PEAK SHAVING CAPABILITY OF HOUSEHOLD GRID-CONNECTED PV-SYSTEM WITH LOCAL STORAGE: A CASE STUDY.

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ABSTRACT: Effect of grid feed-in curtailment of a PV system with heat or electricity storage (battery) is simulated as a function of system dimensioning with a focus on the induced PV power losses (due to this limit) and on cost balance. Heat storage is provided by a domestic hot water tank heated with heat pump or electrical water heating system. The case studied is based on a Swiss household with an annual electricity energy consumption of about 5000 kWh (without thermal loads). The effect of electricity generation forecast imprecision on cost balance optimization is also evaluated. The simulations showed that only relatively small electrical storage capacities or controllable thermal loads are sufficient to reduce considerably the PV-losses. Forecast inaccuracies have a non-negligible detrimental impact on cost balance with the designed algorithm.

Keywords: Battery Storage and Control, Demand-Side, Grid Integration, Small Grid-connected PV Systems

1 INTRODUCTION

High PV penetration in electricity grid can cause an overproduction of power, especially during clear summer days around midday. Those production peaks are detrimental for electric grid stability. Those peaks can be lowered (peak-shaving) by shifting loads to those periods (load shifting). Local electricity storage with a battery or thermal storage in the form of electrical water heating in households could potentially contribute to stabilize the grid by peak shaving [1]. In Switzerland, where 25% of the energy used for water heating of private household is obtained by electrical water heating systems [2], the heat energy storage method would require only limited investment and adaptation.

A simple approach to peak-shaving is to limit the maximum feed-in power into the grid to a share of the PV-nominal-power [3]. If the system cannot absorb the excess PV-power, it is lost. In this paper, those excess power losses are defined as "PV-losses".

The first purpose of this work is to determine which storage capacity is needed to minimize PV-losses as a function of the power limit, with a focus on battery or heat storage in the form of an electrical water heater (EWH) (boiler) or a heat pump (HP).

The second purpose is to evaluate the effect of forecast imprecision and the effectiveness of our energy management algorithm.

For these goals we developed a Matlab program able to simulate those systems. This program include decision algorithms controlling the power fluxes in the system, either based on forecast data or instantaneous data and either optimizing the electricity cost for the user or minimizing PV-losses due to the feed-in limit.

2 DESCRIPTION OF THE SIMULATION

We developed an energy flux simulation with a time step of one minute and simulate two different systems: Electrical storage in a battery and thermal storage in the form of heat. A control algorithm regulates the energy flux to/out of the battery or the heating state of the boiler each minute (see section 3).

2.1 Electrical Storage

For the electrical storage simulation we choose a DC-link configuration where the battery is connected before the DC/AC converter (see figure 1). The efficiencies of the DC-DC converter and the DC-AC inverter are calculated according to typical curves of commercially available systems [4]. We use a simple battery model with a fixed roundtrip efficiency of 90% which is in the range of standard Li-Ion battery. Note that the system is not allowed to charge the battery from the grid.

2.2 Thermal Storage

For heat storage system we choose EWH or HP electrically connected to the AC side. The energy is stored in the form of heat in a water tank. The water tank is modeled according this simple equation that does not take in account temperature stratification [5,6]:

$$m \cdot c \frac{dT_w}{dt} = \dot{Q}_{el} - \mathrm{h}\left(T_w - T_{inf}\right) + \dot{m}_{dem}(h_{in} - h_{out})$$

where $m \cdot c$: the mass and heat storage capacity of the water, T_w : Water temperature, $\dot{Q}_{el}$: electrical input power, $\dot{m}_{dem}$: Enthalpy transfer due to hot water consumption, $h = A/(\frac{1}{h1} + \sum \frac{li}{ki} + \frac{1}{h2})$: heat transfer charachteristic, the value $h = 1.1972$ is taken from [6] . The electrical input power is given for EWH by $\dot{Q}_{el} = x(t) \cdot P_{el}$ where $x(t)$ is on/off state (0 or 1) and P_{el} is the electrical power of the heater, for the HP it is given by $\dot{Q}_{el} = x(t) \cdot P_{el} \cdot COP$, where the coefficient of performance is given by a linear approximation $COP = d_0 + d_1 \cdot T_w + d_2 \cdot T_i$ [7], where $d_0 = 5.6$, $d_1 = -0.066$, $d_2 = 0.057$ are the different coefficients and T_i the inlet temperature. For HP we modelled two different case: classical on/off HP where, $x(t)$ is 0 or 1 and the continous HP (variable power or inverter HP) where $x(t)$ lies betwen a defined minimum and 1.

