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Appropriate storage for high-penetration grid-connected photovoltaic plants

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ABSTRACT

This paper addresses the dual questions: What is the appropriate storage size and its related properties for matching very large photovoltaic plants to the grid; and what are the available technologies for achieving this end. For this purpose a "Usefulness Index" is defined, which, for any grid flexibility, leads to a PV-storage combination that allows high grid-penetration without storage being wastefully large. The paper then examines the sensitivity of this "appropriate storage size" to variations in our assumptions. The specific case of the Israeli electricity grid is employed for numerical discussion, but the formalism should be useful for wider application. In particular, the "appropriate storage size" deduced in this manner is argued to be a valuable point of departure for optimizations of a more sophisticated nature. Regarding available storage technologies, none is found to have all of the required properties for massive PV-grid penetration, but hybrid combinations should be capable of achieving this end.

1. Introduction

Because of the intermittent output of a photovoltaic (PV) plant and the frequent mismatch that occurs between PV output and grid requirements, it is difficult to achieve extensive grid penetration of PV power unless suitable storage is included. In a quantitative study of this fact, we compared the compatibility of the simulated output of a number of PV system types with the hourly demand requirements of the Israel Electric Corporation (IEC) during the year 2006 (Solomon et al., 2010a–c). We found that in the absence of storage, a maximum grid penetration of about 20% of the annual load requirements could have been achieved, albeit at the cost of having to dump approximately 5% of the PV-generated energy, and needing to re-structure the manner in which the grid was then being operated (Solomon et al., 2010a). Furthermore, we found that distributing the PV plants around the Negev desert would not have significantly increased annual grid penetration. For really large penetration appropriately designed storage would have been needed together with a different grid operation strategy.

Our study showed that the required properties of storage (vis-à-vis both energy and power capacity) can be derived by detailed consideration of the three-way mutual interactions among storage, demand profile, and PV output (Solomon et al., 2010c). An important finding was that for a simplified situation in which all energy losses are limited to those from storage inefficiency, grid penetration rises, initially approximately linearly with increasing storage energy capacity and power capacity. After this initial rise, increased storage is found to be less effective in promoting increased grid penetration. Taking a more-or-less arbitrarily sized storage example, and allowing a small amount of PV energy dumping, we showed that approximately 90% annual grid penetration could have been achieved (Solomon et al., 2010b). However, we did not attempt to explain how an appropriately sized large storage system can be calculated.

Within the context of achieving large grid penetration we employ the term "appropriately sized" rather than "optimally sized" storage. This is because a true optimum can only be arrived at by including all kinds of factors such as alternative grid operation strategies, economic constraints, etc., which, as previously explained (Solomon et al., 2010a) are beyond the scope of the present study. Our results accordingly represent a *first estimate* towards an optimal storage size. The purpose of the present paper is therefore to show how one may compute a storage size that can enable a large PV system to achieve high grid-penetration without, on the one hand, needing to dump expensively-generated PV power and, on the other, incurring the expense of over-sized storage that would rarely be needed. We shall also examine the effect on grid-penetration of small amounts of energy dumping and of small increases in storage size, in order to identify reasonable limits (beyond which further increases in storage size would have negligible benefit for enhancing PV grid penetration).

The importance of this kind of pre-economic study is that whatever additional constraints economic considerations may impose on PV+storage system design, it is non-economic factors

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of the kind considered here that determine the limits of grid penetration for various PV-storage combinations.

2. A Usefulness Index, UI, for storage

The mathematical tools employed for deriving our results were previously given in appendices to Solomon et al., 2010a,c and need not be repeated here. Instead, we take as our starting point Fig. 1, similar to one derived in Solomon et al., 2010c.

In Fig. 1, for each increase in PV system size above “no-dump” (ND), we calculated the required energy capacity (EC) of storage that would be needed in order not to waste any of the surplus PV generation. A nominal round-trip efficiency of 75% was assumed for storage (Solomon et al., 2010c; Denholm and Margolis, 2007). These calculations were performed for grid flexibility factors $ff=0.7$, 0.8, and 1. $ff=0.7$ is slightly greater than the flexibility at which the IEC grid was operated during 2006. $ff=0.8$ is the highest flexibility that would have been technically possible for the IEC fleet of plants in operation that year (Solomon et al., 2010b) and $ff=1$ is the maximum theoretically possible flexibility— which could in principle be achieved by a grid consisting entirely of gas-turbine plants. As stated in the Introduction, Fig. 1 shows that for all grid flexibilities, annual penetration starts off by increasing approximately linearly with the increasing storage size but at a certain point the increase levels off. From then onward, large increases in storage capacity (along with concomitant increases in PV system size) achieve relatively small increases in annual grid penetration.

In order to find the point at which this decrease in storage usefulness sets in, we define a storage Usefulness Index (UI) as: *the ratio of energy delivered by storage in a year to the energy capacity of storage*. A large value of UI will consequently represent a well-used storage, whereas a small value will represent an under-used (or unnecessarily large) storage. Mathematically we have:

$$\mathrm{UI}=\frac{\sum_{i=1}^{8760}\eta_c\eta_d P_i}{EC} \qquad (1)$$

In Eq. (1), P_i is the hourly surplus energy from the PV system, η_c is the charging efficiency of storage, and $\eta_d$is its discharging efficiency. It is assumed that no energy dumping occurs, i.e. all surplus PV generation ends up in the grid after passing through storage and being diminished by the round-trip efficiency, $\eta=\eta_c\eta_d$, of the latter.

To obtain a feeling for the numbers involved, consider an artificial situation in which storage is fully charged at the end of every day and fully depleted the next morning. For such a system, we clearly have

$$\mathrm{UI}=365\eta \qquad (2)$$

Our nominal value of $\eta=0.75$ accordingly gives approximately UI=274.

In any practical situation, the storage will not be fully charged every day of the year. Indeed, there may be days in which storage is not required at all. Therefore, many of the terms in the numerator of Eq. (1) will take values less than their maximum and a lower value of UI will result.

We now examine how the amount of delivered energy from storage depends on the energy capacity of storage, in a simulated real situation, i.e. the IEC grid for the year 2006. Fig. 2 shows the annual energy delivered from storage as a function of increasing energy capacity, each value of EC being associated with an appropriately sized PV system (of fixed, tilt=latitude type, located at Sede Boqer in the Negev Desert).

