BATTERY CHARGE CONTROL SCHEMES FOR INCREASED GRID COMPATIBILITY OF DECENTRALIZED PV SYSTEMS

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ABSTRACT: As grid price rises and the feed-in tariff declines, the economics of local storage become increasingly lucrative to the system owner. The attractiveness of a local storage investment is compounded in the presence of a PV grid injection cap. The larger the PV system size is relative to this cap level, the greater the opportunity exists to charge the local storage with PV production that would otherwise be dissipated without credit. This study utilizes two household demand profiles that represent the extremes of the potential for local PV self-consumption and, consequently, the range of economic potential that exists for local storage to be coupled with residential PV systems. A series of algorithms were subsequently developed to analyze the related benefit potential of delayed storage charging to target instances of excess PV production depending upon the grid injection cap.
Keywords: Batteries, Battery Storage and Control, Demand-Side, Economic Analysis, Energy Options, Grid-Connected, Grid Integration, PV System, Sizing, Small Grid-Connected PV Systems, Solar Home System, Storage, System Performance.

1 INTRODUCTION

The local use of PV generated electricity currently provides economic benefit to the user in many locations around the globe, including Germany. At high grid penetration levels, however, much strain is placed upon the supporting electric grid to accommodate the greater variability in power production. Required upgrades to the grid can be quite costly creating resistance to further PV development. In such places, the allowable grid feed-in of PV power production is already being lowered in order to reduce this strain with excess feed-in power often being simply dissipated with no benefit to the PV-owner.

Decentralized battery storage offers a potential solution to capture PV generation in excess of the immediate local electric demand. The primary benefit of the storage system is increased self-consumption. But, if used effectively, the peak feed-in power can also be reduced while producing a greater balance of grid injections throughout the day. Both measures enhance the grid compatibility of PV power production. The extent to which this is possible is dependent upon the nature of a particular household. Importantly, these improvements in grid integration can be accomplished while maintaining high levels of self-consumption [1-2]. As allowable grid injection power levels decrease, the benefit of such storage use amplifies as it can further target PV power production that would otherwise be dissipated.

2 APPROACH

2.1 Definitions

The following nomenclature has been used:

$\sum_{el,total}$ = Total household electricity demand (from applicances);
$\sum_{PV}$ = Locally produced PV energy before losses;
$\sum_{PV,local}$ = Portion of PV energy used locally;
$\sum_{PV,local} / \sum_{PV}$ = Self-Consumption;
$\sum_{PV,local} / \sum_{el,total}$ = Autarky; ratio of household energy demand that coincides with PV generation and total household energy demand.

2.2 Method

Simulations are based upon the analysis of the time-series of PV generation as well as the local demand for electricity to operate household appliances. PV system power generation was extracted from a field test data site in Southern Germany and normalized to a prior to losses power production of 1000 kWh per kW_p of rated system power. The electrical power demand of the households has been derived from a human behavior-based load profile generator developed at Chemnitz Technical University [3].

The load profile generator, while currently within it stages of development, was verified for the validity of its output with adaptations applied to correct for any deficiencies. In total, 50 unique household demand profiles were created with various configurations of the types of denizens; including households of 1 to 6 residents, people of all ages, as well as retired, periodical or shift workers. From this group of 50 households, two were selected for analysis: one exhibiting the highest level (HL) and one the lowest level (LL) of self-consumption of PV power production. Application of such profiles yields a plausible range of results inclusive of all households. The average daily profile of each is displayed in Figure 1.

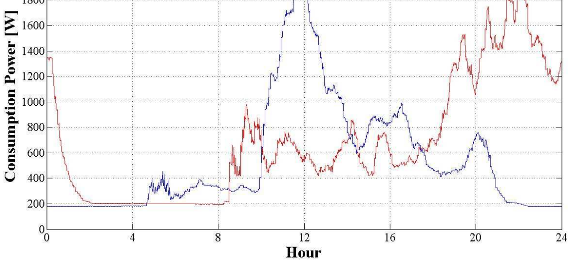

Figure 1: UL & LL Average Daily Demand Profile

The size of the PV system associated with each profile was selected so that its annual output before losses was equal to the demand of the household. A sensitivity analysis on the effect of the battery storage capacity on household autarky was subsequently performed on each profile to include an appropriate storage size: 6 kWh for the LL profile and 4 kWh for the UL profile.

