ECONOMIC OPTIMIZATION OF PV SYSTEMS WITH STORAGE

André Mermoud, Adrien Villoz, Bruno Wittmer, Hizir Apaydin
PVsyst SA
Route de la Maison-Carrée 30, CH 1242 Satigny, Switzerland

ABSTRACT: Financial profitability analysis is a substantial preliminary study topic and a key decision criterion when designing and building a PV system. In this context, energy storage has increased the capability for maximizing the energy self-consumption and the profitability of PV systems, but it has also complexified the optimization strategies. Battery storage in a PV system allows to displace the usage of the solar generated power to times where consumption is needed. However, the sizing of the optimal system depends on many factors, such as meteorological data, load profile, battery size and price, feed-in tariffs, etc. PVsyst is a simulation software used to model PV systems, from small residential size up to large utilities. The new economic evaluation tool included in the software allows to perform a detailed analysis, producing key financial indicators such as the Levelized Cost of Energy (LCOE), payback time and return on investment (ROI). The aim of this study is to establish a methodology for the optimization of PV systems with self-consumption and storage. The optimization of several economic variables, based on parametric simulations, will be presented. We will also show a simple way to estimate the optimal sizing using the results of a single simulation.
Keywords: Simulation, Software, Storage, Grid-Connected, Performance, Sizing, Modelling

1 INTRODUCTION

PV installations with storage are more difficult to plan and design than bare PV plants, because the question arises which battery size is best fit for the requirements of the system. The answer to this question depends on several aspects, the first being the global purpose of the storage. Is it meant to level the injection power of a large PV plant? Is it supposed to optimize self-consumption for a residential or commercial consumer? Should it provide backup power in case of a grid outage? The storage can also provide ancillary services to the grid or take care of peak shaving on the consumer side. All these scenarios lead to a different use of the battery capacity and to different kinds of optimization approaches.

In this study we will focus on storage in the context of self-consumption. This means that the primary goal of the PV plant together with the battery storage, will be to supply a load according to a given profile. We will describe a general approach to optimize the size of the PV plant and the storage capacity.

The examples shown here, use typical residential load profiles, for a few different locations and climates. This will not change the general way of optimizing the sizing. All considerations here apply equally to any other kind of load profile or climate, allowing to get the optimal sizing in any given conditions.

The optimization of the sizing can be performed on a pure technical level, by defining a fraction of desired self-consumption, and determining the PV and battery capacity for which this threshold is reached. This will not always lead to viable systems, because the costs and benefits must be considered, to make sure that the system is not losing money over its lifetime. In fact, in presence of a grid connection, the level of self-consumption is a rather artificial criterion, that depends only on personal considerations. If however a full financial balance is performed, taking into account electricity tariffs together with installation and operation costs, we can confine the sizing to values where the system remains profitable, and even determine the system size where maximal profit is reached.

We used the PVsyst software, that allows to perform simulations of PV systems including battery storage, and that provides detailed hourly simulation results that were used as input for our analysis. The software also includes a tool to perform a financial evaluation and the output includes these economic variables.

2 APPROACH

We will start by looking at the economic analysis based on individual simulation results. A set of simulations has been performed where the PV system and battery size were varied. For each simulation, a set of economic variables is calculated. This allows to find an optimal sizing for the PV and battery capacity by minimizing or maximizing these variables. To understand the impact of the financial input variables, namely PV and battery prices, as well as consumption and feed-in tariffs, we break down the analysis into three steps, as depicted in Figure 1.

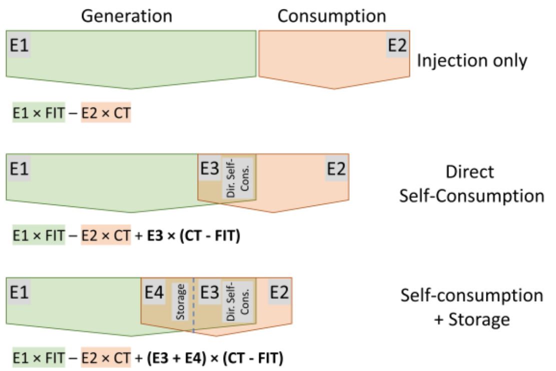

Figure 1: Revenue balance for the three scenarios described in this work. Self-consumption leads to net savings in the grid exchange.

