# Optimal operation and sizing of a residential PV storage system – Instructions for teaching lab

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# 1 Introduction

Welcome to the teaching lab on the operation and design of a household energy system with photovoltaic (PV) generation and a battery storage system! In this lab, we will try to understand and answer the following research questions:

1. What are good operating strategies for a storage system to minimise costs or to minimise $CO_2$ emissions? How do these strategies compare to a "naive" reference strategy?

2. Under a given operating strategy suitable to minimise costs, what is an optimal system design in terms of installed capacities of the PV and storage systems?

This lab may differ slightly from what you are accustomed to. The following points provide an overview of the activities you will be engaging in:

- The preparation for the lab is mostly based on primary scientific literature, i.e. you will read a research paper. To deepen your understanding, you will also conduct online research to update certain figures or data presented in the paper with the most recent developments. This script contains questions that you must answer to prepare for our lab meeting. You don't need to learn any numbers or answers by heart, but can just bring and use notes. The paper is titled "What drives the profitability of household PV investments, self-consumption, and self-sufficiency?", written by Valentin Bertsch, Jutta Geldermann and Tobias Lühn and published in 2017 in Applied Energy 204, 1–17: `https://doi.org/10.1016/j.apenergy.2017.06.055`.

- In the first part of the experiment, you will be provided with Shelly Plugs to measure the electricity consumption of various household appliances. This task must be completed at home prior to our lab session, and you are expected to bring the collected data with you. **Note:** This step is only mandatory for students preparing a report or a presentation. However, all interested students can get a Shelly Plug if they wish.

- In the second part of the experiment, we will use a web-based simulation model to simulate the operation of a household energy system with different system designs, e.g. PV and battery capacities, and operating strategies. This will be a fully digital experiment. It will be carried out in our lab meeting. It is available online at `https://ee-fachlabor.streamlit.app/`. **Note:** We will provide laptops to access to the app during our lab meeting. However, for students preparing a report or presentation it will be useful to carry out the experiment on their own laptop to immediately download and save the data needed for the evaluation. Therefore you are welcome to bring and use your own laptop.

Without further ado, let's get started!

# 2 Background – Working with the research paper

To learn about the motivation and policy background, read the sections **1. Introduction** and **2. Renewable policy background and related work** of the paper. To prepare for the lab meeting, answer the following questions:

- What are Germany's current decarbonisation and renewable targets for the power sector? *Hint:* You may for instance refer to the "Easter Package"[1].

[1] An overview is available at `https://www.bmwk.de/Redaktion/EN/Downloads/Energy/0406_ueberblickspapier_osterpaket_en.html`.

- What is a feed-in tariff (FIT) scheme and how does it work?

To learn more about specific data of household PV installations and battery storage systems, read section **3. Data** of the paper. To prepare for the lab meeting, answer the following questions by researching (updated) data:

- What is the annual electricity demand of German households? *Hint:* Average consumption per household and overall consumption of all German households are published by DESTATIS[2].
- What is the costs of installing household PV and battery systems? *Hint:* See e.g. `https://www.energie-experten.org/erneuerbare-energien/photovoltaik/photovoltaikanlage/kosten`)
- What are current average electricity prices and price components for household end-consumers in Germany? *Hint:* This information can for instance be accessed at `https://strom-report.com/strompreise/strompreis-zusammensetzung/` in German.
- Beyond these static (i.e. constant over time) electricity prices that end-consumer typically see, there is a wholesale market with hourly prices. How large are the fluctuations of hourly wholesale electricity prices in Germany? Can you identify any patterns? *Hint:* This data is provided at `https://www.agora-energiewende.de/daten-tools/agorameter/chart/today/power_price_emission/01.01.2023/31.12.2023/hourly` for the year 2023 by Agora Energiewende. Alternatively, it is also provided by Bundesnetzagentur | SMARD.de[3]
- Similar to the hourly electricity prices, the German electricity generation mix and thus its emission factor varies with time. How large are the fluctuations of hourly emission factors of the German electricity mix? Can you identify any patterns? *Hint:* You may also use the Agorameter[4])
- What is the current PV feed-in tariff in Germany for small household-PV systems below 100 kW? *Hint:* This information is provided by Bundesnetzagentur[5] in German.

