SIMULATION OF GRID-TIED PV SYSTEMS WITH BATTERY STORAGE IN PVSYST

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ABSTRACT: Grid-tied PV systems with battery storage have become a common view in many countries, not only for small residential PV systems, but also for commercial and utility scale installations. The battery storage in a PV system allows to displace the usage of the solar generated power to times where consumption or injection is needed or possible.
The correct sizing of the PV and storage capacity for these systems is challenging, and depend on climatic factors, geographical location and power dispatch strategy. An accurate simulation of the system over one full year allows to make good design choices and check them under varying conditions.
PVsyst is a simulation software that allows to model PV systems, from small residential size up to large utilities. Since end of 2018, the PVsyst software has implemented the possibility to model Grid-tied PV systems with battery storage. Three different dispatch strategies have been foreseen, namely peak shaving, maximizing self-consumption and weak grid support.
After briefly discussing the approaches used for modeling these systems, simulation results are presented for all three strategies at different operating conditions. It is shown how the sizing of the PV array and the battery impact on the system performance. General conclusions are presented, as well as individual aspects that need special care, to achieve an optimal battery and PV sizing.
Keywords: Simulation, Software, Storage, Grid-Connected, Performance, Sizing, Modelling

1 INTRODUCTION

Falling battery prices have made PV systems with battery storage more and more economically viable. To optimize the levelized cost of electricity (LCOE) and levelized cost of storage (LCOS), it is important to study in advance the behavior of these installation, in order to size correctly the system. The PVsyst simulation tool allows, since long, the simulation of grid-connected PV systems and of stand-alone PV systems with battery storage. The two separate tools have now been merged and allow a realistic simulation of grid-connected PV systems with storage, in hourly steps over one whole year.

2 BATTERY MODEL AND DISPATCH STRATEGIES

The simulation of grid-connected systems with PVsyst is well established and widely used. The challenge of adding battery storage to the simulation comes from the fact that different dispatch strategies are possible, depending on the system owner goals. In the current tool, three distinct dispatch strategies can be selected: peak shaving, self-consumption and weak grid islanding. Each of the dispatch strategies can be simulated over a whole year in hourly steps. During the design phase, hints and rules are provided in order to help with the correct sizing of the PV array and the battery capacity. In the following a short description of the implemented battery models are given, followed by an overview of the three dispatch strategies.

2.1 Battery Model

PVsyst implements models for Li-Ion and lead-acid batteries. These models describe the battery behavior as function of charge and discharge rate, temperature and depth of discharge. The modeled properties are state of charge (SOC), battery voltage, losses and ageing (State of Wear SOW). This detailed model is mainly important to determine the battery ageing. The interaction of the battery with the rest of the system (PV generation, grid and load profile) is only dependent of the SOC. Therefore, the main behavior of a PV system with storage will not depend much on the battery technology. Only the battery losses and the ageing will be impacted by it.

2.2 Peak Shaving

The simplest dispatch strategy is the so-called peak shaving, which aims at storing PV generation surplus, in order to inject it to the grid at low generation periods. In this way, curtailed energy from the generation peak is recovered and re-injected outside peak hours. In this mode, the battery is charged as soon as the PV generation exceeds a fixed injection limit threshold. The discharging of the battery starts when the PV generation falls below this threshold. The battery is never charged with energy from the grid.

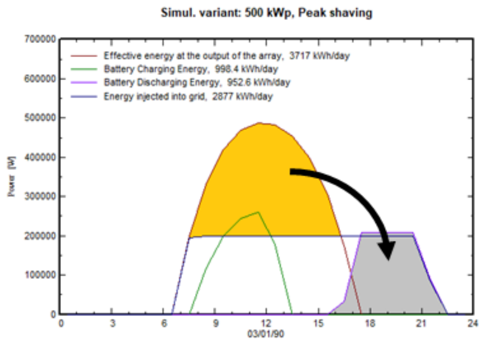

Figure 1: Peak shaving.

2.2 Self-Consumption

The self-consumption dispatch strategy aims at minimizing the power exchange with the grid. It does so by prioritizing the charging of the batteries over grid injection. The stored energy is then used to cover a given load profile in times of low PV generation. The battery does not interact with the grid, it only charges from the

PV system and discharges for load demand.