First, we have a look at a PV system without storage, where generation and consumption are completely independent. There is no optimal size for this kind of system, the only two distinct cases are profitable and a non-profitable system. This distinction is given by the ratio of LCOE and FIT.

When we add direct self-consumption to the system, a part of the generated power will be used to supply the load, and thus reduce the electricity bill. At the same time, less energy will be sold to the grid, but since the FIT is lower than the CT, there will always be a net benefit, which can turn a non-profitable PV system into a profitable one. This dynamic is driven by the ratio of self-consumption that can be achieved and the difference between CT and FIT. As we will see, there can be an optimal PV system size, where either NPV or ROI are maximized.

Finally, when adding storage to the system, the two previous considerations will not change, but there will be an additional amount of self-consumed power generation, that will depend on the installed PV and battery capacity. The optimal battery size is found by balancing this additional self-consumption with the costs of the battery.

The basic quantities that are driving this optimization processes, are the fractions of self-consumption E3 and E4, which are functions of the PV and battery capacity. We will show how these curves can be estimated from a single simulation. This estimation is quite straightforward for the direct self-consumption and more approximate for the self-consumption coming from the battery storage. The aim of this part of the analysis is to devise a simple tool that can efficiently guide the designer of the PV installation towards an optimized sizing of the system.

3 STUDIED SYSTEM

For this study, we based the simulations on a typical residential system with a plane orientation of 0° azimuth and 30° tilt, which is a common roof tilt for houses in the considered latitudes. This system was simulated in PVsyst, using generic components, default losses values and no shading scene. Three variants of the system were simulated:

The first variant is the basic PV system where all energy produced is injected into the grid with no self-consumption.

The second variant is the direct self-consumption case where a load profile must be specified. The PV generation is used to supply the load, and the excess generation is injected into the grid.

The third variant adds energy storage in form of a battery using the self-consumption strategy. This strategy maximizes the self-consumption by prioritizing the user's needs: energy from PV is first used to supply the load, then to charge the battery. The remaining excess is injected into the grid. With this storage strategy, no injection to the grid is coming from the battery.

The load profiles considered here are from two sources. The reference residential load profile used for the simulation in Geneva comes from the BDEW [1]. For the US, the load profiles compared are available on OpenEI [2].

4 ECONOMIC ANALYSIS

4.1 Input parameters

Table I summarizes the economic parameters that were used in this study. The PV system costs are directly proportional to the PV capacity, and include costs for PV modules, supports, inverters, installation, wires, etc. They only describe the part of the cost that scale with system size. Similarly, the battery costs are considered directly proportional to the battery capacity. The overhead costs contain the part of the costs that do not depend on the system size and are constant for each simulation, like for example permits or planning costs.

Table I: Economic input parameters for examples

Parameter	Value	
PV System costs	1250	Euro/kWp
Storage costs	250	Euro/kWh
Overhead costs	6000	Euro (5-25 kWp)
Feed-In Tariff (FIT)	0.025	Euro/kWh
Consumption Tariff (CT)	0.23	Euro/kWh
System lifetime	20	years

The feed-in tariff (FIT) is the price at which the energy is sold to the grid, while the consumption tariff (CT) is the price at which power is purchased. In our examples both tariffs are fixed values that do not depend on the time of the day or the seasons. This is done for simplicity and does not change the general way the analysis is performed.

The parameter values here are chosen to exemplify the approach taken in this analysis. They do not reflect any market survey or real-life example but should not be too far away from realistic values. The general approach described here, is meant to show how the economic analysis of a self-consumption storage system can be broken down to a few elementary considerations in order to make it easier to find the optimum sizing. This does not depend on the specific values for these parameters, but of course the results and conclusions on the profitability and optimal system size do not have general character. If the economic parameters change, the analysis must be performed again. In the following discussion we will however mention when certain values of a parameter can lead to qualitatively different behavior in the results.

4.2 Output variables

The PVsyst simulation calculates several output variables in its economic evaluation. In this analysis we use the following ones:

- LCOE - Levelized Cost of Energy is the ratio between all costs and the generated energy.
- NPV - Net Present Value is the difference between all revenues and all costs.
- ROI - Return Of Investment is the ratio between all revenues and all costs.
- Payback period - This is the time it takes to exactly balance costs and revenues, corresponding to the time when the NPV becomes zero.

