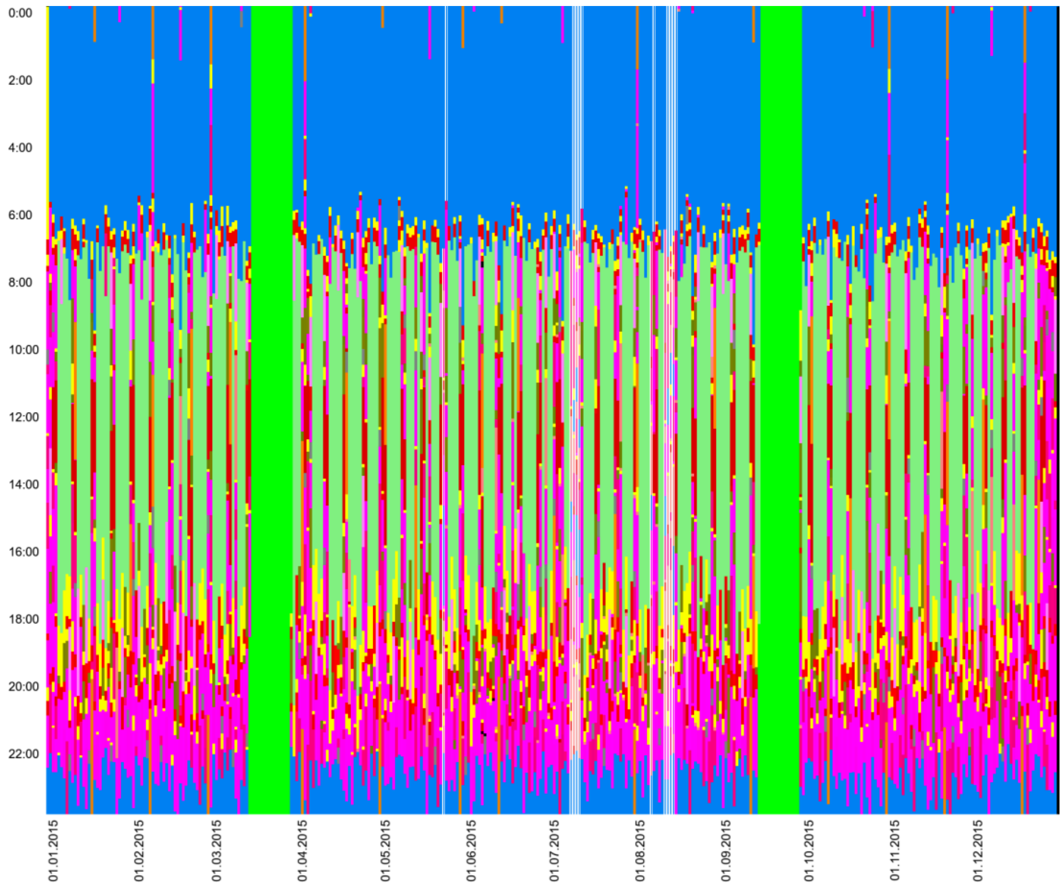

Figure 3: Carpetplot of the activities of the single office worker. Darker green indicates work, neon green is vacation time, blue is sleep, yellow indicates food and the various shades of purple indicate various entertainment activities.

4.2 Charging at home 3.7 kW, 5 km to work

As reference case the household will be used with the parameters of commuting distance of 5 km to work, a charging power of 3.7 kW and a charging station at home. The PV system is sized to be net-zero, meaning that it will generate exactly as much energy over the entire year as will be consumed. As result the average yearly curve for the household demand, the charging power, the PV power and the resulting grid load are shown in Figure 4. It is visible that most charging occurs in the evening, while most of the PV generation happens during the day. The solar charging ratio is 22%. That means 22% of all electricity demand for the car comes from the photovoltaic system. The household consumes 1400 kWh, and the electric car an additional 950 kwh.

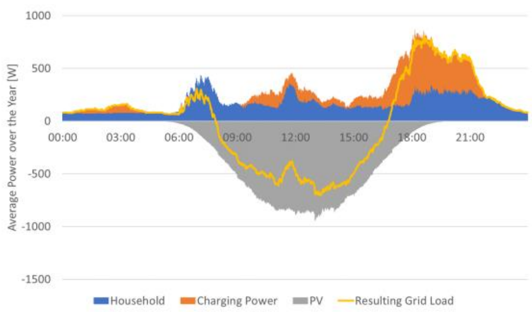

Figure 4: Profiles for the household, the charging, the PV Energy and the resulting grid load, averaged over the entire year.