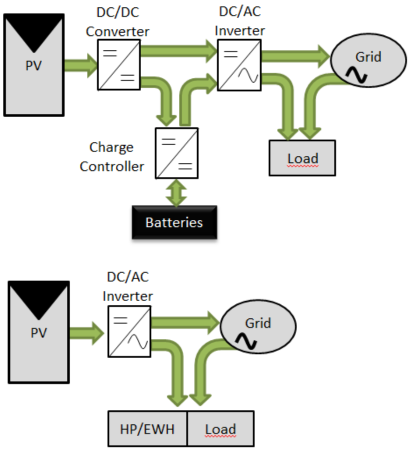

Figure 1: The two simulated systems. Top: Electrical storage. Bottom: Heat storage.

3 DESCRIPTION OF THE CONTROL ALGORITHM

Two different optimization objectives are used: costs minimization and PV-losses minimization only. For HP/EWH a scheduled operation control algorithm is used for comparison.

3.1 Control algorithm for cost minimization

Each 24 h, a cost optimization of the energy flux is done with 30 minutes time step forecast data for the next 48h of PV-production, household load and buying/selling prices. Then, each minute, the control algorithm regulates the battery flux or the HP/EWH state in order to try to reach the optimized state of charge (SOC) or temperature calculated during the previous cost optimization step based on the forecasts. The control algorithm is constrained to the following rules:

- The resulting energy fluxes have to respect the different given limits of the system (inverter power limit, power flux limits of the battery, battery size, temperature limit of the water tank…).
- If the resulting feed-in limit is overrun the excess PV power is stored as long as within the previously cited constraint are met. If it is not possible this excess PV power is lost. In practice, this means that the maximum power tracker of the PV system is no more operated at maximum point.

For electrical storage, a linear programming algorithm optimizing the electricity cost balance for the user is used. To allow linear optimization, the inverter and converter efficiencies are considered as constant in function of incoming power. It is considered as an acceptable approximation as the power flux intensities that give most contribution are on the flat part of the efficiency curve of the inverter.

For heat storage we wrote our own optimization algorithm because, with HP, the problem can no more be linearized. Furthermore, for this on/off problem, the mixed integer problem optimization function built-in in Matlab gave poor results. Our simple optimization algorithm works as follow: at each time step of the forecast, beginning from t=0, it checks, if the tank temperature is under the minimum. If this is the case, the algorithm tests for each time between t=0 and actual time step what would be the cost per gained degree if HP is turned on. Then the HP is effectively turned on where this value has its minimum. This procedure is done again until the temperature cross the lower temperature limit. Finally we get HP states that are very close to the optimized states for a cost balance optimization.

3.2 Control algorithm for PV-loss minimization

For PV-loss minimization no forecast is needed. Every time the feed-in limit is overrun the battery or heat tank tries to absorb this excess energy. For the other cases the goal is to have the state of charge as low as possible in order to be able to absorb the excess PV energy. Moreover the same constraint rules as described above (see subsection 3.1) are applied. An example is shown in Figure 2.