Simulations were first run without any control of the battery storage; the battery consequently being charged with the first amounts of PV energy available after accommodating any household power demands. Grid injection restriction levels were set for 50% and 25% of the rated peak PV system power; the reduction of the cap level to 25% of the PV power is equivalent to keeping a 50% level but doubling the PV system size. This scenario provides the reference for the amount of grid feed-in energy that would be missed without battery control. It is also the scenario that provides the maximum rate of household autarky, as the storage is charged to the extent possible for each given day.

A series of charge control algorithms were subsequently developed. The efficacy of a particular delayed charging algorithm is determined through the balance of two opposing factors. The ability to charge with grid injection power levels above the feed-in cap offers advantages through increased feed-in credits. A delayed charging of the battery, however, has the potential drawback of the storage not possessing a sufficient state of charge (SOC) to supply a local demand that would have been realized through charging at first opportunity. The greater the degree of PV over sizing, the easier it is to yield a positive outcome for delayed charging.

The degree to which a PV system is over sized is relative to the combination of the amount and distribution of daytime power demand as well as the feed-in cap level. In this study, the 50% and 25% grid injection limits mentioned were used to establish the different levels of PV generation over capacity. The grid price was set to 0.30€/kWh and feed-in tariff at 0.15€/kWh to enable the comparison of results for each charge control strategy to the respective reference scenario at each level; thus, self-consumption was attributed with twice the value of feed-in.

The first method of control was a simple linearly delayed charging of the battery bank over the peak production hours of the PV system. This corresponded to the hours from 09:00 to 15:00 for the months of May to September.

The second method was a more complex learning algorithm based upon the historical average daily profile of both PV production and household power demand. The average household power demand was differentiated between weekdays, Saturdays and Sundays. This enabled the capture of specific daily habits of the household under study. The difference between the two average daily profiles provides the basis from which to derive a delayed charging profile for the battery bank to limit peak injections of PV power.

The final method used the learning strategy of the previous, but combined the historical household demand average with a constructed PV production forecast. An ideal forecast was first utilized to highlight the ideal case. A fabricated forecast was subsequently implemented based upon the hourly average of the true irradiance disturbed by a noise sequence. The result of which is an hourly forecast for 24 hours with a 30% normalized distribution from the ideal. This error margin is the approximate accuracy of current numerical weather prediction models for Central Europe [4].

With respect to the learning algorithms, a series of parameters defined their operation. The decision whether to apply a delayed charging profile for a given day, or charge the battery at first opportunity, was dependent upon a minimum threshold of the total historical average of daily PV energy available relative to the size of storage. Furthermore, the delayed charging profile was also permitted to be updated throughout a given day by analyzing the degree of deviation of excess PV energy from the historical average. A cloudy day could thus cause the removal of the delayed charging profile, or shift it further toward the peak production hours on a very sunny day. The amount to which this degree of deviation was permitted to affect the charging profile was also weighted to enable slower or faster reaction times.

Each of these factors could be optimized for a given household. However, to ensure that results remain realistic for a single year's analysis, a general set of parameters that produced the greatest results for the 50 household demand profiles as a whole were employed for a particular grid injection cap level. Through a multi-year analysis, such parameters could be optimized for a particular household as well as for different times of the year for improved results.

To continue to maintain high levels of self-consumption for each strategy, if the surplus PV power was greater than the PV feed-in restriction, the battery bank was permitted to be charged with the amount of energy necessary to reduce the feed-in to within permissible limits. This is due to the fact that PV power feed-in above this limit was afforded no value. If a step-wise reduction of feed-in tariff above the restriction limit were implemented, or a similar reduction function, this approach would need to be revised to optimize the capture of feed-in credits.

For each control strategy described above, anytime that the PV system delivered power or the battery bank possessed charge, a 50 W power reduction was applied to power the energy management system. In reality, this power demand would vary depending upon a number of factors including the complexity of the management system, and is thus only a simple conservative estimate.