4.3 Charging at home 3.7 kW, 30 km to work

The next step is increasing the commuting distance to 30 km, since the higher price of electric vehicles amortizes sooner with a higher the yearly driving distance and thus long distance commuters are more likely to buy an electric car. Now the household consumes 1350 kWh (the person gets home later in the evening and thus has less time to watch TV, so less electricity is consumed) and the electric car consumes 3000 kWh. Due to the higher energy demand late in the evening only 7% of the charging can now be performed by solar power.

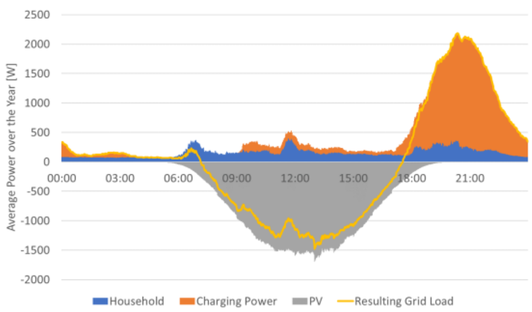

Figure 5: Profiles for the household for a distance of 30 km to work

4.4 Charging at home, 22 kW, 30 km to work

While charging with 3.7 kW is nearly always available, installing fast chargers with 11 kW or 22 kW is very popular because they enable a much faster recharge. While most of these chargers offer the theoretical option to regulate the charging power, based on the observations from the authors this option is so far rarely used. Figure 6 shows the results. The self-charging ratio goes down to 2.5%. This is by far the worst way to charge a car with PV.

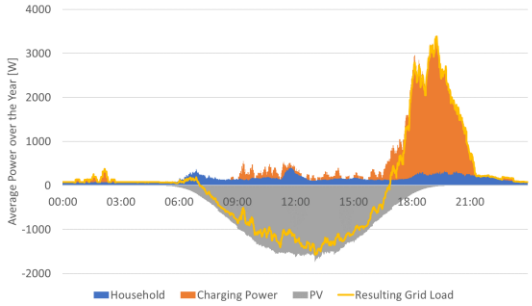

Figure 6: Charging with a 22-kW charger

4.5 Charging at home, 3.7 kW, 30 km to work, big PV

The most intuitive approach might be to simply increase the size of the PV system. In this case it was increased to 500% of the yearly demand. The solar charging ratio stays at 7% though due to the temporal mismatch between available energy and energy demand. The profiles are shown in Figure 7.

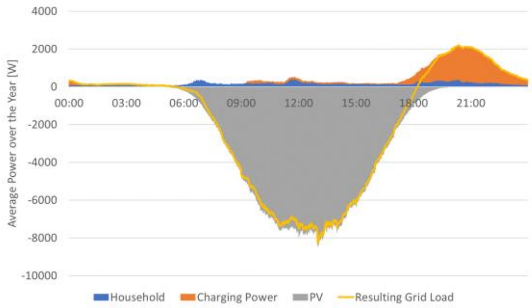

Figure 7: Profiles for increasing the PV system size by a factor of 5

4.6 Charging at work, 3.7 kW, 30 km to work

The best way to increase the solar charging percentage is putting the charging station at the workplace. This yields 63% solar charging, but has a number of legal and economic challenges, such as how to transfer the electricity from the home system to the workplace, who pays for the charging station and who is responsible in the case of technical difficulties. But this result indicates that putting charging stations not at home but at the parking spaces at work will be an absolutely essential part of the energy transition, both as a sink for excess solar energy and as a controllable load for demand side management. The resulting profiles are shown in Figure 8.

