Presented at ASES 2010 Annual Conference,

QUANTIFYING THE COST OF HIGH PHOTOVOLTAIC PENETRATION

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ABSTRACT

This paper presents a methodology to quantify the cost of energy storage required to provide firm capacity on a utility power grid using a combination of energy produced by a specific generation source and storage. Firm capacity is defined to mean that all demand above a given threshold load is satisfied exclusively by the considered generation source, directly or indirectly via storage. The cost of storage is representative of the cost of high penetration since the approach is valid over all penetration levels. The paper applies the methodology to PV as the generation source for three utility case studies. Results suggest that the cost of storage is a small fraction of the installed PV cost up to penetration levels approaching 40% in the best cases.

1. INTRODUCTION

An important benefit of PV generation is its ability to satisfy peak electrical demand [1, 2, 3]. Much of the value of dispersed PV generation, including generation capacity credit, transmission and distribution (T&D) stress mitigation, and grid security enhancement, derives from this effective capacity.

Effective capacity decreases with PV penetration. While peak demand is often indirectly driven by the solar resource via heat waves and resulting air conditioning demand, the secondary peaks and base load demands are not. The result is that dispersed PV generation's peak-shaving ability decreases with increasing penetration. It is important to note, however, that environmental, fossil fuel depletion/price risk mitigation and economic development values are not necessarily a function of penetration.

This paper quantifies the amount and cost of storage required to maintain firm capacity with any level of penetration. The methodology is flexible enough to analyze any penetration level from 0% to 100%.

The methodology is generally applicable to any type of generating resource, intermittent or dispatchable. In order to clearly illustrate how to apply the methodology, however, PV is selected as the generating resource under consideration.

2. METHODOLOGY

This section begins with a definition of variables. The relationship between the variables is illustrated in Fig. 1 using measured load and simulated PV data.

2.1 Definitions

Peak Load: L_{Peak} (MW) is the peak system load over the selected analysis period

Threshold Load: $L_{Threshold}$ (MW) is the system load above which all demand is satisfied by the considered generation resource, either directly or indirectly using storage.

Base Load: L_{Base} (MW) is the load below which power cannot be displaced. It can be expressed as a fraction (γ) of the Peak Load.

Firm Generation Capacity: G_{Firm} (MW) equals Peak Load minus Threshold Load. All loads greater than the Threshold Load are satisfied by energy produced from the considered generation resource, either directly or indirectly using storage. For example, a system with a 1,000 MW Peak Load

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and an 800 MW Threshold Load has Firm Generation Capacity of 200 MW.

Installed Generation Capacity: $G_{Installed}$ (MW) is the rated capacity of the installed generation.

Useful Generation Capacity: G_{Useful} (MW) is the rated capacity of a resource that would provide the same amount of energy as $G_{Installed}$ after accounting for all storage and/or excess production losses (see below).

Excess Energy Production (MWh) is the excess energy that must either be stored or wasted. Energy produced by base load generation, such as nuclear power, cannot be displaced. Thus, Excess Energy Production occurs when the Base Load exceeds Load minus Production.

Storage capacity is composed of power Storage Power Capacity (MW) and Storage Energy Capacity (MWh).

Storage Power Capacity: $S_{Power\ Cap.}$ (MW) is the maximum power output of storage required at any time during the analysis period to ensure a selected firm capacity objective. The Storage Power Capacity can range between a minimum of 0 (if no storage is ever required) and a maximum of Firm Generation Capacity (if storage is required to make up for a total deficit of the resource at the time of the Peak Load).

Storage Energy Capacity: $S_{Energy\ Cap.}$ (MWh) is the maximum storage production capacity required at any time during the analysis period.

Note that the storage is sized to achieve firm capacity and not to absorb all possible Excess Energy Production. All excess production beyond the ability of the capacity-sized storage to absorb it is considered lost.

Two ratios are useful in performing the analysis: Firm Capacity Penetration and Relative Firm Capacity.