The LCOE, NPV and ROI are functions of time. In this analysis, we will always calculate these values for the system lifetime, which is assumed to be 20 years.

4.3 Independent generation

If the generation is independent from the consumption, the LCOE must be lower than the FIT for the PV installation to be profitable. Figure 2 shows the LCOE as function of the installed PV capacity as obtained from different simulations, where the colors represent different DC/AC ratios.

The LCOE drops with the PV capacity due to the constant overhead costs. It never reaches the FIT given by the horizontal line, meaning that for the parameters in this example the pure generation and injection of PV power will never be profitable.

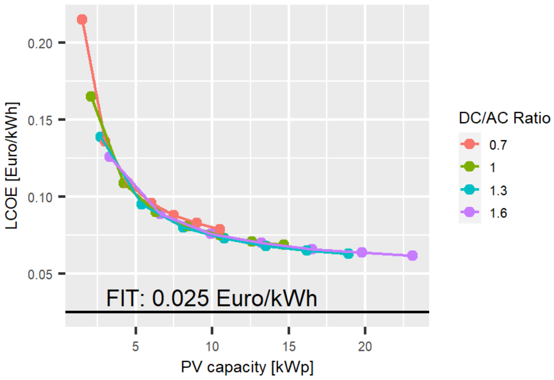

Figure 2: LCOE for the system without storage. In this example the LCOE is larger than the FIT.

This can also be seen when plotting the NPV as function of PV capacity as shown in Figure 3. It is always negative, meaning that there is no simulation with a net profit. The horizontal line in the plot represents the overhead costs, which corresponds to the intercept of these lines with the y-axis.

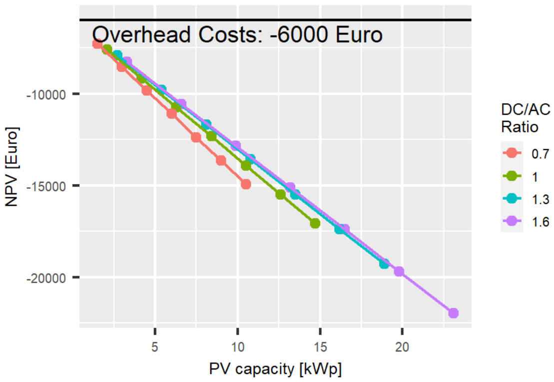

Figure 3: NPV for the bare injection scenario, for which the system is not profitable.

4.4 Self-consumption

The LCOE for the systems with self-consumption is the same as for independent generation. The NPV however displays a quite different behavior as shown in Figure 4. The PV capacity in this graph has been normalized to the yearly consumption, in order to make the curves more general.

When looking at these values, one can see that there is a point where the benefits reach a maximum. The location of this point depends on the DC/AC ratio. In this example the NPV gets maximized at a DC/AC ratio between 1.3 and 1.4, and a PV system size between 0.6 and 0.7 kWp/kWh. This curve is specific to the location and the chosen load profile, and it shows how self-consumption can make an installation profitable, which would lose money on the long term if it would only sell the generated power to the grid. When the NPV curves drop below zero, which happens for large PV capacities, the system is not profitable anymore. The savings coming from the self-consumption do not compensate anymore the non-profitability coming from the low FIT.

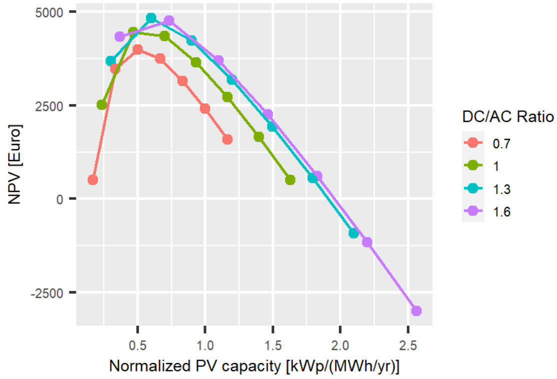

Figure 4: NPV for the system with direct self-consumption. The system has become profitable and the NPV is maximized for a given capacity.