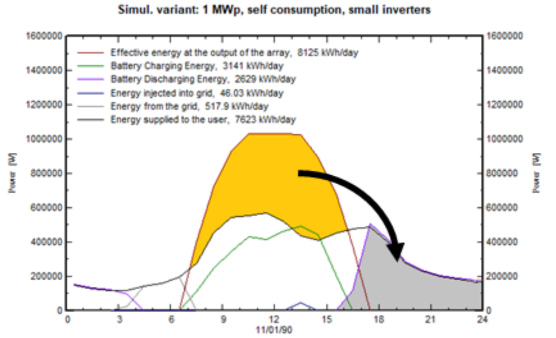

Figure 2: Self-consumption.

2.2 Weak grid islanding

Finally, there is the weak grid supporting strategy, that uses the battery storage as a backup to bridge grid outages. In this mode, the battery is also used to cover a self-consumption load profile, but the discharge level of the battery under normal operation is limited to a threshold that allows to sustain the load profile during a possible grid outage. When a grid outage occurs, the battery is allowed to discharge to a lower level. In these simulations the user can choose whether the PV system can inject into the grid or not. However, the charging or discharging of the battery from or to the grid is not allowed.

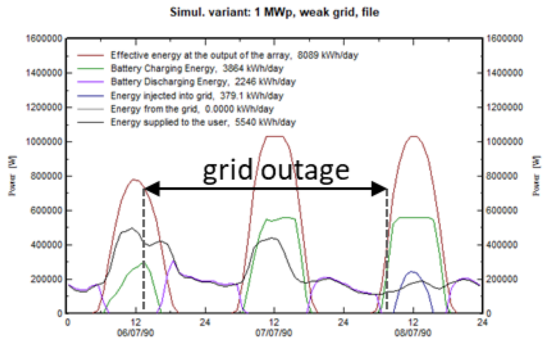

Figure 3: Weak grid islanding.

3 SIZING OF PEAK SHAVING SYSTEMS

These systems need to balance the injection limitation, PV capacity and Storage capacity. The aim is to recover energy that would be curtailed in the absence of the storage system. After determining this curtailed energy, a proper sizing of PV and battery capacity can be performed.

Table I: Different climates used in the simulations

Location	Climate type
Atacama	Desert, sunny and cool
Sharurah	Desert, sunny and hot
Kuala Lumpur	Tropical, cloudy and warm
Geneva	Temperate
Stockholm	High latitude

3.1 Determining curtailed energy

To get an idea of the potentially recoverable energy, one can look at the yearly energy loss caused by curtailing due to the grid injection threshold. In order to obtain a general curve, the PV capacity is normalized to the injection threshold. In the following we will call this quantity ‘oversizing factor’. The curtailed energy as function of the oversizing factor is shown in fig. 1. The points for the curves are from simulations of systems ranging from 340 kWp up to 1700 kWp, with injection thresholds from 100 kW to 500 kW. This was done for four different climates covering different typical conditions as shown in table I.

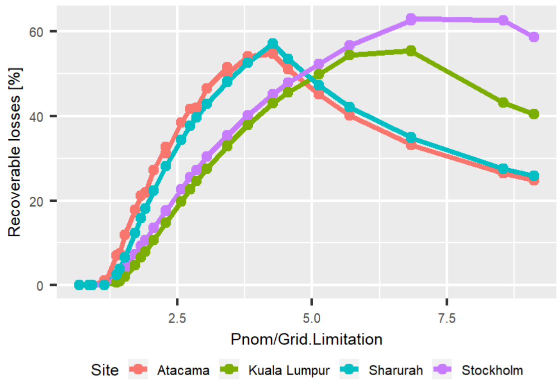

Figure 4: Yearly recoverable losses of curtailed energy as function of oversizing factor for different climates.

The rising part of the curves shows the increasing curtailed energy as the oversizing factor increases. The falling slopes are due to the total injection limitation, given by the injection threshold. The falling slopes are an approximation, since they are based on a period of a full year, neglecting seasonal variations. In summer with high PV generation and shorter nights, the injection limit is reached much sooner than in winter at small generation and long nights. Therefore, the maxima of the curves in this plot should be considered upper limits. As can be seen, the sunny climates show a steeper increase than the less sunny ones. The maxima of the curves, lying around 55%-65%, mark the point where the yearly injection capacity is reached, and an increase beyond this size leads to inevitable curtailing losses. From this plot we see, that the curtailing losses begin to appear at an oversizing factor around 1.25. For the sunny climates, at an oversizing ratio around 4, the point is reached where the full injection capacity is covered by the PV generation. In the less sunny climates, this point is reached at oversizing factors of 6-8.