Firm Capacity Penetration: α equals the ratio of Firm Generation Capacity to Peak Load.

$$\alpha = \frac{G_{Firm}}{L_{Peak}} \qquad (1)$$

Relative Firm Capacity: β is the ratio of Firm Generation Capacity to Installed Generation Capacity.

$$\beta = \frac{G_{Firm}}{G_{Installed}} \qquad (2)$$

There is a limiting factor in the maximum possible value of β in the case of PV generation. Relative Firm Capacity can easily reach 100% or greater at modest penetration levels. The only requirement to provide Firm Generation Capacity is that storage is sufficient to backup PV when needed. As Firm Capacity Penetration increases, the requirement that PV produce enough energy to satisfy all loads above Threshold Load becomes relevant. This may limit the maximum possible value of Relative Firm Capacity.

Consider a simple example of PV achieving 100% Firm Capacity Penetration on a grid with a 50% load factor, and a PV generation resource with a 25% capacity factor. Generating enough energy with PV to satisfy all demand would require $G_{Installed}$ to be twice as large as the L_{Peak} (assuming no conversion losses into and out of storage). As a result, Relative Firm Capacity could not exceed 50%.

Equations (1) and (2) can be combined so that Installed Generation Capacity is expressed as a function of Peak Load, Firm Capacity Penetration, and Relative Firm Capacity.

$$G_{Installed} = \left(\frac{\alpha}{\beta}\right) L_{Peak} \qquad (3)$$

2.2 Cost of Providing Firm Generation Capacity

The cost of providing Firm Generation Capacity can be calculated as the sum of three terms: (1) the capital cost associated with the storage investment, (2) the capital, fuel, and O&M costs associated with needing to oversize the resource to account for round-trip storage efficiency losses and (3) the capital, fuel, and O&M costs associated with needing to oversize the resource to account for excess energy losses.

$$C_{Total} = C_{Storage} + C_{G-Roundtrip} + C_{G-Excess} \qquad (4)$$

In the case of PV, the considered costs are installation costs and do not include lifetime operating costs, to the exception of $C_{Storage}$ where the discounted cost of future replacements is included depending upon the technology choice (see case studies below).

C_{Total} may be expressed per kW of $G_{Installed}$, G_{Firm}, or G_{Useful}.

The cost of storage is a function of the considered storage sizes and charge/discharge time scales. Table 1 provides estimates of energy costs, power costs, discharge times, and operational sizes for current and near-future storage technologies [6].

For this article, we selected lead-acid batteries or equivalent for both short-term (less than one PV system-hour) and medium term needs (less than 10 system-hours) with an installed nominal power/energy cost of $350 per kW/ $200 per kWh for short-term requirements (<1 hour) and $350 per kW/$150 per kWh for 1-10 hour requirements. Batteries are assumed to have a lifetime of 10 years and must therefore be replaced. Beyond 10-hour requirements, large scale compressed air, some form of pumped hydro, or high density metal-air batteries could be considered. Hence we selected a nominal cost of $850 per kW/$50 per kWh, and a lifetime of 30+ years.

Both $C_{Storage}$ and $C_{GRountrip}$ depend upon storage round-trip efficiency. Based on the mix selected, we conservatively assumed a round-trip efficiency of 75% for the batteries and 65% for the large scale technologies.

The sum of $C_{G\text{-}Roundtrip}$ and $C_{G\text{-}Excess}$ is quantifiable in terms of the difference between $G_{Installed}$ and G_{Useful}, i.e., it amounts to the cost oversizing the resource and incuring production losses in order to meet the firm capacity objective. In this article we assume that the nominal resource oversizing cost for PV is $2,500/kW – this represents the lowest cost cutting edge of today's largest scale systems, but likely a mainstream value at the time PV reaches the levels of penetration pertaining to this study.