Fig. 2 reveals the same sudden changes in slope that were observed in Fig. 1. However, we can now understand what is happening. Initially, i.e. for small PV system sizes, there will be many days during which storage is not needed because all of the PV generation would enter the grid directly. For such situations the storage is actually under-used because it will not be called upon to store or deliver any energy. As PV system size is increased, increased storage capacity is required, and its use naturally increases. This situation continues until the PV system becomes so large that there start to appear days in which a single day’s PV surplus production (minus the energy loss due to storage) is larger than the grid can use that night (Solomon et al., 2010c). Some of this surplus will remain in storage, with the consequence that less storage capacity is available the following morning for that day’s surplus. Therefore, if no energy dumping is to occur, the capacity of storage must be increased to a value larger than would hitherto have been necessary. This point appears as the sudden changes of slope in Fig. 2, which, it will be noticed, occur at the same values of Energy Capacity as do the slope changes in Fig. 1.

The corresponding behavior of UI is shown in Fig. 3 where, once again, sudden changes in slope occur. However, in these graphs there is a sign change in the slope: UI, having at first increased with EC, then starts to decrease.

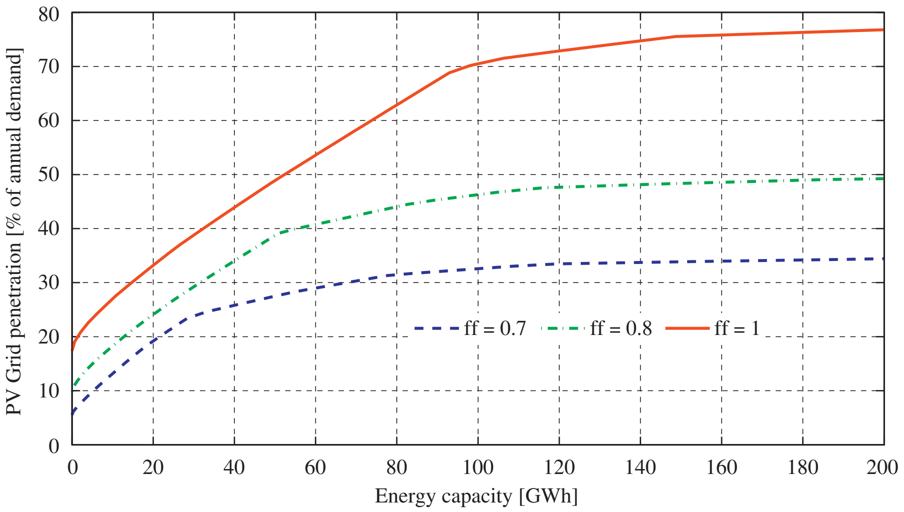

Fig. 1. Dependence of annual PV grid penetration on the storage energy capacity required by arbitrarily increasing PV system size beyond the no-dump size.

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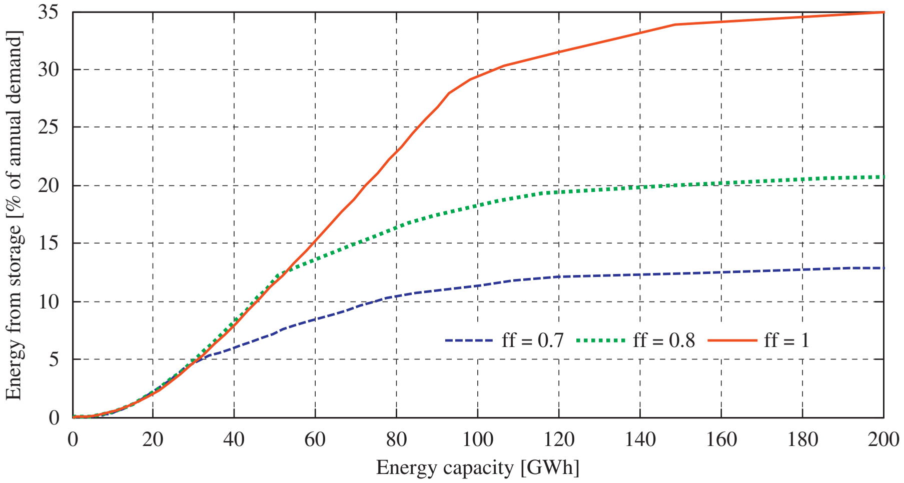

Fig. 2. Dependence on EC of the annual energy delivered to the grid from storage.

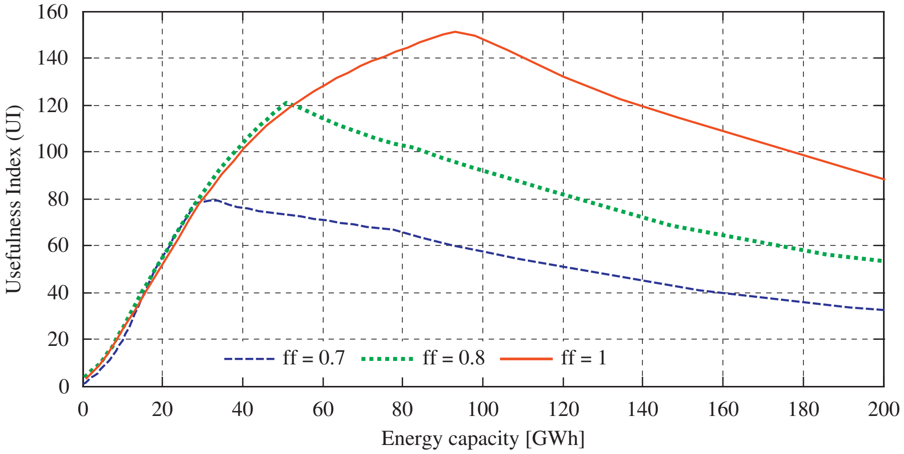

Fig. 3. Dependence of Usefulness Index (UI) on Energy Capacity (EC) of Storage.

All three of the foregoing figures indicate the points, for each grid flexibility, at which further increases in EC become less "useful". However, the virtue of the UI representation lies in the fact that it gives us a maximum, which is easier to identify than a change in slope of what is in any case a curve rather than a straight line. We accordingly refer to the EC value at which the peak in UI occurs as "Peak EC".