Since the battery is operated in a daily charging cycle and is not useful for seasonal storage, the relevant quantity for sizing the battery is the daily curtailed energy. As an upper limit, one can take best clear day, and determine the energy surplus for the given injection limit. A better approach is to perform a yearly simulation and plot the distribution of the daily curtailed energy as in fig. 5. The distribution is highly dependent on the climate. In sunny regions the distribution has a pronounced peak at high values, while in the less sunny climates there is a broad distribution going down to values at zero.

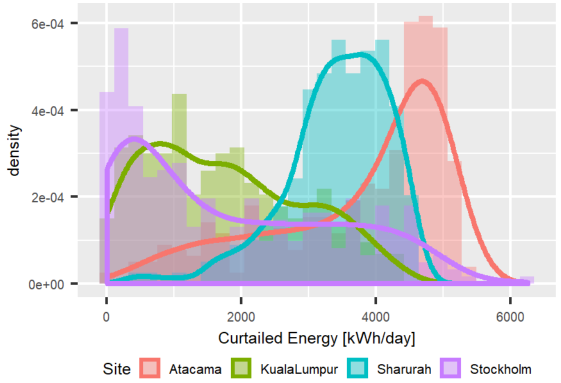

Figure 5: Distribution of daily curtailed energy for a 500 kWp installation in different climates.

As a measure of the battery capacity, we take the 90th percentile of the above distributions. This gives the plot in fig.6 for different climates and oversizing factors.

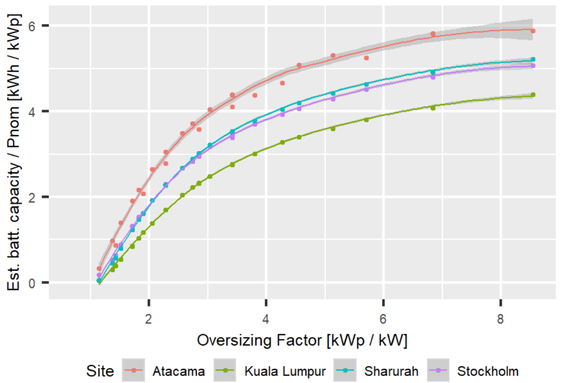

Figure 6: Estimated battery capacity as function of the oversize ratio. The estimation is based on the 90% quantile of the daily curtailing distribution.

Choosing the highest points from fig. 1 for the PV capacity, we get the estimates for PV and battery capacity shown in table II. These estimates are purely based on the technical aspect of adapting the battery size to the daily surplus in PV generation. In practice a cost analysis should be performed to find a good battery size. This is described with a simple example in the next section.

Table II: PV and battery capacity estimated from figs. 4 and 6

Location	Overload ratio kWp/kW	Battery capacity kWh/kWp
Atacama	4.2	5
Sharurah	4.3	4
Kuala Lumpur	6.25	4
Stockholm	7.5	5

3.2 Battery Sizing

The optimal battery size depends on the economical boundary conditions. In the following example we consider a utility scale PV system, that is placed in four different climates. As simple figure of merit for sizing the PV capacity and the battery, we take the difference between costs and revenues. The assumptions going into this calculation are summarized in table III. The battery costs are proportional to the battery capacity, using a price of 120$/kWh. The yearly cost of the battery depends on the battery lifetime, which is a result in each simulation. The PV costs should only consider the fraction of the PV capacity that is used to charge the battery. As a measure for this, we use the ratio of the discharging energy over the difference between total injected energy and discharging energy. This fraction is then multiplied with the PV capacity, the PV costs and normalized to a system lifetime of 25 years. The electricity tariff for grid injection is set at 15 ct/kWh.