3. CASE STUDIES

We illustrate the methodology with three utility case studies, asking the question: what is the cost of ensuring that a firm fraction of PV can satisfy all demand above a firm penetration threshold as this threshold is lowered and approaches base load?

This question is answered for the following set of assumptions:

Firm Capacity Penetration (α)	up to 75%
Relative Firm Capacity (β)	25, 50, 75 and 100%
Base Load Fraction (γ)	25%

Note that β = 75% represents the best case of low-penetration, high-value effective PV capacity observed for US utilities [e.g., 1, 2]. The selected values for α and γ imply that, at 75% Relative Firm Capacity, all loads on the utility grid are met exclusively by PV+storage and base-load generation.

The selected utilities, Nevada Power (NP), Rochester Gas and Electric (RG&E) and Portland General (PG) have markedly distinct environments and operational characteristics. Nevada Power (NP) is a metropolitan utility with a considerable solar resource and a large commercial air-conditioning load. Rochester Gas and Electric (RG&E) serves a medium-sized industrial city in upstate New York, where cloudy conditions are frequent. Portland General (PG) serves the city of Portland, Oregon. Both NP and RG&E are summer peaking utilities while PG has comparable summer and winter demand peaks, but a higher winter energy consumption overall.

For all utilities, nominal PV output was simulated for fixed systems facing southwest at 30° tilt (i.e., optimized for mid-afternoon summer peak shaving). Time/site specific PV simulations were performed using SolarAnywhere and PV Simulator [4, 5]; both have been thoroughly validated [7, 8].

4. RESULTS & DISCUSSION

4.1 Achievable Relative Firm Capacity for PV

As explained in Section 2, there is a limiting factor in the maximum possible value of β for PV generation. Figure 2 illustrates this limit for the three selected utilities. For PG, β can only reach 100% up to 31% firm penetration. The maximum possible β decreases down to 28% at 75% firm penetration. For RG&E and NP, the 100% achievability limit is reached at 48% and 68% firm penetration, respectively.

Achievable Relative Firm Capacities are linked to (1) the resource's capacity factor – highest for NP; (2) the coincidence between demand and solar generation – also highest for NP -- and (3) the utility's load factor – highest for PG at 67%, and lowest for NP at 48%.

4.2 Cost of High Penetration

Storage Requirements: Figure 3 (left side) reports the required Storage Energy Capacity as a function of Firm PV Penetration for Relative Firm PV Capacity strategies of 25%, 50%, 75% and 100%.

Note that some of the curves are truncated because of the above β limit.

It is important to reiterate what the β strategies signify in order to intercompare storage requirements. At any level of Firm Penetration, a β of 25%, 50%, and 75% imply $G_{Installed}$ respectively 4, 2, and 1.33 times larger than the 100% Relative Firm Capacity case. Therefore it is not surprising that storage requirements increase with increasing β (hence decreasing $G_{Installed}$). In fact some of the β strategies do not need storage to achieve firm capacity, e.g., in the case of RG&E, the β = 25% can guarantee its firm objective without any storage up to ~10% firm penetration.

The apparent inflection points and plateaus (enhanced by the log scales used in the plots) reflect causal changes in storage requirements depending on the site and selected firm capacity strategy, first reaching the point where storage cannot be replenished within a 24 hour cycle during a multi-day peak event and then the point where storage begins to be driven by sustained winter PV output deficit.

Cost: The total cost of high penetration, including both its storage and generation oversize components is reported on the left side of Fig. 3. All costs are reported in terms of $ per G_{Firm}.

In order to present results in a context where options can be directly intercompared, the calculated costs are reported so as to answer to the following decision-making question: "What is the cost of maintaining a given low penetration PV value as penetration increases?" Further assuming that this low penetration value derives from a Relative Firm Capacity of 75% based upon [1, 2], Figure 3 reports the total cost of maintaining this low penetration capability as penetration increases for each of the four β strategies. This objective can be achieved either by adding storage as needed, or by oversizing the generator -- e.g., the β = 25% strategy will achieve this objective at the cost of an oversized array by a factor of 3, while the β = 100% strategy will achieve it with an undersized array (i.e., delivering a benefit) but at the possible cost of more storage.