It is instructive to note that, even for grid flexibility $ff=1$, the peak value of UI=150 is considerably less than the maximum value of 274 calculated for the artificial example discussed above.

The foregoing discussion shows that, for any given grid flexibility, there exists a corresponding combination of PV system size and storage size, that maximizes the usefulness index of storage, producing large grid penetration while, at the same time, avoiding an unnecessarily large investment in storage. Before investigating the sensitivity of this quasi-optimal combination of PV plant size and storage size to our assumptions, we must first discuss a number of important related properties of storage.

3. Identifying the values of peak EC and the corresponding power capacity of storage

As regarding the properties of storage, so far our discussion has been exclusively in terms of Energy Capacity. However, we must also consider the Power Capacity (PC) of storage.

In the investigations summarized above, each of the curves shown was generated as a discrete set of computations. Each such computation started by defining a PV system size and then calculating the corresponding value of EC, in the manner explained in Solomon et al., 2010c, and the UI for that system size. These calculations were performed at intervals representing 10% increases above no-dump PV system size. A curve-fitting procedure was then employed for the UI vs. EC sets of points in order to arrive at the numerical value of Peak EC for each grid flexibility. In principle, these maxima could have been arrived at by appropriately reducing the step size between successive calculations, but in the interests of computational simplicity, a curve fitting procedure was preferred.

Now in Solomon et al., 2010c we saw how the demand profile and solar availability create a relationship between PC and EC if we impose the constraint that no PV generated energy is lost other than that due to storage inefficiency. Fig. 4 shows that relationship.

Therefore, knowing the value of Peak EC for any given grid flexibility, Fig. 4 tells us what the corresponding value of PC must be. We refer to this as "Peak PC". In Fig. 5 we plot Peak PC and Peak EC as functions of grid flexibility ff. One sees that both Peak EC and Peak PC increase almost linearly with the rising ff. This circumstance has a fortunate practical consequence, because such trends will simplify the gradual restructuring with time of the existing grid. This matter will be elaborated later.

We now address the sensitivity of Peak EC to small changes in either direction, and to the effect of modest PV energy dumping.

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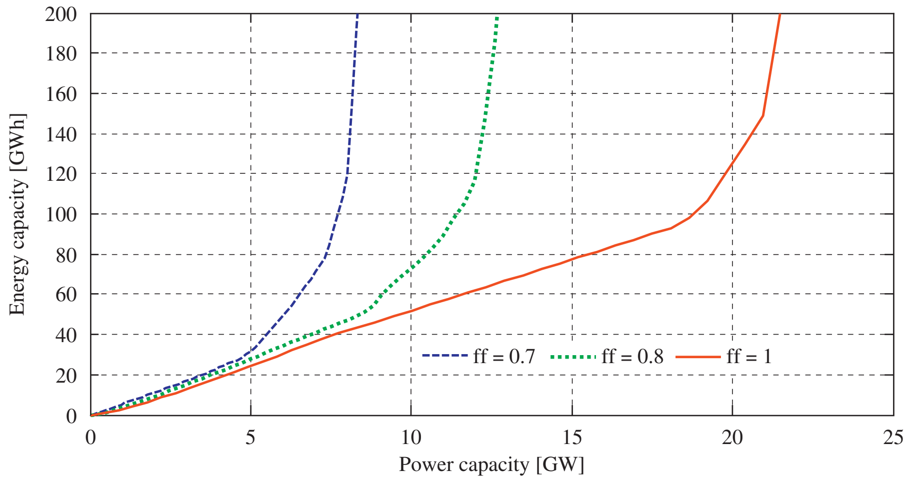

Fig. 4. Relationship between PC and EC imposed by demand profile, solar output profile, and the condition that the only allowed PV losses are due to storage inefficiency.

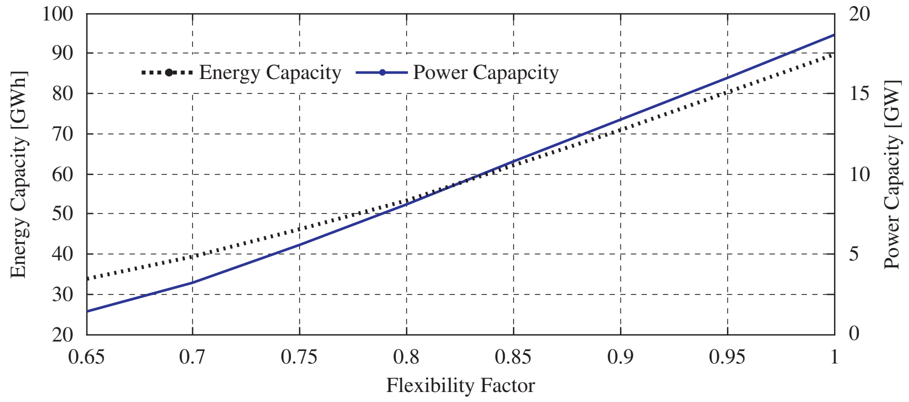

Fig. 5. Variations of Peak EC and Peak PC with grid flexibility.

4. Effect of energy dumping and increasing EC beyond peak EC

4.1. PV energy dumping

Thus far we have limited PV energy loss exclusively to that associated with storage inefficiency. However, in Solomon et al., 2010c, we found that for any given storage EC, it was possible to effect a significant increase in annual grid penetration by dumping a modest amount of PV generated energy. It is therefore desirable to examine the effect that such energy dumping might have on the value of Peak EC and more generally on the appropriate capacity of storage.

With this in mind, we first fix the properties of storage at their Peak EC and PC values appropriate to the previously-discussed situation (in which the only PV energy losses are due to storage), and consider the consequences of increasing PV system size and dumping various amounts of surplus PV energy. Fig. 6 shows how annual grid penetration varies with total lost PV energy (i.e due to 75% storage efficiency *and* some energy dumping) for various grid flexibilities.

Fig. 6 reveals, even for this situation, an initial sharp rise followed by a leveling off at all grid flexibilities. The curves in Fig. 6 start at the penetration level where the only energy loss is due to storage inefficiency alone, and then rise as total energy loss increases (mainly due to energy dumping) before leveling off. In the case of $ff=1$, we see that by allowing total PV losses to rise to 20%, annual penetration rises from an initial level of 69% to approximately 87%. Even in the $ff=0.7$ situation, a 20% total forfeiture in PV generated energy would result in an increase in annual energy provision by some 12% points.