Then, read the section **4. Simulation model** of the paper to understand how this data is used to study the profitability of household PV and storage systems. You only need to read this section until the paragraph starting with "For the economic assessment, ..." at the bottom of page 6. From that point onward, the remainder of the section addresses how profitability is measured in terms of internal rates of return (IRRs). The IRR[6] is a concept to a assess the profitability of investments with a lifetime of multiple years while taking into account the time value of money. We will not use the IRR concept in this lab. Instead, we will work with costs

[2] `https://www.destatis.de/EN/Themes/Society-Environment/Environment/Environmental-Economic-Accounting/private-households/Tables/electricity-consumption-private-households.html?nn=475374`

[3] For instance, at `https://www.smard.de/en` under "Data download" by selecting Main category: Market – Data category: Day-ahead prices – Bidding zone: DE/LU. Visualisations are available from the same website, but under Market data visuals – Market – Day-ahead prices.

[4] Hourly emission factors for the year 2023 can be accessed at `https://www.agora-energiewende.de/daten-tools/agorameter/chart/today/power_price_emission/01.01.2023/31.12.2023/hourly` by Agora Energiewende.

[5] `https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/ErneuerbareEnergien/EEG_Foerderung/start.html`

[6] See e.g. `https://en.wikipedia.org/wiki/Internal_rate_of_return` and `https://en.wikipedia.org/wiki/Time_value_of_money`.

and revenues arising in a short time span. To understand the results discussed in the following sections of the paper, you must only understand that higher IRRs, e.g. above 0%, may indicate a good profitability, i.e. revenues that exceed the costs. In contrast, low IRRs, e.g. below 0%, may indicate unprofitable investments, i.e. costs that exceed the revenues. To prepare for the lab meeting, answer the following questions:

- What is the meaning of Equation (3) in the paper?
- Are the sizes of the PV system (peak power) and the storage system (storage capacity) input or output parameters of the model?
- Is the state of charge profile of the battery storage a model input or output?
- How does the reference strategy operate? Briefly summarise the operating strategy shown in Table 2 of the paper in your own words.

Note that in the presented strategy, the conditions ruling the storage operation in time step $t$ do only involve the PV generation $P_{\mathrm{PV}}$, the load $P_{\mathrm{Load}}$ and the state of charge SoC in exactly this time step. In particular, further (potentially time-dependent) parameters like the electricity purchase price or the emission factor of grid electricity are not utilised. Therefore, charging and discharging of the battery is done "naively" as early as possible while neglecting that, for instance, later discharging may shift grid purchases to times of lower prices or emissions.

In preparation for the lab meeting, try to **improve the naive strategy** presented in Table 2 of the paper by adding conditions[7] $(<, >, =)$ on the electricity price $\Pi$ and/or the emission factor $E$ in time step $t$. More precisely, come up with two improved strategies:

- One strategy using electricity price information to minimise the operating costs of the system, and
- one strategy using emission factor information to minimise the emissions of the system.

You can for instance formulate these strategies by adding a new column with conditions like "and $\Pi > 90\,\mathrm{EUR/MWh}$". We will use these strategies later for the simulation experiment. The price and emission time series you researched may help you in coming up with these conditions.

**Note:** Often times students come up with strategies that sell stored electricity when prices are high, independently of the PV generation. This is a great idea and large-scale storages actually follow such strategies based on so-called arbitrage. However, households are only allowed to sell (i.e. feed in the grid) PV-generated electricity under the typical regulation. Moreover, they will typically receive the same feed-in tariff at any time, regardless of the current price. Therefore your strategy should focus on optimising purchasing decisions.

Now read the subsections 5.1 and 5.2 of the section **5. Results**. You do not need to read subsection 5.3 and you can also skip the results on self-consumption rates and autonomy rates in Figures 10 and 11. Focusing on the profitability results in Figure 7, answer the following question to prepare for the lab meeting:

- What ratio of storage capacity to PV peak power is the most profitable for a five person household with storage costs of 500 EUR/kWh? How do the optimal peak power and storage capacity relate to the average annual electricity demand of a five person household (cf. Figures 2 and 3)?

[7] The strategies should not contain price or emission information from future time steps $t+1, t+2, \ldots$, as such a perfect foresight is unrealistic or at least comes with considerable uncertainty. Similarly, you should not refer to prices or emission factors from previous time steps $t-1, t-2, \ldots$. Although this is possible in reality, we want to neglect it here for simplicity.

Finally, read the sections **6. Discussion and limitations** and **7. Conclusions and outlook** and answer the following questions to prepare for the lab meeting:

- What are limitations of the paper? Describe one major limitation in your own words.
- What is, in your opinion, the most interesting overall finding of the paper?

# 3 Electricity consumption measurement at home with a Shelly Plug

**Note:** The electricity consumption measurement at home with a Shelly Plug as described in this section 3 is only mandatory for students preparing a report or a presentation. However, all interested students can get a Shelly plug to make measurements at home.