As firm penetration increases, the tradeoffs between the strategies become apparent. At low penetration, the lowest firm capacity costs is achieved for the highest β, but as penetration increases, the least cost options switch to lower and lower β, as the cost of storage overtakes the cost of oversizing the generator.

The cost of high penetration per se, starting from the low penetration ideal case (defined here as 75% PV capacity) is the low boundary tangent to the network of curves highlighted in the plots with the thick semi transparent curve.

4.3 Bottom Line

Considering a target relative firm capacity of 75% (representative of high-value low penetration) penetration costs remain well under $100 per firm kW up to firm penetrations of 18%, 13% and 5% for NP, RG&E and PG, respectively. For these respective utilities, cost reaches $1,000 per firm kW for penetrations of 28%, 20% and 11%, and $3,000 per firm KW for penetrations of 44%, 40% and 18%.

Significant firm capacity PV penetrations can thus be achieved for both NP and RG&E while incurring manageable logistical expenses. For instance in the case of RG&E, representing a typical northeastern utility (and by extension, much of the northeast power grid), 20% firm penetration could be achieved at a cost of $1,100 per firm kW with a β=75% strategy, amounting to a cost of $825 per installed PV kW ($835 per useful PV kW) i.e., an extra levelized 4.5 cents per generated PV kWh. This represents a small fraction of the low penetration value that PV can deliver for New York's ratepayers/taxpayers which has been estimated at upwards of 30 cents per kWh for metropolitan northeastern utilities [e.g., 9].

The poorer solar-load synergy in the PG territory tends to limit the economically viable penetration domain to more modest values.

It is however important to note that these results are based upon locally dispersed PV generation. Local generation strongly exploits local load-solar synergies up to 35-40% penetration in the best case. At very high penetration, the seasonal solar output deficit of locally based generation becomes the main cost driver.

Therefore higher penetration levels could be better served with either geographically decentralized PV generation (e.g., the type of continental deployment envisaged projects like Desertec [10]); or by exploiting seasonal synergies with other renewables, such as wind generation that can mitigate seasonal deficits. In addition, the solar geometry, selected here to maximize peak-matching, does become non-ideal at very high penetration when seasonal deficit becomes the dominant storage cost driver, hence optimizing PV geometry as a function of penetration may be advisable. Finally, load management and efficiency gains focusing on the periods of low solar resource (particularly lighting and heating loads) could substantially increase the economically viable penetration domain.

It is our intension to apply the methodology developed here to explore/optimize these very high penetration options in a continuing phase of this research.

5. CONCLUSIONS

The most important result of this study is that considerable firm PV capacity can be achieved at a modest integration cost up to significant resource penetration. The low-penetration value of PV, including its capacity, grid security, and distributed benefits, in addition to its non-penetration dependent environmental, fuel depletion and economic growth benefits, can be maintained at a manageable expense until local dispersed PV generation becomes a considerable part of the generation mix. For instance, a state such as New York should be capable of absorbing and benefiting from well over 7 GW of -high-value PV without having to incur significant integration costs beyond the cost of PV itself, further noting that the storage sizes involved could well be met with a smart deployment of interactive plug-in transportation.

At very high penetration, integration costs escalate exponentially, and the study suggests that other solar deployment logistics should be considered including, continental-scale deployments, pairing with other renewables, solar geometry optimization maximizing winter output, and demand optimization minimizing off-season requirements. Nevertheless, the low-cost penetration potential is large enough to allow for the development of a considerable localized, high-value PV generation market worth 100's of GW in the US.

The present conclusions are of course dependent upon both the considered storage choices and costs, and the considered cost of the PV resource. Thermochemical hydrogen and flow-batteries could hypothetically reduce large-volume storage costs much further than assumed here [11] and push the high-value local PV generation potential well beyond the penetration range identified here.