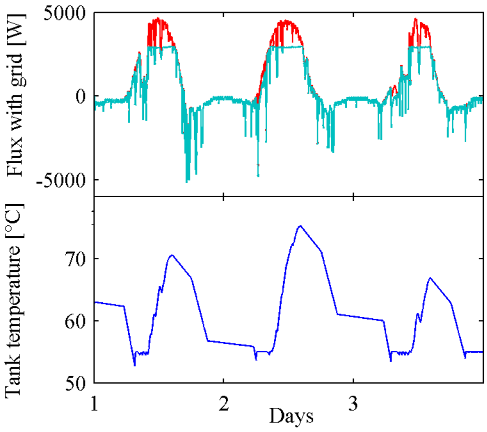

Figure 2: Continuous 3 kW HP and a feed-in limit of 60% using the minimizing PV-loss algorithm. Top: power flux with grid (with (blue)/without (red) storage and feed-in limit), bottom: water tank temperature.

3.3 Control algorithm for scheduled operation

This algorithm was written to have a comparison with a non-dynamically controlled system for HP/EWH. Each day at 11 a.m. the water in the tank is heated to the limit temperature. Otherwise each time when the temperature undergoes the minimum temperature it heats the water during 30 minutes.

3 CASE STUDIED AND INPUTS

3.1 Household specification

The load profile used for this case study is based on data measured at one minute interval data in a Swiss household of five people, from April 2012 to March 2013 located near to Neuchâtel. The annual load consumption without HP/EWH was 4943 kWh.

The hot water consumption profile was estimated from a survey of the household. The same profile was used for each day. Then the profile was normalized such that the total heating energy equals 6500 kWh per year. This is slightly higher than the Swiss average [2].

3.2 PV production

The PV production curve was generated with the PV-lib toolbox [8], using real global horizontal irradiance and temperature 10-minute-interval-data recorded by a MeteoSwiss [9] station nearby as input. We used the module modeling parameter for a 270 W multi-crystalline module taken from the PV-lib toolbox library. The resulting module power was then interpolated to one minute.

The PV installation was sized such that the annual energy yield equals the total load. For the given period without taking in account HP/EWH loads this corresponds to a 4.2 kWp installation. With a HP the total load depends on the control algorithm, but is in the range of 6600 kWh for this period which corresponds to a 5.5 kWp installation. For EWH, we have about 9600 kWh which corresponds to 8 kWp.

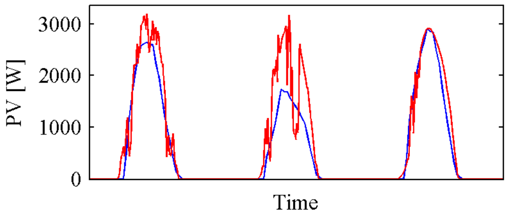

Figure 3: PV forecast comparison. Red line: PV production, blue line: forecasted PV production.

3.3 Forecast data

For PV forecast, historical forecast data of irradiance and temperature given by Meteotest a company specialized in meteorology was used. The dataset was composed of 48 hour forecast for each day with a time step of 1 hour. The forecast was interpolated to 30 minutes time step data (see figure 3).

The load forecast was generated by averaging for each 30 minutes the load profiles of each day of the week for each season. During days when the household was unoccupied a special holiday average load curve was generated.

To compare the effect of forecast errors, we introduce an exact forecast, that have the same format as the real forecast, but use the same input data that is used in the one minute modeling.

3.4 Heat storage inputs

For heat storage we simulated a 300 l water tank with water temperature limits between 55°C and 80°C. This tank therefore can store about 8.7 kWh of thermal energy for EWH and about the half for HP because the COP is around 2. The continuous HP can vary its power from 10%-100% of P_{el}. In our case the HP is assume to only heat hot water.

4 RESULTS AND DISCUSSION

4.1 PV-loss

The histogram in figure 4 shows the distribution of the daily excess energy due to the feed-in limit of 60%. By summing up the area above the different lines corresponding to the different storage capacities we can estimate the PV-loss energy for the studied period. We see that only few days have an excess PV energy above 3 kWh. Therefore storage sizes under 3 kWh are sufficient.