In order to understand the manner in which energy dumping increases the annual grid penetration, we plot, in Fig. 7, the fractional amount of generated PV energy that enters the grid via storage sized at Peak EC, as a function of total PV lost energy when the PV system size is increased.

Fig. 7 enables us to see that, for all relevant grid flexibilities, the fraction of PV energy delivered from storage rises steeply as more energy is dumped, achieving a maximum when the total lost energy reaches between 15 and 20% of total PV generation, and then falls off. By comparison, in Solomon et al., 2010c, we noticed that a total forfeiture of 20% in annual generated PV energy resulted in significantly improved penetration. The present analysis shows why this is approximately the case.

It is instructive to examine the *daily* use of storage in the two cases when, PV energy losses are caused only by storage inefficiency, and when total PV energy losses are allowed to reach a nominal 20% of the annual generated PV energy, respectively. Fig. 8 shows these results for the entire year, where $ff=1$ is assumed, together with its appropriate Peak EC value of 94.5 GWh. [For purposes of scale, we recall that during 2006, the total IEC generating capacity was 10.5 GW and the total energy generated was 50.4 TWh (IEC, 2007)]

From Fig. 8 we see that in the situation where energy loss is restricted to that caused by storage inefficiency, there is only one day in the year for which storage is almost full. For all other days barely more than 50% of its energy capacity is used. On the other hand, when PV energy losses are allowed to reach a total of 20%,

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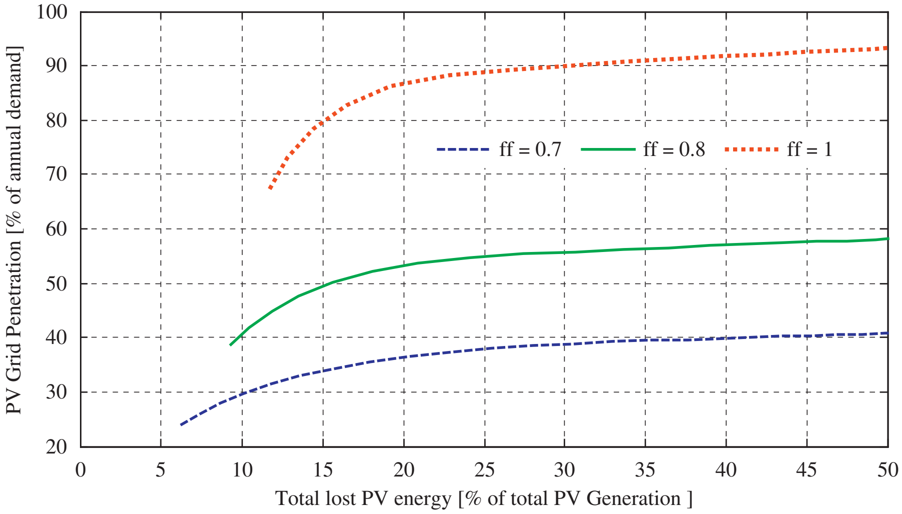

Fig. 6. Grid penetration as a function of total PV energy loss (maintaining storage capacity at Peak EC), for various grid flexibilities.

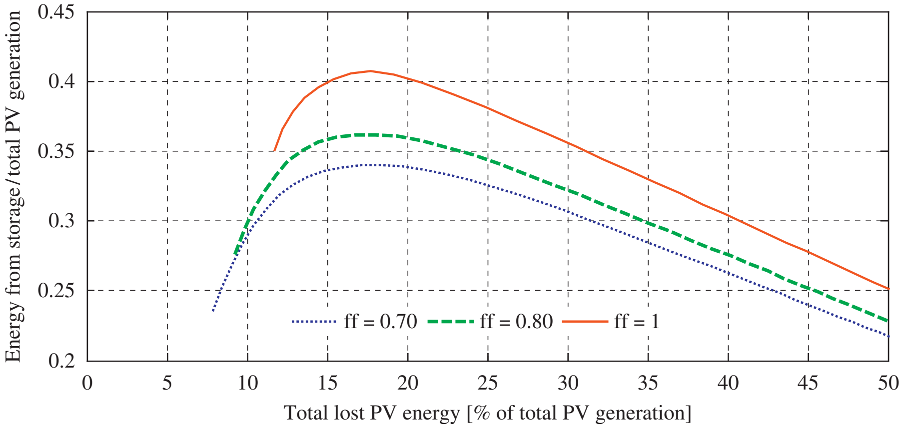

Fig. 7. Fraction of PV energy supplied to the grid via storage sized at Peak EC, as a function of total PV energy losses, for various grid flexibilities.

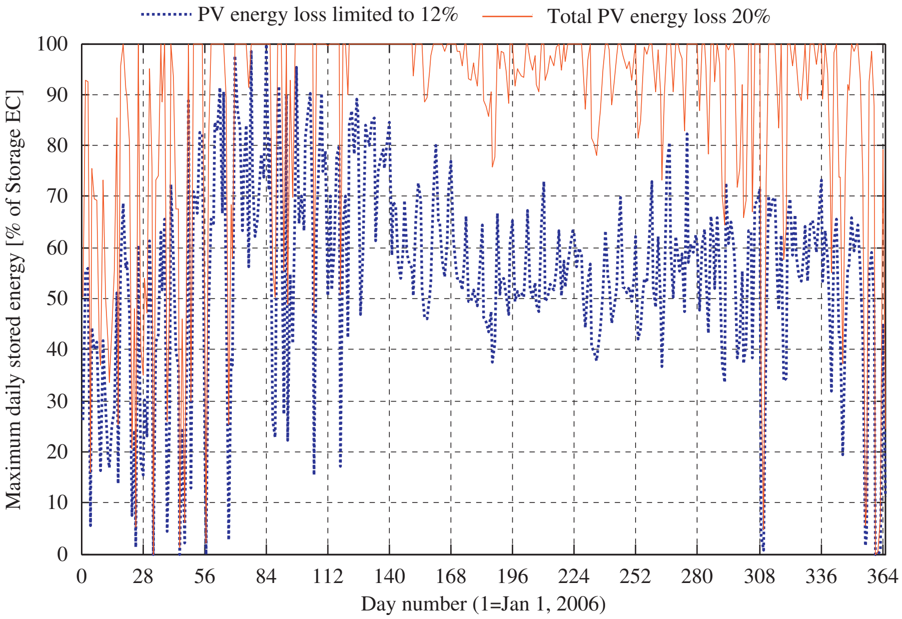

Fig. 8. Maximum daily stored energy, as a percentage of Peak EC=94.5 GWh, for: (a) energy loss due to storage inefficiency only (approximate loss=12%) [dotted curve]; (b) total loss=20% (including approximately 8% energy dumping) [piecewise continuous curve].