Finally, while we focused on the issue of achieving firm capacity via storage, it is important to recognize that we did not take in account the very short-term fluctuations of the solar resource, an important penetration-related issue which will also require mitigation [12] addressable via storage. However, it may not be overly speculative to state that, as penetration increases the short term fluctuations from a dispersed PV fleet will tend to mitigate [13] and could be handled by a small fraction of the storage dedicated to firm capacity.

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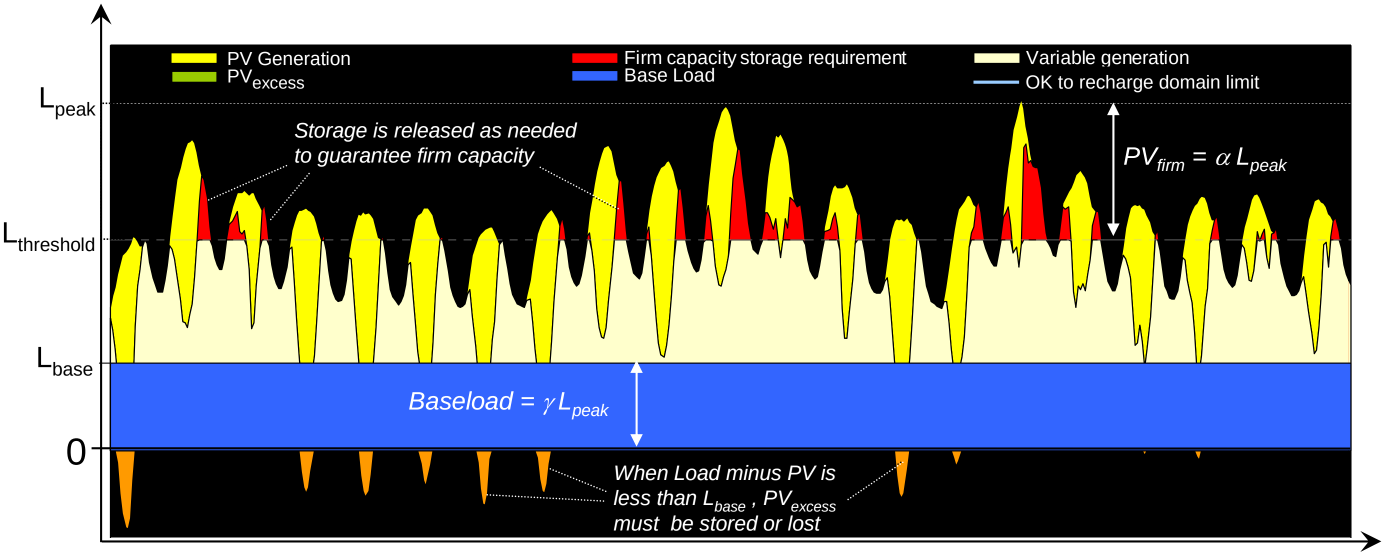

Figure 1: Illustrating the interrelationship between the study's variables with a 21-day peak demand period in Rochester Gas & Electric

TABLE 1

Cost, efficiency and time scale of current and prospective energy storage technologies (source [6])