3 RESULTS

Table I displays the results of the simulations including those for the scenario with direct feed-in of PV power generation as well as with self-consumption of PV power without accompanying battery storage to illustrate the full progression of benefits. The 'Annual Return' refers the annual cash flow that can be used to pay for the household system as a whole (4.8268 kWp & 4 kWh for the UL profile and 5.998 kWp & 6 kWh for the LL profile); this given the 0.30€ grid price and 0.15€ feed-in tariff. The benefit of the battery addition alone is derived by the comparison of this value for a particular scenario that includes storage to the 'After SC w/o Battery' scenario, which is simply a PV system that is permitted to help satisfy household power demands.

3.1 Optimization of Smart Algorithm Parameters

For each grid injection cap level, a 25-day and 3-day historical averaging period was found to be optimum for the PV production and household demand, respectively. For the PV production, it is at this length of time that a

Table I: Charging Strategy Benefit Comparison

		UL Profile (4.8268 kWp & 4 kWh)				**LL Profile** (5.9988 kWp & 6 kWh)			
		PV Yield (before losses) = 4826.8 kWh/a				PV Yield (before losses) = 5998.8 kWh/a			
	Grid Injection Limit	Self-Consumption	Grid Injection Credits	Grid Injection Losses	Annual Return	Self-Consumption	Grid Injection Credits	Grid Injection Losses	Annual Return
	[% PV kWp]	[kWh]	[kWh]	[kWh]	[€/a]	[kWh]	[kWh]	[kWh]	[€/a]
Direct PV Feed-In	50	--	4222	366	**633.3**	--	5248	455	**787.2**
After SC w/o Battery		1897	2564	127	**953.7**	1381	4023	247	**1017.75**
No Storage Management		2943	1139	83	**1053.75**	2996	2085	178	**1211.55**
Linear Delay		2889	1268	19	**1056.9**	2975	2245	42	**1229.25**
Historical Delay		2931	1203	33	**1059.75**	2961	2284	19	**1230.9**
Ideal Forecasted Delay		2937	1211	18	**1062.75**	2981	2269	11	**1234.65**
Forecasted Delay		2927	1200	42	**1058.1**	2961	2248	55	**1225.5**
Direct PV Feed-In	25	--	2924	1664	**438.6**	--	3635	2068	**545.25**
After SC w/o Battery		1897	1852	840	**846.9**	1433	2809	1460	**851.25**
No Storage Management		2943	748	475	**995.1**	2996	1342	920	**1100.1**
Linear Delay		2899	1005	269	**1020.45**	2979	1711	572	**1150.35**
Historical Delay		2921	999	250	**1026.15**	2960	1924	381	**1176.6**
Ideal Forecasted Delay		2930	1024	214	**1032.6**	2974	1951	337	**1184.85**
Forecasted Delay		2920	964	285	**1020.6**	2956	1845	464	**1163.6**

balance is struck between capturing the current seasonal trend without being influenced too greatly by the prevailing weather pattern. The addition of the weather forecast in the final approach eliminates the need for this parameter, but continues to employ a historical daily household demand profile based upon the previous 3 days of a given day type.

At a grid injection cap level of 50% of the rated peak PV power, the economics of delayed charging tend to be affected greater by the level of household autarky due to the relatively small amount of feed-in above the cap; this being influenced by the 2:1 value ratio of self-consumption to feed-in being employed. Therefore, the intent in this scenario is to maintain levels of self-consumption. In contrast, there is a significantly larger amount of feed-in being lost with a feed-in cap of 25% of rated peak PV power. The potential to reduce these feed-in losses relative to the consequential self-consumption losses is much greater than the 2:1 value paradigm used. In this manner, each case presents a different focus for the battery value economics.

It is for this reason that the input parameters to the charge control learning algorithms also differ. These parameters are outlined in Table II. In the 25% cap scenario, a minimum level of available PV from the historical analysis is not necessary because enough days in the year experience PV production power levels available to the battery system above this cap to apply it any given day.