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Fig. 8 shows that storage becomes full, or nearly so, for a large number of days in the year. A corollary of this finding is that very little can be gained by increasing total PV energy losses above the 20% level, as storage is seen to be almost fully used by the time energy dumping has reached this level.

4.2. *Varying EC around peak EC*

We now fix grid flexibility at *ff*=0.8 (the value at which, as previously indicated, the IEC grid *could* have been operated in 2006) and examine the sensitivity of the previous result to changes in storage capacity. Specifically we study the effect that varying the storage energy capacity by small amounts on either side of Peak EC has on annual grid penetration as a function of total lost energy. It should be kept in mind that in varying EC we are also varying PC and PV system sizes following the constraints upon them caused by their interaction with the demand profile (Solomon et al., 2010c). The results are shown in Fig. 9.

Fig. 9 shows that for any allowed amount of lost PV energy, grid penetration increase with increasing EC, but that the improvement diminishes ever more rapidly as one passes through Peak EC from below to above. Quantitatively, it can be seen that some small improvement (approximately 3% in annual energy requirements) may result from increasing the storage capacity by about 20% above the Peak EC but any further increase would be even less advantageous.

It is also important to examine the effect of increasing storage above Peak EC for a range of grid flexibilities. For this purpose we fix the total energy losses at our nominal value of 20% of the annual PV generation. The resulting grid penetration as function of EC is shown in Fig. 10.

Fig. 10 shows that annual penetration increases, for all grid flexibilities, if EC is increased beyond Peak EC. This is particularly apparent at the higher grid flexibilities for which a small increase in penetration (also in the vicinity of 3% of the annual requirements) can be achieved for a roughly 20% increase in storage energy capacity.

5. Choosing appropriately sized storage for high PV penetration

The foregoing discussion has shown that slight increases in annual grid penetration may be achieved at all grid flexibilities if total PV energy losses of approximately 20% are permitted, and if storage capacity is increased by approximately 20% above the Peak EC. However, it must be kept in mind that a truly appropriate storage capacity can only be arrived at by including

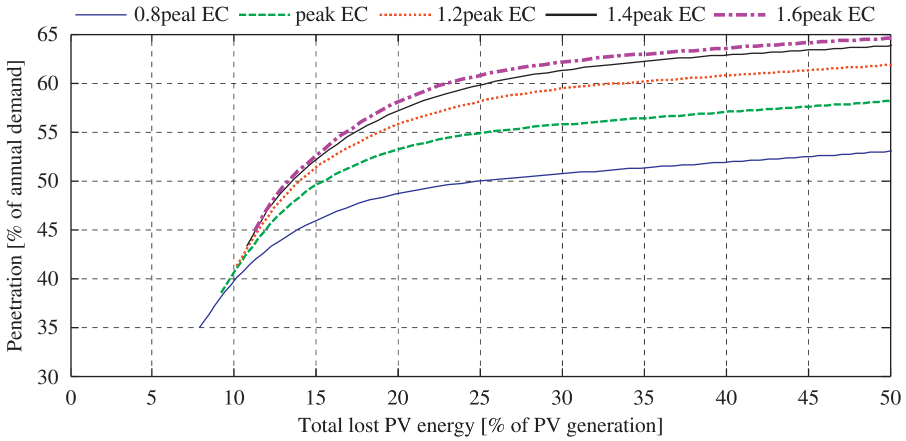

Fig. 9. Annual grid penetration as a function of total lost PV energy, for various storage capacities in the vicinity of Peak EC, assuming *ff*=0.8.

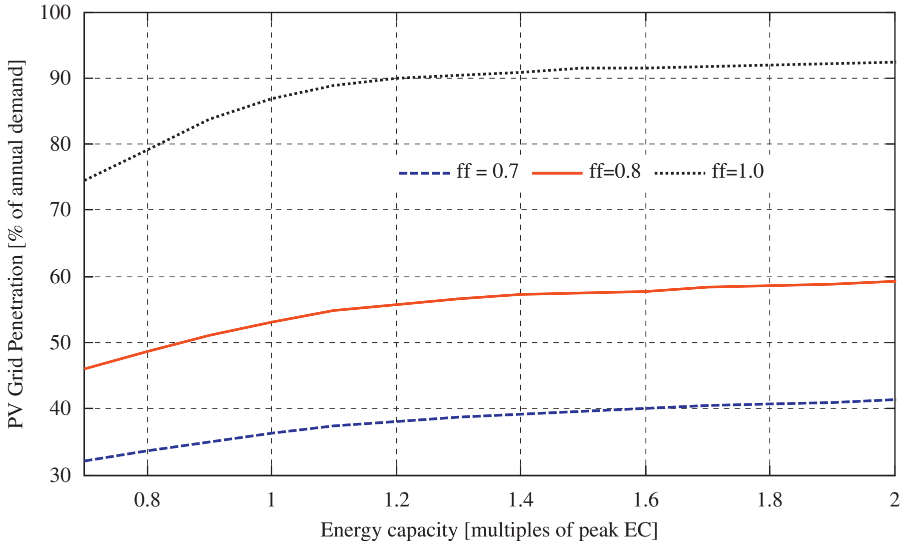

Fig. 10. Grid penetration vs. Energy Capacity for various grid flexibilities. Assumes 20% total PV energy losses.

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additional technical considerations such as the properties of the associated conventional plants, grid operating strategy, and of course various economic constraints. Nevertheless, the results discussed above provide a set of technical constraints within which these additional considerations must fit in order to achieve high grid penetration.

In order to provide an indication of the various magnitudes involved, we set the total allowed PV energy loss at 20%, and tabulate as functions of grid flexibility: EC, PC, PV system sizes, and annual grid penetration. This is done for a band of EC values in the range 1.0–1.2 Peak EC—the range within which, as we have already seen, it is important to maintain EC should other considerations warrant a departure from Peak EC. The results are shown in Table 1.