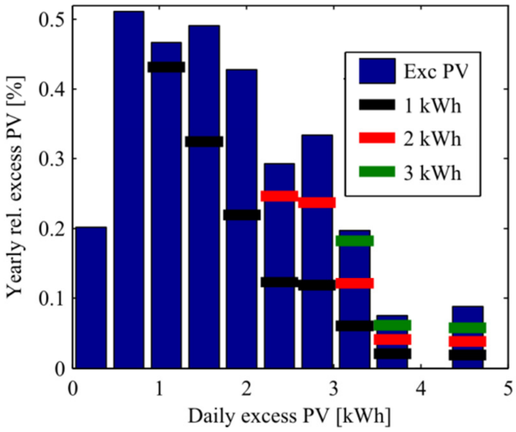

Figure 4: Distribution of the daily excess PV energy in means of total energy ratio from April 2012 to March 2013 for 60% feed-in limit. The areas above the different lines represent the PV-losses corresponding to the respective idealized storage size.

Figure 5 shows the PV-losses modeled for HP, EWH and battery in function of the feed-in limit. Table I shows same data completed by the other scenarios for a feed-in limit of 60% of the PV-rating. For this calculation the battery effective capacity was 3 kWh and the HP/EHW power (P_{el}) set to 2 kW. The PV-loss minimization control algorithm was used (no forecast).

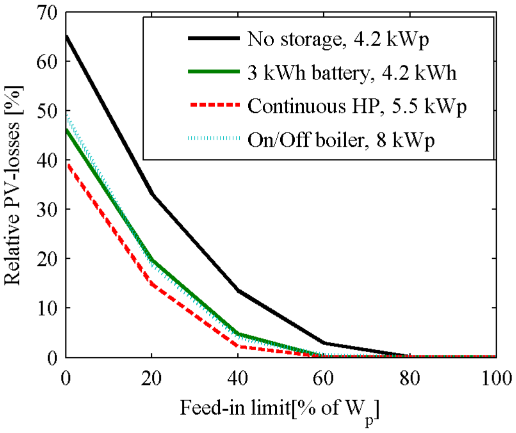

Figure 5: Relative PV-loss vs feed-in limit. The PV-algorithm is used

Table I: Relative PV-loss with a 60% and 40% feed-in limit, using PV-loss minimization algorithm. HP or EWH P_{el} = 2 kW.

Mode	PV rating [kWp]	[%] at 60%	[%] at 40%
No storage	4.2	2.9	13.6
3 kWh battery	4.2	0.1	4.8
Continuous HP	5.5	0.1	2.2
On/Off HP	5.5	0.8	5.7
Scheduled HP	5.5	1.2	7.4
Scheduled EWH	8	1.0	6.6
On/Off EWH	8	0.4	4.0

Comparing to the case without storage, all modes (even the scheduled one) reduces PV-loss by a factor 2 or more. Moreover, a relatively small battery size allows for reducing PV-losses to an acceptable level as already stated in [10]. The smallest losses are obtained with heat storage with continuous HP because its storage capacity is bigger than that of the battery. On/Off heating induces higher PV-losses because the power is fixed and cannot be adjusted to the excess power. Therefore the sizing of the On/Off HP/EHW (P_{el}) has to be adapted according to the feed-in limit such that its value is in the order of the mean excess PV power in order to minimize PV-losses.

4.2 Forecast error

In this section, only the cost optimization algorithm is used as it is the only one that needs forecasts. For the tariffs we use a feed-in price of 0.08 CHF/kWh and for electricity taken from the grid we chose 0.2 CHF/kWh. Both tariffs are assumed constant in our case study. Therefore the logical consequence of cost optimization algorithm will be first the minimization of the PV-loss and with the remaining storage capacity the maximization of self-consumption.