The 50% cap is better applied with an update frequency of 120 minutes whereas the 25% cap prefers not to be updated. This is due to the nature of the irradiation profile possessing a greater degree of mornings with below average PV production. Updating the daily profile in the 50% case is therefore able to protect self-consumption on cloudy days that remain cloudy. In the 25% case, however, the risk for loss of feed-in credits is too great if the sun begins to shine later. In this case, the preference is therefore to hold onto a charge profile throughout the day. If the opposite were true for morning irradiation, the 25% case would likely be served better with updating and vise versa.

This difference in preference for updating between the scenarios also highlights the potential to vary the parameters for a given household within a given year. Not only would it be possible to capture different seasonal daily irradiation trends, but depending upon the level of irradiation, the focus be placed upon either maintaining self-consumption or gaining feed-in credits.

Table II: Historical Learning Algorithm Input Parameters

	Grid Injection Cap [% of kWp]	
	50%	25%
Demand Averaging Period [days]	3	3
PV Averaging Period [days]	25	25
Min Daily PV Available [% of Storage Capacity (kWh)]	100	0
Update Frequency [min]	120	0
Update Deviation Weighting [%]	25	N/A

The effects of the delayed charging parameters described above are evident in Table I. The relative decreases of the self-consumption from the 'No Storage Management' scenario at each cap level for the learning algorithms are greater at the 25% cap level for each household. However, as shown these losses are more than compensated by the gains in feed-in credited.

3.2 Benefit of Delayed Charging Strategies

The LL profile grid injection power duration curves for each of the PV utilization scenarios outlined in Table I are shown in Figures 2 & 3 for the grid injection limits of 50% and 25%, respectively. The corresponding grid injection duration curves associated with the UL profile exhibit similar characteristics. The potential possessed by delayed charging techniques to limit the majority of high grid injection power levels to the feed-in restriction limit is quite evident. In each case, the great amount of energy fed into the grid at exactly the cap level is due to the fact that the feed-in power was always reduced to the cap level, while being able to deviate from the delayed charging profile, if sufficient storage capacity was available.

To further enhance the visual representation of the effects and functionality of the smart storage control, the time series of grid injection over the entire year at a 1-minute time resolution is displayed in Figures 4 to 7 below.