Table 1 reveals a monotonic increase of all system properties with increasing grid flexibility. This is a potentially important finding because if future grid restructuring will occur so as to accommodate ever more PV input, it will be necessary to raise grid flexibility. However, Table 1 also indicates that such restructuring can occur in stages, with each storage addition having the necessary ratio of EC-to-PC in order to keep pace with grid requirements.

Interestingly, in Solomon et al., 2010c we had arbitrarily considered a storage with EC=100 GWh. There we found that for a grid flexibility $ff=1$ and 20% allowed PV energy loss, the annual grid penetration would have been 88.5%. The present study confirms that this value of storage falls within the desired range of Peak EC to 1.2 Peak EC, and that the associated grid penetration is indeed within the corresponding penetration range of 86.6% to 90.0%, as seen in Table 1.

Table 1
Allowed ranges of system properties and corresponding grid penetration, for various grid flexibilities, when total annual PV losses of 20% are permitted.

Grid flexibility *ff*	Achievable penetration [% of annual demand]	PV system rating [GW$_p$]	Energy capacity [GWh]	Power capacity [GW]
0.65	28.7–29.8	5.6–6.0	25.6–30.7	3.5–3.8
0.70	36.3–38.1	8.1–8.5	32.8–39.4	4.9–5.4
0.75	44.6–46.8	11.0–11.3	42.4–50.9	6.5–7.3
0.80	53.2–55.8	13.5–14.2	52.5–63.0	8.4–9.4
0.85	61.9–64.8	16.2–17.1	63.2–75.8	10.5–11.8
0.90	70.3–73.2	19.0–19.9	73.5–88.2	12.7–14.3
0.95	78.7–81.7	21.7–22.6	83.8–100.6	15.1–16.8
1.00	86.9–89.9	24.3–25.4	94.5–113.4	17.4–19.3

However, in Solomon et al., 2010c we also considered the *same* 100 GWh storage size for the case of grid flexibility $ff=0.8$, instead of what we now see to be the more appropriate size of approximately 60 GWh as indicated in Table 1. The calculated penetration for that oversized storage was found to be 58.5% (Solomon et al., 2010c). This is only slightly larger that the penetration of about 55% that Table 1 indicates would have been achievable with far less storage. Thus, we see that for grid flexibility $ff=0.8$ our previous guess had oversized storage by almost a factor of 2, illustrating the importance of the present study.

6. Other required characteristics of storage

In addition to appropriate values of EC and PC, there are a number of additional requirements of storage and its operation if the resulting PV system is to achieve high penetration.

The first additional requirement is that the storage system must be able to store and supply over a wide power range depending on the available PV power and the concomitant load requirement. In order to see what this means, we have plotted in Fig. 11, the number of hours per year, in descending magnitude, during which storage would have been required to accept or deliver energy in various quantities above any given level. The figure assumes Peak EC (=94.5 GWh, and the corresponding Peak PC=15 GW), 20% total PV energy loss, and grid flexibility $ff=1$.

Fig. 11 shows that storage would have been in its charging mode for approximately 2750 h of the year. During those hours the hourly charging capacity would have varied between approximately 0% and 100% of storage power capacity (15 GW)). Similarly, the storage would have been in its discharging mode for approximately 4360 h of the year, with the hourly discharging varying from approximately 0% to nearly 60% of the storage power capacity.

Now the maximum observed IEC demand during the year 2006 was 9.5 GW, which, if it had been provided by storage, would have required a discharging capacity of approximately 65% of PC. The fact that during 2006 the maximum calculated hourly discharge was only 60% of PC is a consequence of the circumstance that storage would not have been full on the particular winter hour in which the load demand peaked. For that hour, conventional backup would have been required. The required size of such standby backup will be discussed elsewhere.

A second important consideration addresses the simplifying fact we have made that Fig. 11 treats all hours equivalently. This implies

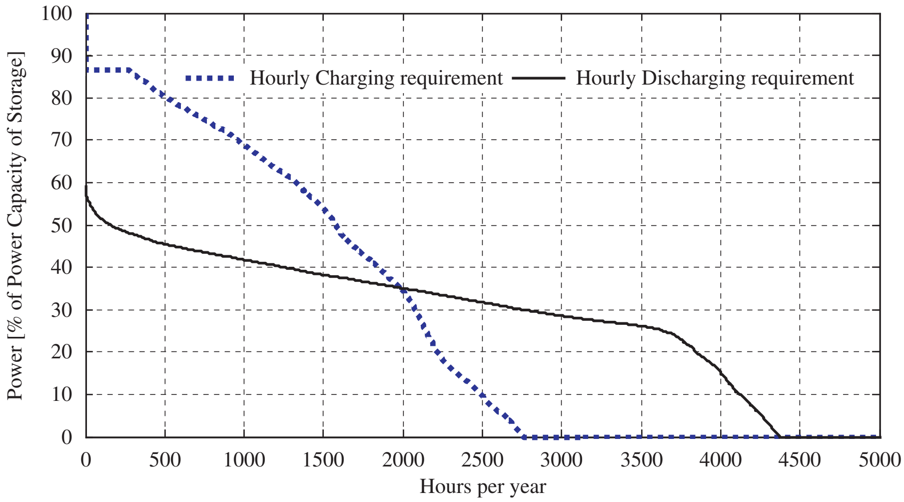

Fig. 11. Hourly charging and discharging requirement for Peak EC storage at $ff=1$ when total energy loss is 20% of PV generation. (Peak EC=94.5 GWh and Peak PC=15 GW).