A slightly different picture arises, if instead of optimizing the NPV, we attempt to maximize the ROI, which is shown in Figure 5.As can be seen, the highest rates of return are achieved with relatively small systems and a high DC/AC ratio. Again, if the ROI drops below zero, we get the systems that will not be profitable over the lifetime of 20 years.

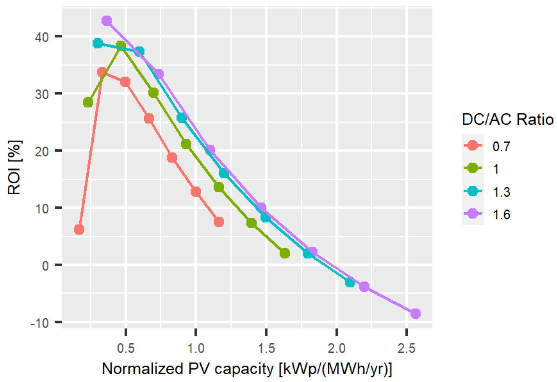

Figure 5: ROI for the system with direct self-consumption.

4.5 Self-consumption with storage

Adding a battery to the system will not change the direct self-consumption, however, the battery will make an additional part of the generation available to self-consumption. For a given location and load profile, this additional fraction will depend on the battery capacity as well as on the size of the PV system. The PV capacity will determine how much over-production will be available for storage, and the battery capacity determines how much of this over-production can effectively be transferred to time periods with little generation and high load.

After varying these two parameters, running the simulation and calculating the financial balance, we obtain the curves in Figure 6 for the NPV. The optimal system size for this specific example is a PV array of 10 kWp/(MWh/yr) with a battery capacity around 1.4 kWh/(MWh/yr). It needs to be stressed, that this is not a general result, but will depend on the location, load profile, system costs and tariffs. The point here, is to show that there can be situations where the optimal system size is not straightforward to choose and needs to be determined from this kind of graphs.

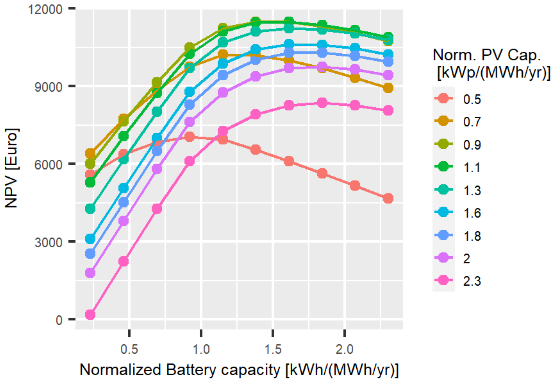

Figure 6: NPV for self-consumption with storage, calculated with individual simulations.

It is perfectly possible that there is no local maximum in these curves. If for example the battery costs were considerably higher than the 250 Euro/kWh assumed for this study, a battery would never be profitable, and the NPV would be maximized for zero battery capacity. Another example would be if the FIT would be higher than the LCOE calculated for the independent injection. In this case the PV capacity would have no local maximum and the NPV would be maximized for the largest PV system possible.

If we maximize the ROI instead of the NPV, the curves do again slightly change (Figure 7). We can see that for this kind of optimization a smaller PV system with less storage capacity is favored. The reason for this is, that other than the NPV, which is the absolute difference of benefits and costs, the ROI is the ratio of these two values. For a smaller system, a larger fraction of the PV capacity contributes to self-consumption and there will be a smaller fraction of excess generation that is injected into the grid at an unfavorable tariff.

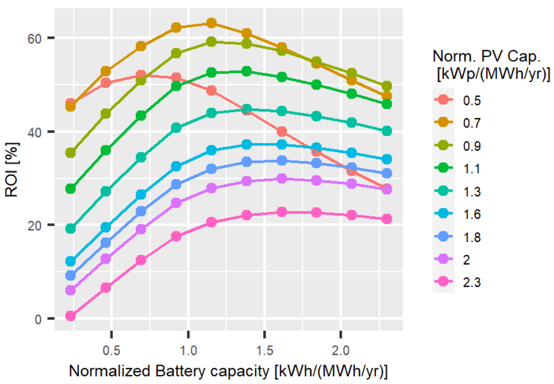

Figure 7: ROI for self-consumption with storage, calculated with individual simulations.