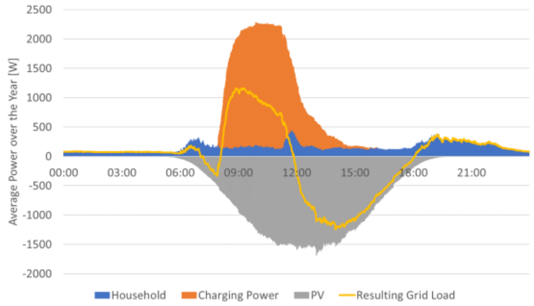

Figure 8: Profiles for putting the charging station at the workplace

4.7 Shift-worker charging at home

More than 17% of Germans work in shifts. This includes not only manufacturing, but also health care and sales in nearly all stores that are open more than 10 hours per day. The example shown in Figure 9 is for a shift worker couple in a rotating three shift industry job, where each week the people are working a different shift. This leads to a solar charging percentage that is slightly lower than for the office worker. The profile is shown in Figure 9

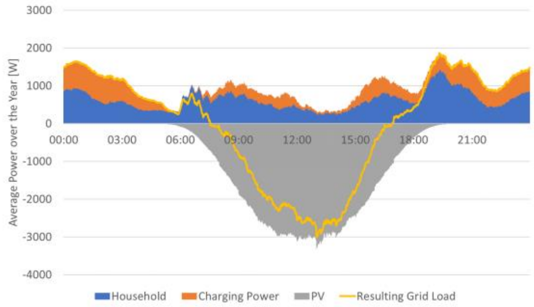

Figure 9: Averaged yearly profiles for a shift worker couple in a rotating three shift industry job

4.8 Shift-worker Charging at Work, 3.7 kW, 30 km to work

Moving the charging station to work for the shift workers improves the solar charging ratio somewhat, but it is still rather low at 36%. This indicates that simple solar charging is not a good match for the changing schedules of a shift worker and that for optimal integration of this large group into the future energy system they will either need to have cars with large batteries that can cover entire weeks without charging or charging stations both at home and at work.

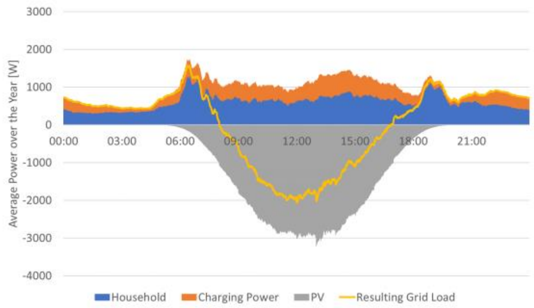

Figure 10: Profiles for the shift workers with a charging station at work

4.9 Retirees, 3.7 kW

Retirees are the last group to be investigated. This is shown in Figure 11. It is visible that even in this case a large percentage of the charging occurs at night because they come back late in the day and then plug in the car. Without any kind of smart charging control, they only reach a solar charging percentage of 19%.

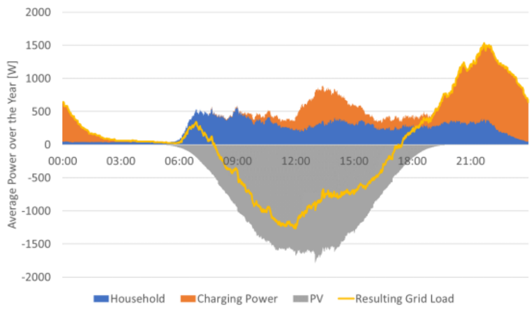

Figure 11: Charging profiles for a retired couple

4.10 Comparison Table

The total energy consumption for each case is shown in Table 2. The results again clearly indicate that putting charging stations at the work place parking lots is by far the most efficient way to increase the solar charging percentage and to avoid costly solutions where large amounts of solar energy first needs to be stored temporarily before being moved into the car batteries at night.

Table 2: Overview of the results

Household	Self-Consumption	Autarky	Solar Charging Percentage
Single, Office Worker	32%	19%	22%
Single, Office Worker	18%	13%	7%
Single, Office Worker	14%	11%	2.5%
Single, Office Worker	4%	20%	7%
Single, Office Worker	56%	32%	63%
Shift Workers	21%	19%	17%
Shift Workers	33%	30%	36%
Retirees	32%	22%	19%

5 CONCLUSIONS

There is a large influence of behavior on the percentage of solar energy that can be used to charge the car. In general, if the charging location is at home, the solar charging percentage is going to be less than 25%. If the charging power is high, it can be even as low as only 2.5%.

The best way to increase the percentage of solar charging is to install charging points at the workplaces and install sufficient smart charging control solutions to spread out the charging event over the entire duration of the day without impacting user comfort.

The second conclusion of this paper is that the developed solution for synthesizing charging profiles is working very well for generating realistic charging profiles for the base case. But what is missing is smart charging control and time limits on the charging so that solar-only charging can be modelled. This will be implemented in one of the next versions.

6 ACKNOWLEDGEMENTS

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