Table III: Assumptions for the financial balance of the peak shaving examples

Electricity to grid	0.15 $/kWh
Battery costs	120 $/kWh
Battery lifetime	6-10 years
PV costs	0.4 $/Wp
System lifetime	25 years

The result of this calculation is shown in fig.7. The battery capacity has been normalized to the PV capacity, to generalize the result. As can be seen, the sunny climates favor a smaller oversizing factor. The battery capacity that maximizes the revenues is about 5 kWh/kWp for the sunny climates and considerably smaller for the other examples at 2.5- 3.5 kWh/kWp. As can be seen, this cost/benefits optimization gives similar oversize ratios as in table II, but the battery capacity that is found is clearly smaller for the less sunny climates. This is a consequence of the daily surplus distributions like the ones shown in fig. 5, which show that a battery capacity based on the 90th percentile leads to oversized batteries for a large fraction of the days in the year.
Finally it must be stressed, that these results, especially the absolute numbers of the balance, highly depend on the assumptions made for the costs and revenues from table III.

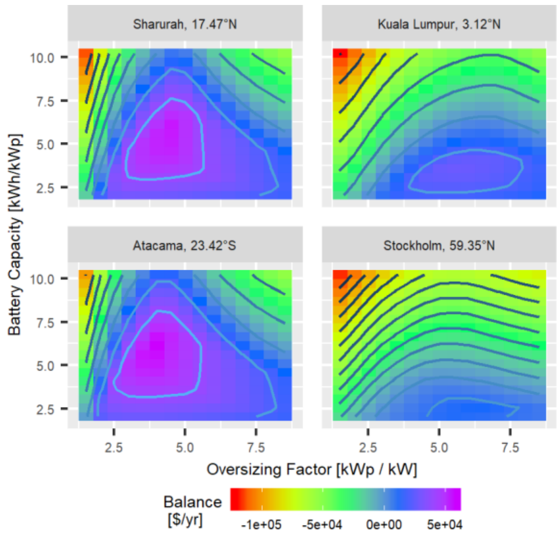

Figure 7: Cost/benefits balance for peak shaving systems

4 SIZING OF SELF-CONSUMPTION SYSTEMS

The self-consumption scenario is meant for systems that aim to reduce the energy drawn from the grid. In this case a yearly load profile is part of the simulation input parameters. As soon as the PV generation exceeds this load, the battery is charged. If the battery is full, the excess generation is injected into the grid. When the PV generation drops below the required load, the battery discharges to support the load. If the battery is fully discharged, the missing energy is drawn from the grid. For this dispatch strategy, the battery is only used to supply the load, it will never inject into the grid.

4.1 Load Profiles

For the following studies, typical load profiles published by the German Federal Association of Energy and Water were used [1]. These profiles are grouped into residential, commercial and agricultural consumers. The load profiles distinguish between the weekdays, Saturdays and Sundays. They are also varying along the seasons, with specific profiles given for summer, winter and intermediate seasons. The residential load profile is modulated with an additional function depending on the day of the year to give an even more detailed seasonal variation. For the following studies of residential PV systems with storage, the load profile was normalized to yearly consumptions between 3000 kWh and 15000 kWh.

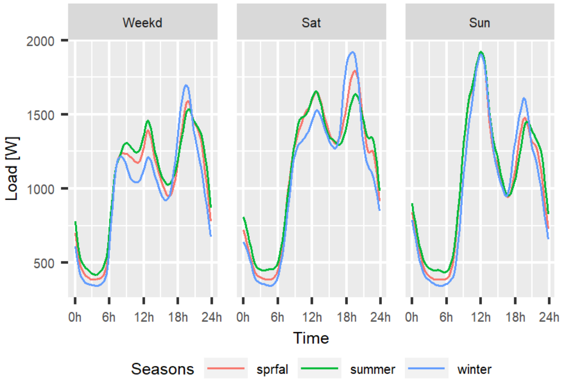

Figure 8: Typical residential load profile used in the simulations.

4.2 Economical balance

When sizing a PV+storage system for self-consumption, the costs of the entire system must be balanced against the benefits coming from the saved electricity. For this study we will neglect the revenues coming from injecting the PV generation to the grid. The scenario is the one of electricity consumers that would like to reduce the amount of purchased electricity by installing a certain PV and storage capacity, and grid injection not being allowed.

Table IV: Assumptions for the financial balance of the self-consumption examples

Electricity from grid	0.25 $/kWh
Battery costs	250 $/kWh
Battery lifetime	5-10 years
PV costs	1.5 $/Wp
System lifetime	25 years

The parameters entering this example analysis are summarized in Table IV. As metric for optimizing the PV and storage capacity, we take simply the difference between costs and savings. The PV costs are proportional to the PV capacity and normalized to the expected lifetime of the PV system, which is taken fixed at 25 years. The storage costs are proportional to the battery capacity and normalized to the battery lifetime, which is not constant but calculated separately in each simulation. The savings are calculated by taking the part of the energy of the load profile that is directly or indirectly coming from PV generation. This energy may have been stored in the battery. It is equivalent to the yearly energy consumption from which the energy taken from the grid has been subtracted.