A Shelly Plug is a smart plug used for energy monitoring, remote control and automation. It fits into a standard power socket and can be controlled remotely via Wi-Fi using a smartphone app or home automation system. In this experiment, you will use the Shelly Plug at home for energy consumption monitoring, i.e. to track the energy consumption of home appliances. It will not only measure the overall consumption, but track a temporal profile. To dive deeper into what a Shelly Plug is and how it works, you may take a look at an introductory video or the user guide[8].
This first part of the experiment proceeds as follows:

1. You are given a Shelly Plug at least two weeks prior to our scheduled lab meeting, along with brief usage instructions. The date, time, and location of the meeting to hand out the Shelly Plug devices will be communicated in advance via the moodle course platform.
2. The Shelly Plugs need to be registered to your own (new) Shelly Cloud[9]. account. Instructions on how to do this are given in the user guide, which is available online or in the moodle folder of lab A.
3. Over the course of the following weeks, use the Shelly Plug to measure the electricity consumption of **four** different appliances. Measure three appliances over a **one-day period** each, and one additional appliance for a **full week**. You may choose to monitor individual devices, such as a fridge, kettle, computer, or Wi-Fi router, or a combination of multiple devices, like a power strip at your desk or in your living room.
4. From the Shelly Cloud, download the load profiles of the one-day period appliances. In order to do this, in the Shelly Cloud go to the room that your Shelly Plug is assigned to, then select your Shelly Plug and click on the diagrams icon in the right submenu. In the diagram menu, in the first dropdown menu, you need to select “Day” (English) or “Tag” (German). Only if you select this period, the time series that you will download has the correct resolution of 24 time steps per day. Then you can select individual days. To download the data, scroll down to the button “CSV file export” to export the selected data. After completing your three one-day measurements, download them and arrange each measured time series seven times in a row to create three time series of one week each, using a spreadsheet software like LibreOffice. For the device that you measured one week, consecutively download seven CSV files for the corresponding time (here also set the period to “Day” or “Tag”) and then connect them to one 168 time steps long CSV.

[8] See `https://www.youtube.com/watch?v=_huPdu7paYw` and `https://www.bedienungsanleitu.ng/shelly/plug-s/anleitung`.

[9] See `https://control.shelly.cloud`

The CSV files created by the Shelly App can be handled with any standard spreadsheet software, e.g. LibreOffice.

5. Attend our scheduled lab meeting and bring the recorded data (a total of four time series with 168 hourly consumption measurements each) in CSV format. For the correct formatting of the CSV files, please check the examples on the Streamlit app. We will use the data to customize the electricity demand given in the simulation experiment by adding it onto generic load profiles. Also, if you are preparing a report or presentation, you can upload your own electricity price and emission factor time series.

6. You **must return the Shelly Plug** at the beginning of our lab meeting.

# 4 Storage operation simulation with a web-based app

In this experiment, more precisely in the lab meeting, you will simulate the operation of a battery storage. The simulation tool is provided as a web application based on python and streamlit[10]. It is designed for analysing and visualizing energy flow data for a household PV system with battery storage and available at `https://ee-fachlabor.streamlit.app/`.

## 4.1 How does the simulation app work?

Below is a brief overview of the key components and functionalities of the app. It starts with a figure showing the setup of the simulation with the different system elements and the energy flow between them.

1. PV generation and electricity demand. Users can ...
   - ... upload own data for PV capacity factors (optional). If no files are uploaded, the app uses default data.
   - ... select the capacity of the PV system.
   - ... select one of three available predefined demand profile and/or choose to upload own data containing electricity demand data (e.g. measured data with the Shelly Plug). If desired, the uploaded demand data can be added to the selected profile.
   - ... visualise the data for PV generation and electricity demand.
2. Electricity price and $CO_2$ emissions. Users can ...
   - ... upload own data for electricity prices and $CO_2$ emissions. If no files are uploaded, the app uses default data.
   - ... visualise the data for electricity prices and $CO_2$ emissions
3. Further input data section. Users can ...
   - select a feed-in tariff.
   - select the capacity of the battery.
4. Operating strategy.
   - Users can select one of the following storage **operating strategies**: Reference, No battery, or Custom, as described in the following Section 4.2.

[10] https://streamlit.io/

- If you selected the Custom strategy, you can define your own strategy, e.g. the ones you came up with in the preparation to minimise emissions or costs. The provided strategy is internally submitted as JSON code, therefore your own strategy needs to be in line with the structure of the JSON format. A button to check the integrity of your own strategy, formalized in the JSON format, is available. This check needs to be done after every change of your strategy in order to be able to start the simulation.