5 ESTIMATIONS FROM SINGLE SIMULATION

The analysis and graphs in the previous sections were based on a set of simulations where the PV and battery capacity were varied. Depending on the system size and the detail of simulation, this can be time-consuming and make the search of the optimal system size inefficient.

In this section we will show that a reasonable estimation of the optimal system size can already be made, based on the results of a single simulation. The idea is to obtain the fractions of direct and storage-enabled self-consumption as function of PV and battery capacity.

Once these curves are known, the impact on the financial balance is quickly calculated.

5.1 Self-consumption as function of PV capacity

The power generation of a PV system is typically proportional to the installed PV capacity. If the hourly values of the PV generation for an entire year have been calculated in a simulation, we can easily re-scale these values to obtain the generation for a different PV capacity. This is an approximation because it neglects non-linear effects like clipping or ohmic losses in cables. Then we can compare the hourly generation values with the hourly load and determine the fraction of the load that can be covered by self-consumption. Also, this is an approximation, because there can be sub-hourly fluctuations in the generation as well as in the load, which are not in phase.

By summing up these calculated values we get an estimation of the fraction of direct self-consumption for the entire year. We can therefore obtain this fraction as function of the PV capacity from a single simulation.

Figure 8 shows the estimated self-consumption as a solid curve, with the overlaid points being the result of individual simulations. The red horizontal line is the theoretical maximum for the direct self-consumption. It represents the load that occurs during daylight hours and that can thus be directly covered by PV generation. The scattering of the points around the curve comes from the fact that the simulations do not all have the same DC/AC ratio, which leads to non-linear clipping losses as explained before.

We can see that the curve passes very well through the individual simulation results, and that this is a good way of estimating the self-consumption ratio.

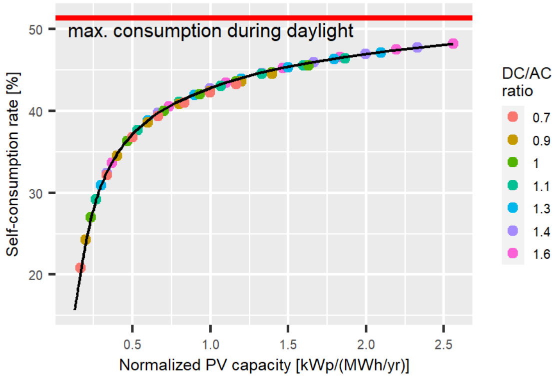

Figure 8: Fraction of direct self-consumption. Points are individual simulations, the solid line is the estimation from a single simulation.

5.2 Different load profiles in different climates

To get an idea of the effect of different load profiles and climates, we simulated the same system with specific residential load profiles from multiple places in the US (ref) with the corresponding meteo data (NSRDB), and compared it to the reference defined in Geneva (Figure 8). All the sites with their characteristics are resumed in Table II.

Table II: Sites with local load profiles used in the examples. (AC: Air Conditioning)

Site	GHI kWh/m^2/y	Load MWh/y	Climate	AC
Roswell	2095	9.7	Semi-arid	×
Geneva	1293	9	Temperate	
Dallas	1846	16.5	Humid subtropical	×
Seattle	1220	7.8	Temperate	

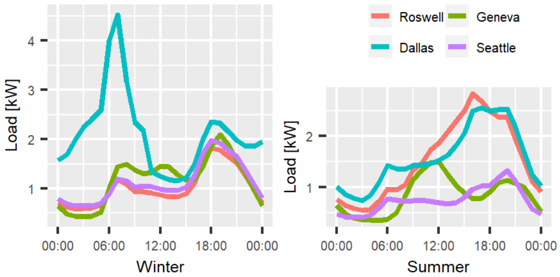

Figure 9: Typical winter and summer day for the load profiles used in the examples.

The total consumption of the selected sites are different from the reference 9MWh analyzed in Geneva as shown in the table, but this has no impact on the curves, since we normalize the PV capacity to the annual consumption to a normalized capacity in [kWp / MWh]. The global irradiation of the sites ranges from 1200 to 2100 kWh/m2/y.