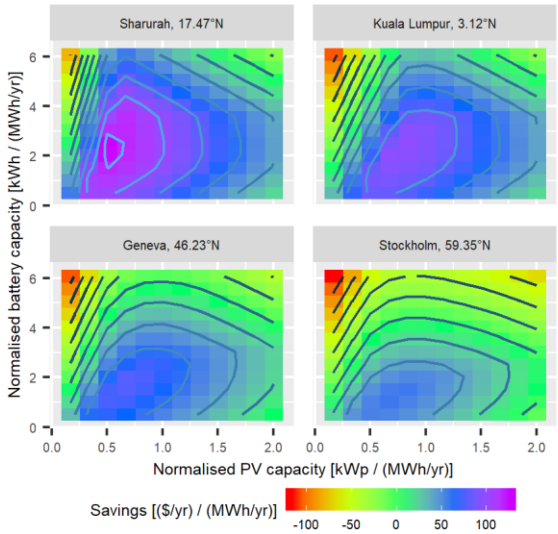

Figure 9: Cost/savings balance for a residential PV system with self-consumption and storage.

The results of the simulations are shown in fig. 9. In order to get more general results, the x-axis with the PV capacity and the y-axis with the storage have been normalized to the total yearly consumption. As expected, the savings are more significant in the sunny climate, and rather marginal in the high latitude example. The exact figures will strongly depend on the assumptions made for the prices and tariffs. In this specific case the optimal PV capacity for the desert climate is around 0.5 kWp/(MWh/yr), while the other climates have a broader maximum that extends between 0.5 and 1 kWp/(MWh/yr). The optimal battery capacity is around 2 kWh/(MWh/yr), the diffuse climate tending to slightly higher values, and the high latitude to slightly smaller ones.

Fig. 10 shows the solar fraction or self-consumption rate that is obtained for these systems. Superimposed are the iso-lines of the financial optimization in fig. 9. As can be seen, the financial optimum in the sunny climate reaches a solar fraction close to 100%. For the other climates the self-consumption rate rises less steep with PV and storage capacity. While for the diffuse climate a solar fraction of 90% is still reached at the optimum, this figure drops already to 70-80% for the temperate climate and is only around 60% in the high latitude example. These differences in self-consumption rates are explained mainly by the seasonal asymmetries in PV generation, which grow with latitude. This means that with a high seasonal asymmetry, a PV+storage system optimal in summer will be undersized in winter, and a system optimized for the winter months will be largely oversized during summer.

As said above, the exact figures of the economic optimization will strongly depend on the costs and tariff assumptions that go into the calculation. With dropping costs and increased tariffs, the optimum would move towards larger sizes of battery and more PV capacity. In the sunny climates it seems realistic to reach a solar fraction close to 100%. For the temperate climate and the high latitude these levels of self-consumption are currently not reachable.

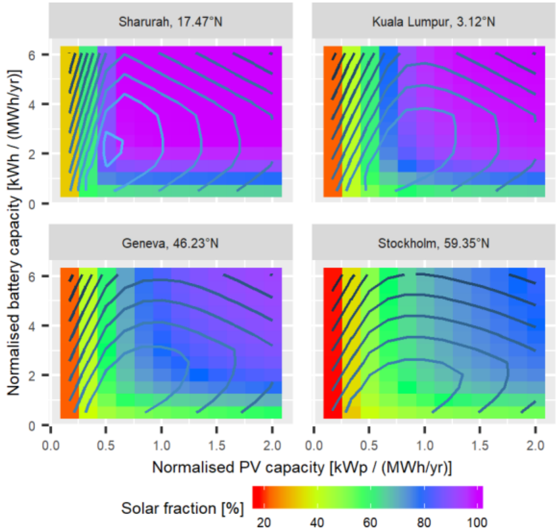

Figure 10: Solar fraction (self-consumption rate) for the simulations from fig.5. The isolines are from the financial optimization.