5. Simulation.

   - Users can click the "Simulate" button to perform the simulation based on the selected strategy. This simulation is similar, but not identical, to the simulation model described in the paper. All data you uploaded or selections that you made in Steps 1, 2 and 3 are exogenously given to the simulation, i.e. it is fixed. The only degrees of freedom that are decided upon in the simulation are the operation of the storage, i.e. how much energy it (dis)charges in each time step, as well as the electricity purchase from the grid and the electricity feed in to the grid (both also in each time step). This operation is decided following the rules defined by the strategy. The (dis)charging decisions also yield the state of charge profile as a result.

6. Outputs.

   - Temporally resolved simulation results are visualised, in particular time series for state of charge and cost per time step.
   - Aggregated results are shown in a text field as numbers, in particular the overall costs and emissions of the system.
   - You can download the results as a CSV file.

## 4.2 Storage operating strategies

As previously mentioned, the app provides two predefined storage operating strategies to simulate energy balance. The **Reference strategy** incorporates a battery, while the **No battery strategy** serves as a comparison without any storage. In both strategies, the household's electricity demand must always be satisfied. When in any time step, electricity generation from the PV system exceeds consumption, an energy surplus occurs, and when energy generation falls short of consumption, an energy shortage arises. The core distinction between the two strategies lies in how they manage these surpluses and shortages.

**Table 1:** The No-battery operating strategy.

| Conditions | Consequence |
|---|---|
| $P_{\text{PV}} > P_{\text{Load}}$ | $P_{\text{Feed-in},t} = P_{\text{PV},t} - P_{\text{Load},t}$ |
| $P_{\text{PV}} \leq P_{\text{Load}}$ | $P_{\text{Purchase},t} = P_{\text{PV},t} - P_{\text{Load},t}$ |

In the No battery strategy, any energy surplus is fed into the grid and any energy shortage must be covered by purchasing electricity from the grid (cf. Table 1). In the Reference strategy, any energy surplus is used to immediately charge the battery, if it is not already full. Excess electricity that cannot be used to charge the battery is fed into the grid. Similarly, any energy shortage is covered immediately by discharging the battery, if it is not already empty. Energy demand that cannot be met by either the PV generation or by discharging the battery are compensated by electricity purchases from the grid (cf. Table 2).

**Table 2:** Reference operating strategy as described by Bertsch et al. (2017), Table 2 therein.

| Conditions | | | Consequence | | |
|---|---|---|---|---|---|
| $P_{\text{PV}} > P_{\text{Load}}$ | and | SoC $< 1$ | then | $P_{\text{Charge},t} = P_{\text{PV},t} - P_{\text{Load},t}$<br>$P_{\text{Discharge},t} = 0$ | and | $P_{\text{Feed-in},t} = 0$<br>$P_{\text{Purchase},t} = 0$ |
| | | SoC $= 1$ | | $P_{\text{Charge},t} = 0$<br>$P_{\text{Discharge},t} = 0$ | | $P_{\text{Feed-in},t} = P_{\text{PV},t} - P_{\text{Load},t}$<br>$P_{\text{Purchase},t} = 0$ |
| $P_{\text{PV}} \leq P_{\text{Load}}$ | | SoC $> 0$ | | $P_{\text{Charge},t} = 0$<br>$P_{\text{Discharge},t} = P_{\text{PV},t} - P_{\text{Load},t}$ | | $P_{\text{Feed-in},t} = 0$<br>$P_{\text{Purchase},t} = 0$ |
| | | SoC $= 0$ | | $P_{\text{Charge},t} = 0$<br>$P_{\text{Discharge},t} = 0$ | | $P_{\text{Feed-in},t} = 0$<br>$P_{\text{Purchase},t} = P_{\text{PV},t} - P_{\text{Load},t}$ |

## 4.3 Experimental procedure

We will start our lab meeting by checking that everyone has prepared (read this script, answered the questions and did the data research). You don't have to learn the answers and data by heart for our meeting – you can prepare, bring and use notes! Then, we will go through the simulation app together and discuss how it works. At this point, we will also finalise the experimental setup:

- Select default PV profile
- Select appropriate PV capacity (this will vary throughout the experiment as described below)
- Choose demand profile 1 (five person household)
- Use own load profiles, upload your consumption time series measured at home
- Use defaults for taxes and fees and grid fees
- Select "Apply additional costs."
- Use default time series for electricity price and $CO_2$ emissions
- Use default feed-in tariff
- Select appropriate capacity of the battery (this will also vary throughout the experiment as described below)
- Select appropriate operating strategy (this will also vary throughout the experiment and require that you enter your own "Custom" strategies as described below). You always need to check the syntax of the strategy before you can proceed to the simulation.