As seen in Figure 10, there is a wide range of self-consumption ratios for different climates and profiles. This observation tells us that the sizing of a residential system to maximize the self-consumption will be highly dependent on the load profile and place. The next comparison between cities in the US shows the impact of air-conditioning in the load profile. The places where there is a high need of cooling during the day have a higher maximum self-consumption ratio from PV, and at the same time a higher global irradiation. This counteracted for Dallas that has a high consumption for electric heating in the morning on winter days, lowering the daytime self-consumption possible.

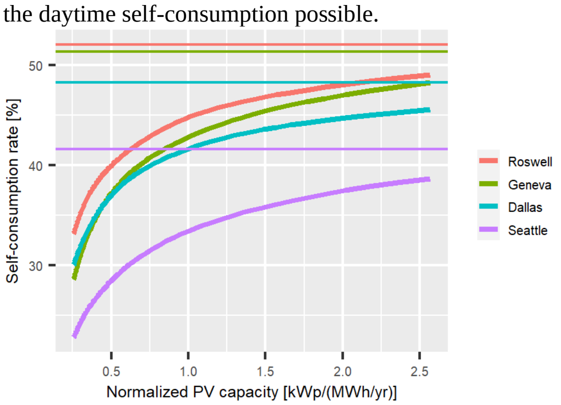

Figure 10: Fraction of direct self-consumption, estimated for each site from a single simulation.

5.3 Comparison of estimation with individual simulations

Once we have an estimate for the rate of self-consumption as fraction of PV capacity, it becomes possible to also estimate the variables of the economic calculation. As explained in the first section, the additional value coming from self-consumption, is the amount of self-consumption multiplied by the difference between consumption tariff and feed-in tariff (see Figure 1.).

Adding this value to the NPV of the simple PV installation leads to the blue curve in Figure 11.

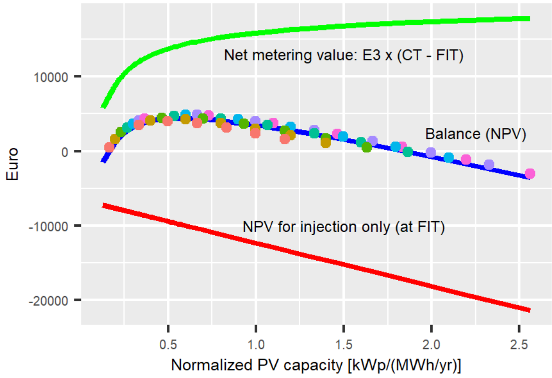

Figure 11: Estimated NPV for self-consumption

Again, the solid curve represents the calculated estimation, while the points are the results from individual simulations. We see that the estimation describes quite well the behavior. The points scatter around the curves because the estimation of the system costs is simplified. It assumes a pricing that goes linear with PV capacity, but when changing the PV capacity, the number of PV modules and inverters change in steps, leading to non-linear system costs.

If the PV injection would be profitable from the beginning, the red curve would have a positive slope, and the NPV would always increase, becoming maximal at the highest PV capacity.

5.4 Self-consumption increase with storage

It is also possible to estimate the increase of self-consumption due to storage, starting from a single simulation of the bare PV system, and using again the information in the hourly load profile. This estimate is now done as a function of two parameters, namely the PV and battery capacity.

In a first step, we calculate as before the amount of direct self-consumption for a given PV capacity, by re-scaling the PV generation and comparing the hourly values to the load as explained before. From this we get hourly values for the excess PV generation and the missing load. These two values, together with the battery capacity, will determine how much energy can be transferred from hours of excess generation to hours of missing load.

As a simple approximation, we will assume that the battery operates in daily cycles and aggregate the hourly values into daily sums. Then we estimate the transferred energy as the minimum of the excess generation, the missing load, and the battery capacity. This value will be interpreted as the additional amount of self-consumption coming from storage.

The result is shown in Figure 12, where the solid curves are the estimated values and the points the values obtained from individual simulations. The different colors code different PV capacities.

As can be seen, the curves describe the qualitative behavior of the simulated values. The curves become flat for high battery capacity, because in the calculation we considered only energy transfer within a single day. The simulation values keep increasing with battery capacity, because the energy can be stored for longer than 24 h and transferred more than a single day.