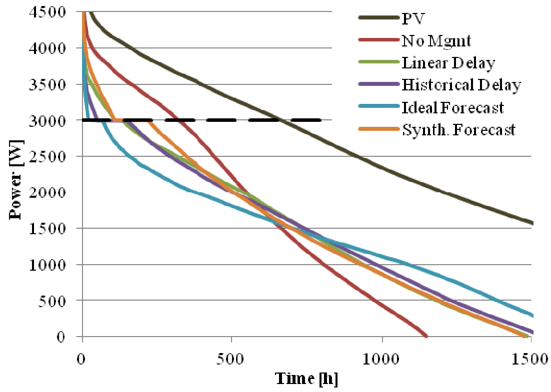

Figure 2: LL Profile Grid Injection Duration Curve – 50% Cap

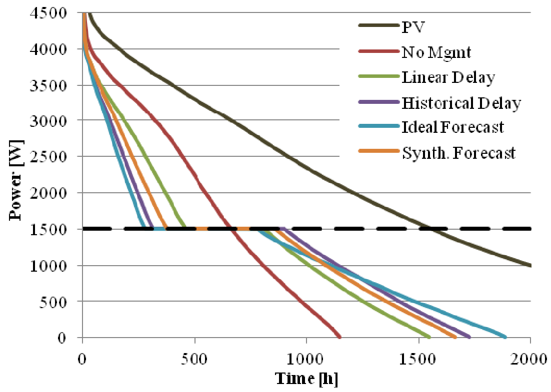

Figure 3: LL Profile Grid Injection Duration Curve – 25% Cap

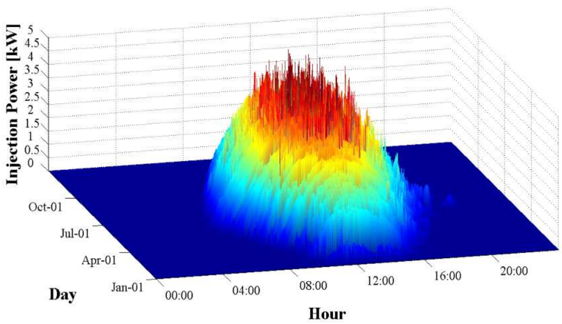

Figure 4: LL Profile Straight PV Grid Injection Time Series – 50% Cap

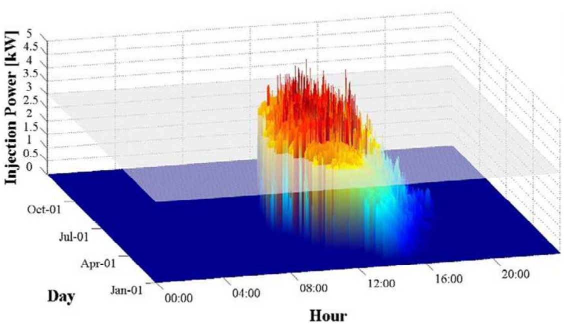

Figure 5: LL Profile No Management Grid Injection Time Series – 50% Cap

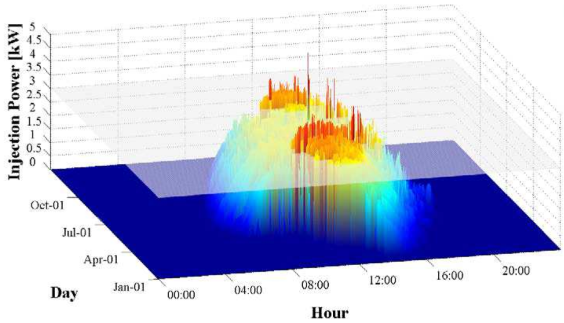

Figure 6: LL Profile Historical Delay Grid Injection Time Series – 50% Cap

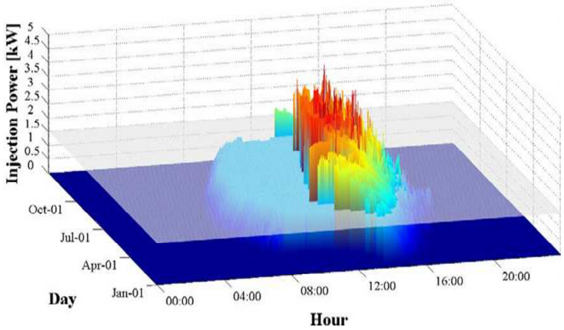

Figure 7: LL Profile Historical Delay Grid Injection Time Series – 25% Cap

Each of the delayed charging algorithms was able to offer economic benefit to the homeowner under all defined scenarios. This benefit was low, however, in all cases except given the LL profile with a 25% of peak PV power grid injection limit. It was only in this case that enough gains were available from reducing feed-in losses, that a significant benefit could be realized in comparison to the 'No Storage Management' reference scenario.

Income generated through a delayed charging of the battery under these conditions ranged from 6 to 20 €/annum and 30 to 75 €/annum for the 50% and 25% grid cap scenarios, respectively. As described in Section 2, the household demand profiles used to generate these results are opposite profiles and, thus, produce a plausible value range inclusive of all households for a battery installation.

In all cases, the completely historical based delayed charging proved to offer the most benefits, other than using the unrealistic ideal PV forecast. The inferior results produced by the forecasted PV learning algorithm seems counter-intuitive but as described in Section 2, this forecast was produced by applying a noise sequence that produces a 30% normalized distribution from the ideal. The final result is a RMSE with magnitude of approximately 800W. For this particular PV profile, a historical based averaging is able to yield a forecast with a RMSE with a magnitude of approximately 630W. Further study is necessary to determine whether this can be said to be a property applicable to most systems, or if the irradiation profile being used was simply a statistical anomaly. It is possible that the basis of the historical PV profile being the system's precise location is able to offer a better prediction for a given day than extrapolating a high resolution prediction from a lower resolution regional forecast.

In each case, the linearly delayed profile also produced positive results. This was in an opposite manner in comparison to the historical basis due to its rigidity. Without being able to shift concentration, grid injection losses were focused upon with the UL profile and maintaining self-consumption for the LL profile.