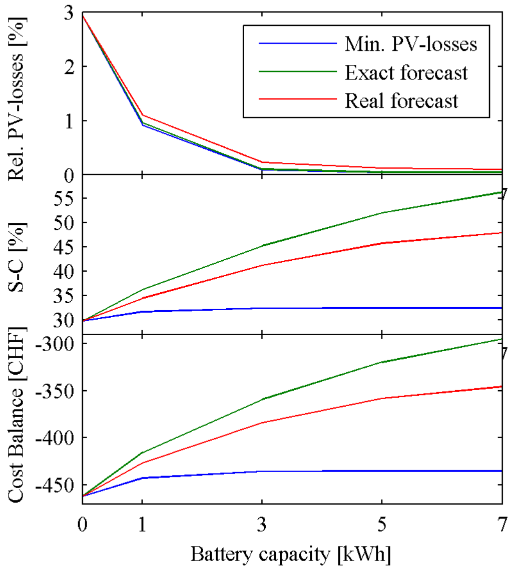

Figure 6: Relative PV-losses, self-consumption and yearly cost balance in function of battery storage capacity for 60% feed-in limit and 4.2 kWp PV rating.

Figure 6 shows the result of the modeling for the PV-losses minimization (as a control mode), cost minimization with exact forecast and cost minimization with real forecast.

As expected the PV-losses is smallest for the PV-loss minimization mode. Theoretically, the cost minimization with exact forecast mode should give equal PV-losses values as the PV-loss minimization mode. This is almost the case; the differences are due to the different time step of the optimization algorithm (30 minutes) and the simulation time step (1 minute) and the constant inverter efficiency approximation which result in slightly higher PV-losses for the cost minimization with exact forecast mode. With real forecast the PV-losses are higher, for example with a 3 kWh battery, they are more than two times higher than for PV-loss minimization. Those higher losses arise at days when the forecasted amount of excess PV is underestimated and therefore the storage is already full when it is needed.

Regarding self-consumption and cost balance, the control mode without forecast is the less profitable because it uses the storage capacity only to absorb excess PV power and not as for the two other modes also to enhance PV self-consumption with the remaining capacity. This result in a higher financial gain for the modes with cost optimization, see Table II. This gain increases with higher storage capacities (note that the cost of the storage is here not taken into account).

Table II: Self-consumption (S-C), financial gain and relative PV-losses as a function the various modes (as in Fig. 6) and compared to “no storage” mode for a 60% feed-in limit and 3 kWh battery capacity. For the “no storage” mode, the cost balance for April 2012-March 2013 is -457 CHF.

Mode	S-C[%]	Gain[CHF]	Losses [%]
No storage	30	0	2.93
Min. Losses	32	26	0.09
Exact forecast	45	103	0.11
Real forecast	41	78	0.23

5 CONCLUSION

The first purpose of this study was to compare the ability to reduce PV-losses due to feed-in curtailment as a function of battery sizes and for heat (hot water) storages. In our case study (typical family household) a relatively small battery capacity in the order of 3kWh is sufficient to reduce considerably the induced PV-losses. When water is heated with EWH or HP, our modeling showed that with a water tank and a smart control of the thermal loads the induced PV-loss can also be considerably reduced. In those cases the electrical power of the devices should be adequately chosen. It is found that variable power heat pumps (continuous heat pump) perform much better comparing to On/Off operation in reducing PV-losses because they can adapt their power to the excess PV power. As thermal and battery storage have about same capability to reduce considerably PV-losses, using thermal storage, if HP/EWH are already available could be an interesting cost effective solution to avoid buying expensive batteries.

For cost optimization, forecast data have to be used in order to not only reduce PV-losses, but also to increase self-consumption and therefore optimize cost balance. We studied the effect of forecast imprecisions on the total electricity flux cost balance. We also compared it to the PV-loss minimization control mode without forecast. For small storage capacities under 2 kWh there are no significant self-consumption differences, for those cases the simpler algorithm without forecast is sufficient. For higher storage capacities, control algorithms with forecast result in higher self-consumption and therefore better cost balance. The self-consumption difference between modes with and without forecast reach in our case more than 15 absolute percent for storage capacities of 7 kWh and 60% feed-in limit.

Forecast imprecisions induced higher PV-losses than with exact forecast mode and minimize PV-loss mode. Regarding cost balance, forecast errors induce slightly lower values than for the ideal case, nevertheless the cost balance is still quite higher than for the minimize PV-loss mode. Therefore, for higher battery capacities it is worth to use the cost optimization mode needing forecast even if there are forecast errors.

6 ACKNOWLEDGEMENT

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