5 SIZING OF SYSTEMS WITH WEAK GRID ISLANDING

The weak grid islanding mode is also a self-consumption scenario, where a load profile is supplied by PV generation, battery storage or grid backup. In addition to this, the storage is also foreseen to cover possible periods of grid outage. For this to be possible, the battery should not be discharged below a given threshold during normal operation. In this way there will always be a minimum reserve charge available to sustain the load during the outage. This level of discharge is a simulation parameter and impacts the battery sizing.

5.1 Determining the Battery Capacity

To size the battery for this kind of system, we look at two different variables of the simulation results. The first one is the 'solar fraction' or self-consumption rate, which expresses how much of the yearly load profile is covered by direct PV generation or battery discharging. This is similar to self-consumption scenarios. The second variable is called 'loss of load', which is the fraction of the yearly load profile that is neither covered by PV generation nor by grid injection. This can be seen as the effective outages to be expected over one year.

For the example shown here, a PV system of 1MWp was considered, that is meant to supply the electricity for a commercial consumer with a yearly consumption of 2500 MWh. The simulations were performed for the Sharurah site with a sunny desert climate. The grid outages were generated randomly for one year as shown in fig.11. They represent a total of 580 hours (7%) distributed among 38 periods of 1-35h. This pattern was generated once and kept the same for all simulations.

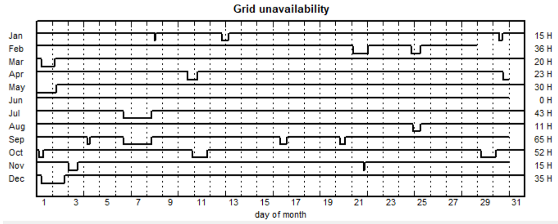

Figure 11: Random grid outages used in the simulations of the weak grid islanding scenario.

The result of varying the battery capacity is shown in fig.12. The solar fraction rises with growing capacity until it saturates at a self-consumption rate of 85%. The saturation is reached, because the PV capacity and the load profile are kept constant in these simulations. The figure shows also the evolution of the loss of load. As the battery capacity increases, the loss of load falls until it settles around 0.5%. The loss of load will not drop to zero in this example, because the PV capacity is kept constant. The residual loss of load is therefore given by the days where there is a grid outage and the battery charging from the previous days is not enough to cover the load profile during the outage.

As can be seen from the plot, the maximum of the solar fraction and the loss of load are not reached at the same battery capacity. The point where the saturation is reached is a complex interplay between load profile, grid outage pattern, weather data, PV capacity and the reserve discharge level of the battery. The latter one could also be optimized by running further simulations varying this parameter.

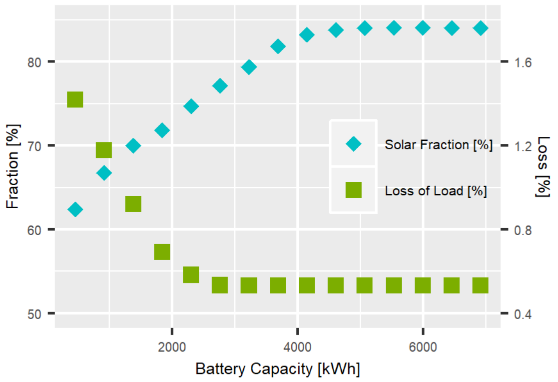

Figure 12: Solar fraction and loss of load for the weak grid islanding scenario.

6 SUMMARY AND OUTLOOK

In this paper we presented the different simulation possibilities in PVsyst for grid-connected PV systems with storage. The three implemented dispatch strategies are peak shaving, that shifts overproduction into the evening hours, self-consumption, which aims at supplying a given load profile with PV generation+storage, and the weak grid islanding, that uses part of the storage capacity as reserve to bridge possible grid outages. For each dispatch strategy examples were given on how to optimize the PV and battery capacity. The peak-shaving systems are clearly favored in sunny climates and need rather optimistic pricing assumptions in order to be profitable. The self-consumption examples allow savings in all climates, the sunny ones being more profitable. In the weak grid islanding an example was shown on how to choose the battery size to reach a certain level of self-consumption and/or supply reliability.

In the future, PVsyst will introduce a fourth dispatch strategy, the 'Load Shifting', that will allow to target the grid injection into specific time windows. This can be used for an economic optimization in a context of dynamic grid tariffs.

7 REFERENCES

[1] BDEW, Standardlastprofile Strom, https://www.bdew.de/energie/standardlastprofile-strom/