At the lowered grid injection limit of 25% of peak PV power, the benefits of the historically delayed charging become more apparent. In the case of the UL profile, these gains are only slightly above the linearly delayed profile (6 €/annum more), but this extends to 26 €/annum more than the linear charging for the LL profile. At such levels of PV system over capacity, the ability of the historical approach to concentrate charging during key parts of the day previously described becomes significantly enhanced. The result is close to 200 kWh/annum improvement in feed-in credits for the LL profile.

As shown in Figure 7, in the case of the LL profile and a 25% of peak PV system power grid injection limit, much potential still exists for additional storage capacity to be able to capture non-rewarded grid feed-in. This fact is highlighted by a clear onset of feed-in powers above the cap around mid-day throughout the peak production season indicating that the storage capacity has become saturated.

Figure 8 below depicts the economic benefit gained through storage addition for the LL profile. The superiority of the historical based management approach is clear for all battery sizes. The benefits begin to taper off between 8 and 12 kWh yielding approximately an additional 400 to 460 €/annum, respectively, as compared to system without storage. This value is significantly higher than the 325 €/annum yielded through the 6 kWh utilized. Depending upon the cost for storage, however, a system operator may choose a storage level below this level as the largest gains are experienced with smaller storage capacities.

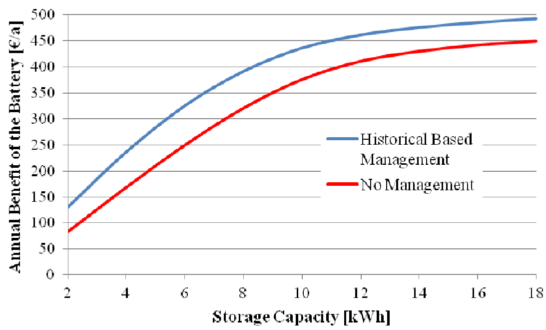

Figure 8: Storage Size Sensitivity Analysis

In addition to the economic benefits described, applying a delayed charging profile reduces the battery dwell time while fully charged (>95% SOC). This is quantified for each SOC within Figure 9 below for the LL profile. This reduction was from 55 days/year to 38 days/year for the historically based charging control in comparison to that for no energy management. Reduced dwell times at the fully charged state increases the lifetime of many Li-ion based battery types [5]-[7].

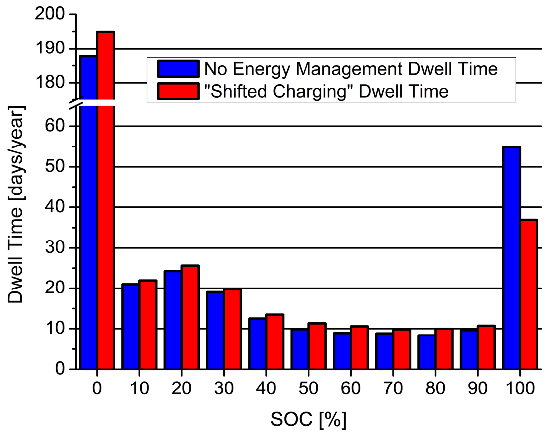

Figure 9: SOC Histogram – LL Profile @ cap=25%

Through delayed charging, enhanced grid compatibility of household PV systems with local storage is also an indirect benefit. Grid injection of PV power is more balanced throughout the day reducing the possibility of grid overload during the peak production hours. A daily projection of local grid power needs could also be constructed by the grid operator, and associated price points directed to household systems to use as the basis for definition of the charging profile. In this manner, economic benefit of storage could be provided to the homeowner while working with the grid operator to enable even higher PV penetrations within a given area. Participation in such a market could also enable grid price to feed-in tariff ratios significantly higher than the strict 2:1 ratio being utilized within this study. This would enable higher economic returns from the addition of storage, and in particular from the smart charging of storage.

In the absence of such price signals, the simplicity of the linearly delayed charging method could outweigh any advantages gained through a historical or forecast based delay. As described, this depends upon the ratio of battery size to the degree to which the PV system is over-sized in comparison to household demand as well as the power demand of the associated energy management system. The UL profile with a 50% grid injection cap scenario presented would be the most likely candidate for such an outcome.

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