To answer the two overarching research questions raised in the introduction, you will then carry out two types of simulation experiments. Make sure to **always export and save the results** appropriately if you are preparing a report or presentation! This includes the *STRATEGY*_results_*CAPACITIES*.csv containing all result time series and important input data as well as the applied_os.json file containing the operating strategy you are using.

### 4.3.1 Series of simulations 1 – Storage operation strategies

In the first round of experiments, carry out simulations for four different operation strategies. Start with simulations of the No storage and the "naive" Reference strategies that are already implemented in the app and described above. Then simulate the operation with your own two strategies that use the price and emission information to minimise costs and emission, respectively. Use the default PV and storage capacities of X kW and Y kWh for all these simulations.

### 4.3.2 Series of simulations 2 – System design optimisation

In the second round of experiments, vary the installed capacities of the PV and storage systems while always using the same operation strategy that minimises costs. Carry out simulations for all nine parameter combinations of PV capacities of 3, 6 and 9 kW and storage capacities of 3, 6 and 9 kWh.

# 5 Evaluation Tasks

If (and only if) you are preparing a report or a presentation, complete the following tasks at home. Tasks 1.1 and 1.2 relate to the first series of simulations and the first research question. Tasks 2.1 and 2.2. relate to the second research question and the second series of simulations.

**Series of simulations 1 – Storage operation strategies**

1.1 The first task is dedicated to the overall performance of the four operating strategies. Analyse and discuss in how far adding a storage or utilising the price or emission information improves the costs and emission of the energy supply!

    Compute the overall costs and $CO_2$ emissions resulting from each of the four strategies (No battery, Reference and your own two strategies minimising costs and emission, respectively). Build your discussion on the overall costs and emissions you computed and refer to them explicitly.

1.2 The second task is dedicated to temporal operation profiles. Analyse and discuss in what hours the operations under the four different strategies differ from each other! It is sufficient to make three pair-wise comparisons: (i) No battery vs Reference strategy, (ii) Reference vs cost-minimising strategy and (iii) Reference vs emission-minimising strategy. In particular, analyse and discuss how your own strategies achieve cost or emission reductions as compared to the reference strategy!

    Build your discussions on plots of simulated operational profiles. These plots should show time on the x-axis and results of your choice on the y-axis. It might make sense to include model results on the storage operation, e.g. the state of charge, as well as model input data, e.g. the electricity price or emission factor, in these plots. You should make one plot for each of the three pair-wise comparisons (i) to (iii).

**Series of simulations 2 – System design optimisation**

2.1 This task is dedicated to the overall performance of the different PV and storage sizes in terms of costs. Analyse and discuss the optimal sizing of the PV and battery systems! Moreover, relate the optimal PV and battery capacities to each other, and also to the demand, for instance the peak load. Compare these relations to the results of the paper shown in Figure 7.

Compute the overall costs resulting from the nine different parameter combinations. In this task, you must take into account that not only the operating costs, but also the investment costs differ between the system designs. Consider a share of 0.1% of the total PV and storage investment costs in addition to the operating costs resulting from the simulation model. This small share accounts for the fact that the PV and storage system can be used for many years while the operating costs from the simulation model are for one week. Use the investment costs for PV and batteries you researched in preparation for the lab meeting.

Plot the overall costs you computed in a heat map, i.e. the PV capacity on the y-axis, the storage capacity on the x-axis and indicate the costs with colour. Build your discussion on these results and explicitly refer to them.

2.2 Similar to Task 1.2, this task is dedicated to temporal operation profiles. Analyse and discuss in what hours the operations under different system designs differ from each other! It is sufficient to make two pair-wise comparisons: (i) Lowest vs highest PV capacity (3 vs 9 kW) under the medium storage capacity of 6 kWh, and (ii) lowest vs highest storage capacity (3 vs 9 kWh) under the medium PV capacity of 6 kW. In particular, analyse and discuss how the different system designs enable or prevent cost reductions.

Build your discussions on plots of simulated operational profiles. These plots should show time on the x-axis and results of your choice on the y-axis. It might make sense to include model results on the storage operaion, e.g. the state of charge, as well as model input data, e.g. the electricity price, in these plots. You should make one plot for each of the two pair-wise comparisons (i) and (ii)..

## Conclusion

3.1 Discuss two limitations of the simulation model and how they affect your findings!

3.2 To conclude, answer the two overarching research questions raised in the introduction!

With your report or presentation, hand in the original, unmodified data and strategy files you downloaded (*STRATEGY*_results_*CAPACITIES*.csv and applied_os.json) as well as your calculations, e.g. a python, matlab or excel file.