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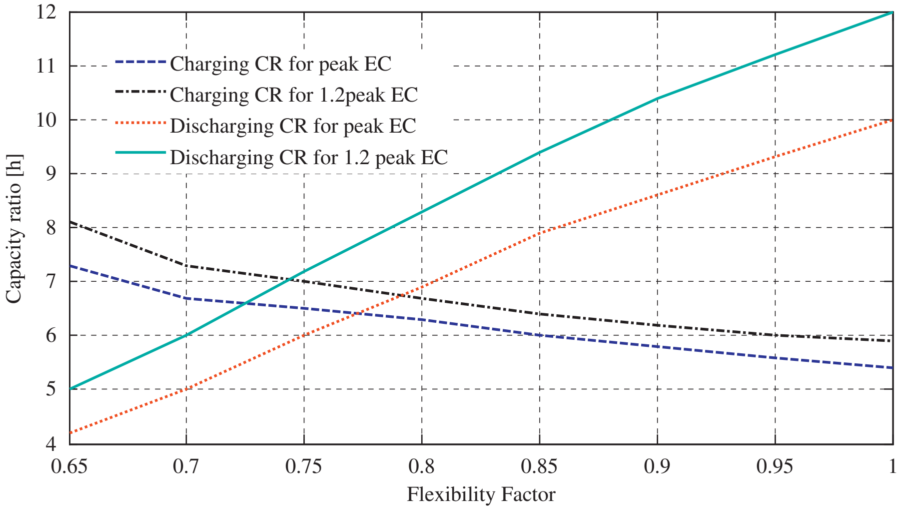

Fig. 12. Fastest required charging and discharging times (capacity ratios) of storage as functions of grid flexibility.

an assumption that the efficiency of charging (and discharging) remains constant for all rates of charge (and discharge) and for all levels of energy in storage. If this is not the case (as it rarely is for real batteries), then it is necessary to employ some appropriate device (physical or logical), as will now be discussed, in order to maintain losses at their desired level.

In the event that storage efficiency does not remain constant with differing energy levels and rates of charging or discharging, the discharging problem is relatively easy to solve. This may be done via short-term (i.e. daily and less) forecasts of load and PV output, together with an appropriate employment of fast-ramping conventional plants in the grid. Moreover, if for a particular storage type, there exists a minimum level below which damage or some other penalty would occur, then EC must be redefined as the useable storage above this danger level.

However, although forecasting is also important on the charging side, the total charging problem is more complicated because we have no control over the intermittent input from PV. One method of overcoming the problem would be to employ a mix of storage technologies with different properties from one another. A smart operation strategy would then be combined with forecasting of load, PV output and state of charge in the various storage units, in order to optimize the manner in which the individual components of storage are charged and discharged.

Yet a third additional important property of storage is that it must allow for the differences between the required fastest rates of charging and discharging that will be called upon during the year. In particular, as was already evident from Fig. 11, the storage system should have the ability to accept energy over relatively short periods of time compared to the time needed for delivery to the grid. In Solomon et al., 2010c we introduced the concept of storage capacity ratio CR=EC/PC, which has the dimensions of time. In the simplified situation for which the storage has identical charging and discharging rates, CR represents the minimum time needed either to fully charge an empty storage of energy capacity EC or to fully discharge the full storage. In the more realistic situation, as now encountered, we must distinguish between these two times. Specifically, the fastest charging (discharging) rate will be the largest hourly increase (decrease) in stored energy. As a technical aside, the linkages between EC and PC we have calculated in Fig. 4, define CR, as used thus far, as the *charging* capacity ratio. We therefore define a discharging capacity ratio as EC divided by the largest expected hourly decrease in storage energy (which depends on the load and in this case, also on grid flexibility). It has the units of h, because we are using hourly data. Fig. 12 plots these two CR curves as functions of grid flexibility, for the range of energy capacities between Peak EC and 1.2 Peak EC.

Fig. 12 indicates that at a grid flexibility $ff=0.8$, the fastest required charging time is seen to be approximately 6.5 h, whereas the fastest required discharge time is in the approximate range 7–8.5 h. For higher flexibilities the difference between the required maximum charging and discharging times is seen to be even larger.

7. An assessment of available storage technologies for large-scale PV-grid application

Storing large amounts of PV energy, as discussed above, requires the maintaining of power quality in the face of incoming intermittent PV energy; the shifting of large amounts of daytime PV surplus energy to nighttime; and ensuring the continuity of changeover among the various power supply sources (PV, storage, and conventional plants). To this end it is instructive to examine the various storage technologies that are available.

Existing storage technologies are often grouped into three general categories, based on their response time, power delivery requirements, and duration of their services (EPRI, 2002; Nourai, 2002; MacDowall, 2006; Ibrahim et al., 2008; Chen et al., 2009; Toledo et al., 2010). In particular, those suitable for power applications, those employed as buffer or emergency systems, and those used for energy applications.

Technologies, such as ultra-capacitors, fly wheels, and superconducting magnetic energy storage (SMES), are suitable for power applications, which last from fractions of a second to a few seconds, since they are capable of providing large amounts of power at short notice in order to maintain power quality during sudden disturbance in the power system.

Storage types used for buffering applications generally serve as bridges for seconds to minutes, ensuring continuity of service during the switching over of electricity sources from one to another, or during sudden power losses. Batteries are good for such applications.

Storage technologies employed for energy applications do not need such fast time responses but they must operate for longer periods of time (hours). Pumped hydro and compressed air energy storage (CAES) are suitable for such kinds of applications.

Existing storage technologies have widely varying power ratings depending on their design. The ranges of power ratings of various existing systems have been given in the review by

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Chen et al., 2009. This review indicated that the range of power ratings for pumped hydro is 100–5000 MW, 5–300 MW for CAES, 0–50 MW for different electrochemical batteries, 100 kW–10 MW for SMES, and 0–300 MW for ultra-capacitors. Furthermore, discharge time range varies from less than a second to hours depending on the technology type and design within a given technology. The range of the discharge time for pumped hydro and CAES is 1–24 h. The corresponding range for batteries is seconds to 10 h, milliseconds to 8 s for SMES, and milliseconds to 1 h for ultra-capacitors.

For our purposes all of these technologies would have a certain amount of design flexibility in the event that we needed to combine them in order to arrive at some specific set of power ratings and discharge times. The modularity of batteries gives them more design flexibility than mechanical technologies such as pumped hydro and CAES, which later are also more dependent on geographic location, geology, and other mechanical factors.