Technology	Capital Cost per Unit Power ($/kW)	Capital Cost per Unit Energy ($/kWh-output)	Efficiency (without power electronics) --> %	Discharge Time (hr)
High-Power Electrochemical Capacitors	100 - 500	4000 - 10000	96 - 99%	0.0001 - 0.01
Long-Duration Electrochemical Capacitors	200 - 600	100-200		
Long-Duration Flywheels	3000 - 10000	1000 - 3000	90 - 96%	0.001 - 0.8
High-Power Flywheels	200 - 600	2300 - 4600		
CAES + gas	500-1000	28 - 100	70 - 79%	1.3 - 30+
Pumped Hydro	600 - 1500	30 - 130	70 - 85%	10 - 100+
Flow Batteries	700 - 2600	100 - 1300	72 - 85%	1 - 30+
NaS	1000 - 2300	200 - 900	85 - 90%	4 - 10
Li-Ion	1100 - 3800	600 - 2800	93 - 98 %	0.1 -16
Ni-cd	600 - 1200	700 - 2200	60 - 67%	0.02 - 10
Lead-Acid	300 - 800	190 - 1000	72 - 76%	0.01 - 10
Metal-Air Batteries	900 - 2000	20 - 50	43 - 50%	10 - 100+
Hydrogen (hydrolysis + ICE)	600 - 800	10 - 40	35 - 40%	1 - 100+
Hydrogen (hydrolysis + fuel cell)	800 - 2000	5 - 25	55 - 70%	0.1 - 100+

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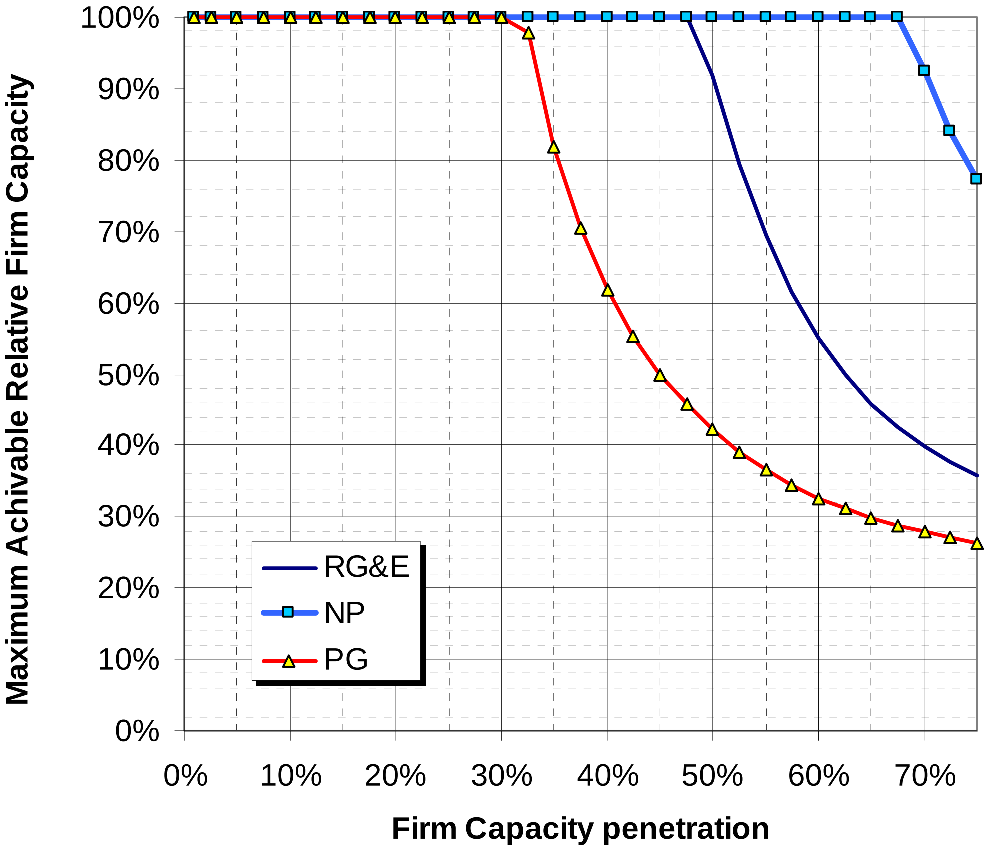

Figure 2: Achievable Relative Firm Capacity of PV Generation as a Function of Firm Penetration