The simple calculation does also not account for the battery losses, which leads to an additional discrepancy between curves and points. This could probably be improved by estimating a value for the losses during the charging and discharging of the batteries.

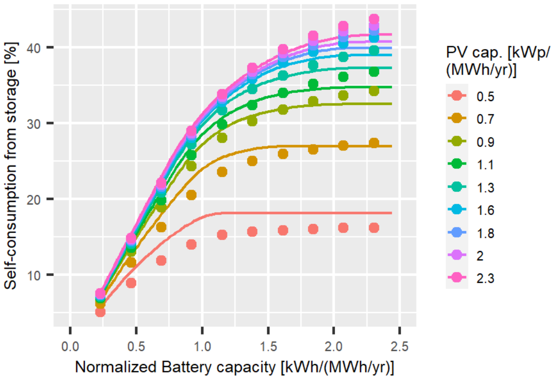

Figure 12: Fraction of storage self-consumption. Points are individual simulations, and solid lines are the estimation from a single simulation.

5.5 Economic estimations and comparison to detailed simulations

The additional value coming from the storage is the amount of self-consumption enabled by the battery, multiplied with the difference between consumption and feed-in tariff (E4 x (CT-FIT) in Figure 1). This must be balanced by the costs of the battery, which we assume to increase linearly with capacity.

If we add these values to the NPV that was estimated for system with direct self-consumption, we will get the graph shown in Figure 13. The PV and battery capacity are the values on x- and y-axis respectively, while the color shows the NPV. The optimal system sizing for the example system in Geneva from this graph, is a PV capacity of 1.0 kWp/(MWh/yr) and a battery of 1.42 kWh/(MWh/yr). This corresponds quite well to the optimization obtained from the series of single simulations in Figure 6. The advantage of this approach is that the plot with its 10^4 data points was generated in a few seconds, starting from the hourly data of a single simulation, whereas the 49 simulations in the batch optimization took several minutes to compute. The increase in speed is bought at the price of losing some accuracy. In a real-life optimization process, one would therefore use this approach to narrow in the range of PV and battery capacity, and then perform the final optimization by comparing results of individual simulations.

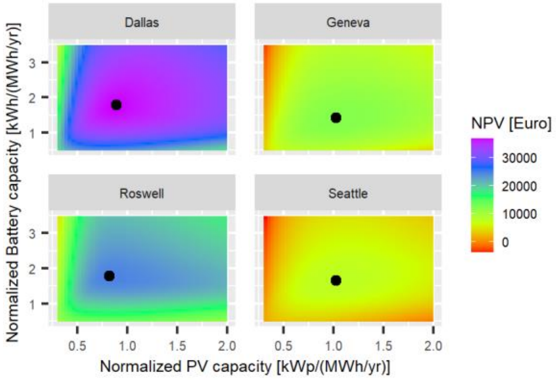

Figure 13: NPV optimization for PV and battery capacity, based on estimation of single simulation.

6 CONCLUSION AND OUTLOOK

In this work we have shown a general way to optimize the sizing of a PV system with storage and self-consumption. The criteria for optimization were the maximization of either the net present value (NPV) or the return of investment (ROI). To understand the impact that self-consumption and storage have on the economic variables, we broke down the analysis into three steps. First, we considered the bare generation and selling of energy to the grid, to which we added then the contribution of direct self-consumption. After this, we finally examined how adding battery storage to the system influences the economic variables.

The key to understanding these economics, are the curves describing the amount of self-consumption as function of the PV and battery capacity. We then showed, that for a given yearly load profile, these curves can be estimated from a single simulation. The optimal sizing obtained from this approximation corresponds to the detailed search of the optimum by performing many individual simulations.

The insights obtained in this study will be used to implement tools in the PVsyst software that will guide the user efficiently when optimizing a PV system with storage.

8 REFERENCES

[1] European residential load profiles - BDEW, Standardlastprofile Strom: https://www.bdew.de/energie/standardlastprofilestrom/

[2] US residential load profiles, from the US DoE, maintained by the NREL for locations of the historical TMY3 ground stations: https://openei.org/datasets/dataset/commercial-and-residential-hourly-load-profiles-for-all-tmy3-locations-in-the-united-states