Each of these technologies also differs from the others with respect to: output properties, charging and discharging characteristics, the manner in which power and energy capacities are defined, number of cycle life, etc. Some detailed comparisons can be found in (Kondoh et al., 2000; Schoenung, 2001; EPRI, 2002; Du Pasquier et al., 2003; MacDowall, 2006; EPRI, 2007; Ibrahim et al., 2008; Chen et al., 2009; Inage, 2009; Toledo et al., 2010). On the one hand, these differences allow considerable latitude in designing a hybrid storage system having all of the required properties for our needs. On the other hand, they complicate the management of a PV-(Hybrid) storage–Grid complex. This management problem is exacerbated still further by the often varying efficiency of a storage unit with its state of charge (SOC), as the following lead-acid battery example illustrates:

The charging efficiency of a lead-acid battery depends on its SOC and charging rate. Similarly the discharging efficiency also varies with SOC and discharge rate. Specifically, the discharge efficiency decreases rapidly as the battery SOC approaches zero, while the charging efficiency decreases sharply as the battery approaches 100% SOC (Stevens and Corey, 1996; Ibrahim et al., 2008). This indicates that, for a given charge and discharge rate, the battery maintains its optimal round trip efficiency only within a relatively narrow range of SOC. Furthermore, the battery needs periodic charging to full capacity in order to minimize loss of its energy capacity. Full charging is, therefore, carried out by subsequently reducing the charge rate as the battery approaches 100% SOC in order to limit efficiency losses. On the other hand, discharging the battery to low levels of SOC has little benefit since frequent full discharge leads to the additional penalty of significant decrease in life time. All of these factors indicate that the available energy capacity of lead-acid batteries is much lower than that indicated in the manufacturer's rating.

Corresponding limiting characteristics can be found for other energy storage technologies (Ter-Gazarian, 1994; Kuwabara et al., 1996; Masuda and Shintomi (1977); Taylor et al., 1997; Wagner, 1997; Slobodkin, 1998; Sporilod et al., 1999,2000; Burke, 2000; Kondoh et al., 2000; Parker, 2001; EPRI, 2002; Du Pasquier et al., 2003; Jung et al., 2003; Tamyurek et al., 2003; Bito, 2005; MacDowall, 2006; Succar and Williams, 2008; EPRI, 2007; Barote et al., 2009;Chen et al., 2009; Divya and Ostergaard, 2009; Hadjipaschalis et al., 2009; Doughty et al., 2010; Lippert et al., 2010). But it is encouraging to note that several technologies, such as SMES, ultra-capacitors, flywheels, CAES, pumped hydro, vanadium redox flow batteries (VRB), and sodium sulfur (NAS) batteries experience little loss of lifetime from deep discharging but they may still experience efficiency loss at low levels of SOC.

Based on this brief summary of existing technologies, two conclusions become clear. First, that no single storage type has all of the necessary properties for large-scale matching of PV to the grid. Moreover, it must not be forgotten that even our calculated EC, PC, and CR requirements are not the entire story, because our analysis was confined to hourly considerations due to a lack of data on a finer time scale. It accordingly ignores the often faster time responses from storage that will be required by the intermittent nature of the PV input.

Regarding this first conclusion, both pumped hydro and CAES are large enough for utility-scale purposes but they take a relatively long time (minutes) to come on line. On the other hand, fast-acting storage technologies (seconds and less) such as flywheels, ultra-capacitors, SMES, and certain types of battery, are all, at the present state of their development, too small to handle storage for many hours at a time. However, NAS and VRB batteries and SMES show promise for being able to overcome this problem in the future; typically with of order 10 h of peak power delivery at their respective rated powers (EPRI, 2002).

Our second conclusion is that it should be possible to combine units of different technology types, which, together, could perform the task of matching PV output to grid requirements. Regarding this second conclusion, in designing a hybrid storage system, one must choose an appropriate mix of storage technologies in order to satisfy the requirements, when called upon, for: rapid response times; sufficient energy capacity; and long or short charging and delivery times. As far as the grid is concerned, such hybrid storage, together with direct solar input will function in analogous manner to the way conventional power plants with different response times are dispatched.

Finally, it is important to keep in mind that not all of the storage units (whether hybrid or monolithic) need be kept at a single location. Thus a full analysis for optimizing a future PV-storage-grid system would need to include transmission and inter-connection losses too.

8. Conclusions

In the present paper we have studied the manner in which it is possible to arrive at a first approximation to appropriately sized PV-storage combinations in order to achieve high grid penetration for various grid flexibilities. By drawing on some regularities we had observed in a previous paper on the subject (Solomon et al., 2010c) we are now able to come up with a storage size recommendation, which is neither too small to increase grid penetration in a significant manner nor wastefully large. For this purpose we found it convenient to define a storage *Usefulness Index*, UI, which has the property of peaking at the desired value of storage energy capacity, which we term *Peak EC*.

A second finding was that Peak EC, together with the corresponding value of Peak PC—energy capacity and power capacity having previously been shown to be mutually linked by the PV–Grid interaction (Solomon et al., 2010c)—were both found to increase approximately linearly with increasing grid flexibility. This fact will facilitate the long-term planning of grid development in which rising flexibility will allow an ever increasing contribution from appropriately-sized PV-storage combinations.

We studied the sensitivity of Peak EC (the value of which was arrived at by assuming that the *only* energy losses are those due to storage inefficiency) to a modest amount of energy dumping, the need for which would be brought about by increasing the PV system size. We had previously found that some energy dumping in this manner would increase grid penetration (Solomon et al., 2010c). However the present study shows that very little can be gained by increasing total PV energy losses above about 20% of total PV generation. This is because by the time energy dumping has reached this level, storage is almost fully used, and further gains in grid penetration would be negligibly small.

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A further finding of the sensitivity study was that, should additional circumstances (outside the scope of the present study) require it, EC may be increased by up to approximately 20% above Peak EC with a resulting slight increase in grid penetration. But further increase in the size of EC would be wasteful.

In addition to our previous study of EC and PC, the present paper draws attention to the different requirements of storage vis-à-vis its charging and discharging power capacities. In particular, storage has to be capable of storing and supplying energy over a wide range of levels and time scales, depending on the available PV power and the concomitant load requirement. For this purpose it will probably be necessary to employ forecasting, smart control technologies, and possibly a storage system constructed out of subunits involving a variety of technologies. Furthermore, the design of such a hybrid storage system at any given moment of time will have to take into consideration future plans regarding targeted grid flexibility.

Our last pair of important findings, based upon a review of existing storage technologies, are that: (a) no single existing storage technology type has all of the required properties; However, (b) it should be possible to devise a hybrid storage system, composed of subunits of various technologies, that would have appropriate properties for large PV grid penetration.

Finally, it is important to emphasize that even though we have not yet performed an economic optimization—for reasons that were stated in (Solomon et al., 2010a)—the present study provides physical bounds within which an eventual economic optimization would need to fall if it is not to incur serious penalties in grid penetration.

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