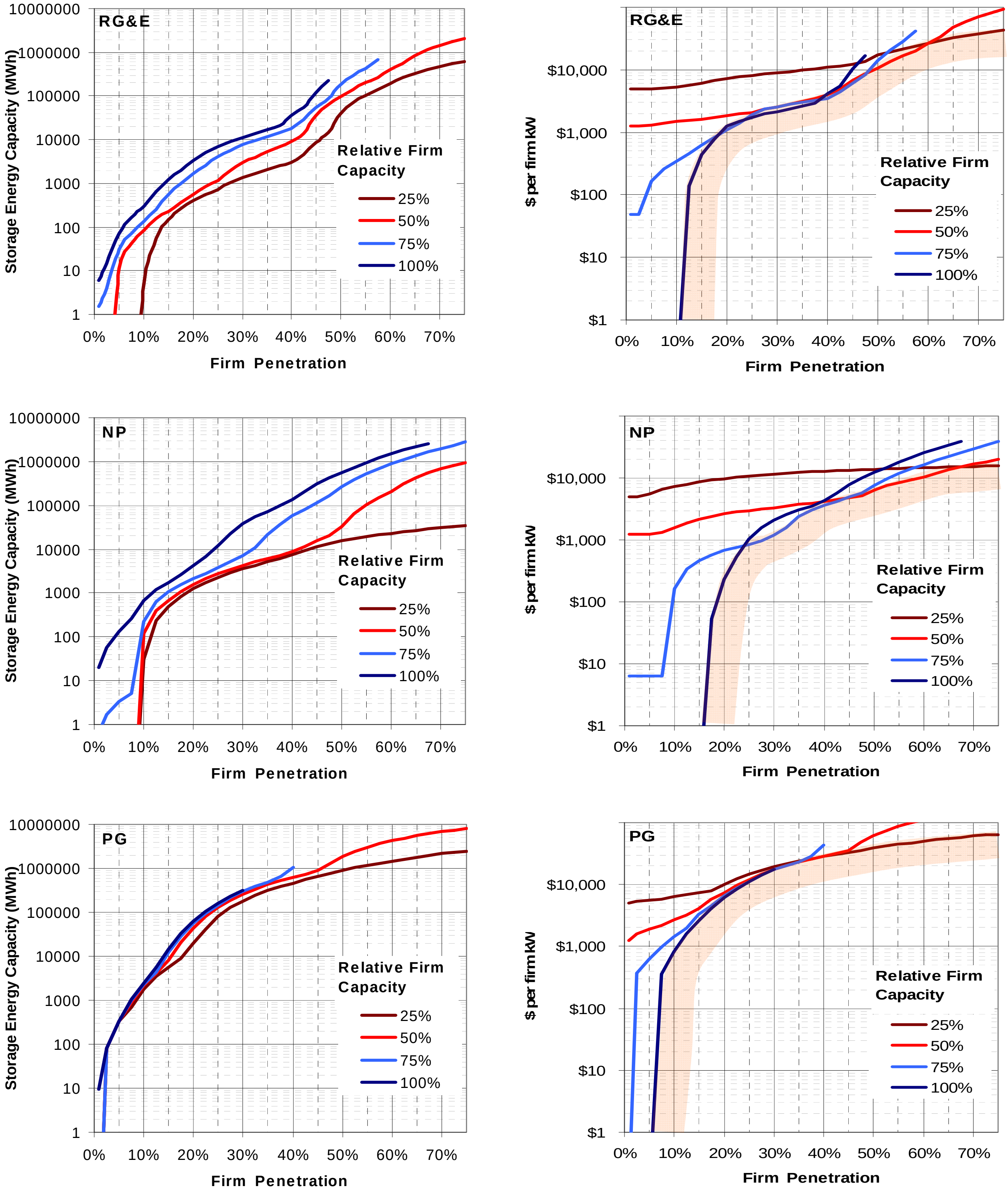

Figure 3: Energy Storage Requirements (left) and cost (right) necessary to maintaining a low-penetration firm capacity of 75% as a function of firm PV penetration. Costs are reportred in terms of $ per firm kW delivered.

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