UPDATE: EFFECTIVE LOAD CARRYING CAPABILITY OF PHOTOVOLTAICS IN THE UNITED STATES

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ABSTRACT

We provide an update on the US distribution of PV's Effective Load Carrying Capability (ELLC) by analyzing recent load data from 39 US utilities and time-coincident output of PV installations simulated from high resolution, time/site-specific satellite data. Results show that overall regional trends identified in the early 1990s remain pertinent today, while noting a significant increase in PV ELCC the Western and Northern US, and a modest decrease in the central and eastern US.

1. BACKGROUND AND RATIONALE

This study is an update and an expansion of the original work of Perez et al. (1993, 1996). In this original work, selected utility loads from the late 1980s and early 1990s were analyzed in conjunction with PV output simulated from low resolution 3-hourly satellite data (Justus et al., 1986). The results from the selected utility sample were extrapolated to all US utilities by modeling ELCC from the robust relationship observed between ELCC and utility summer to winter peak load (SWP) ratio.

The published results of the original study were limited to sun-tracking PV at very low grid penetration.

Using a higher resolution and more accurate satellite model to simulate site/time specific PV output, the emphasis of the present work is placed on reporting state-by-state potential and on assessing the impact of grid penetration and array geometry on ELCC. We consider PV penetrations ranging from 2% to 20%. Selected PV geometries include two-axis tracking (ideal case), horizontal, south-facing 30^o-tilt and southwest-facing 30^o-tilt.

2. METHODOLOGY

2. 1 Effective Load Carrying Capability (ELCC)

The ELCC of a power generator represents its ability to effectively increase the generating capacity available to a utility or a regional power grid without increasing the utility's loss of load risk (Garver, 1966). For instance, a utility with a current peaking capability of 2.5 GW could increase its capability 2.55 GW with the same reliability by adding 100 MW PV, provided the ELCC of the 100 MW PV is 50 MW, or in relative terms, 50%.

Ideally dispatchable generators with no down time have a relative ELCC of 100%. Non-dispatchable generators such as wind or photovoltaics (PVs) are a priori assumed to have no or little ELCC. For PV however, the ELCC can be significant because PV generation may be reliably available at critical demand times (e.g., Perez et al., 2005) and thus may effectively increase the grid's generating capacity.

ELCC may be statistically derived from the analysis of time-coincident series of load demand and power generation data (Garver, 1966). As in the original study, our approach here is to experimentally determine ELCC for a representative sample of utilities, and to project the results to the entire country using observed regional and load shape patterns.

2.2 Experimental Data

Utility Loads: We selected 39 utilities distributed throughout the country (see list in Fig. 1), and acquired two recent years of hourly load data (2002 and 2003) for each (FERC, 2005). Load data obtained from FERC were corrected for daylight savings time adjustment, as needed in order to be synchronous with PV generation data.

<u>PV generation</u>: PV output was modeled for each selected array configuration. Time/site specific hourly irradiances used as input to the model were obtained from high-resolution satellite observations (Perez et al., 2002, 2004). Time/site-specific wind speed and temperature data were obtained from the National Climatic Data Center (NCDC, 2005).

The first step was to experimentally derive ELCC for the selected utility sample for each selected PV configuration and grid penetration. Utility-specific results are provided in Fig. 1 for the 2-axis-tracking, low penetration case. The values reported are 2002-03 averages and contrasted against 1991 values from the original study for the same utilities.

The second step was to observe and to model the relationship between the reference ELCC – 2-axis tracking at 2% grid penetration – and ELCCs for other PV geometries and grid penetrations. An example of such experimental relationship is shown in Figure 2 between the southwest facing ELCC at 5% penetration and the reference ELCC. These relationships are very well defined and can be easily fitted with a linear approximation. Such linear relationships were defined for each case, resulting in modeled ELCC standard error of 1-4% (see Table 1).

The third step was to investigate whether the relationship between the reference ELCC and the utility SWP Ratio observed in the original study remained valid with the new data points. Fig. 3 compares the original and current trends. These

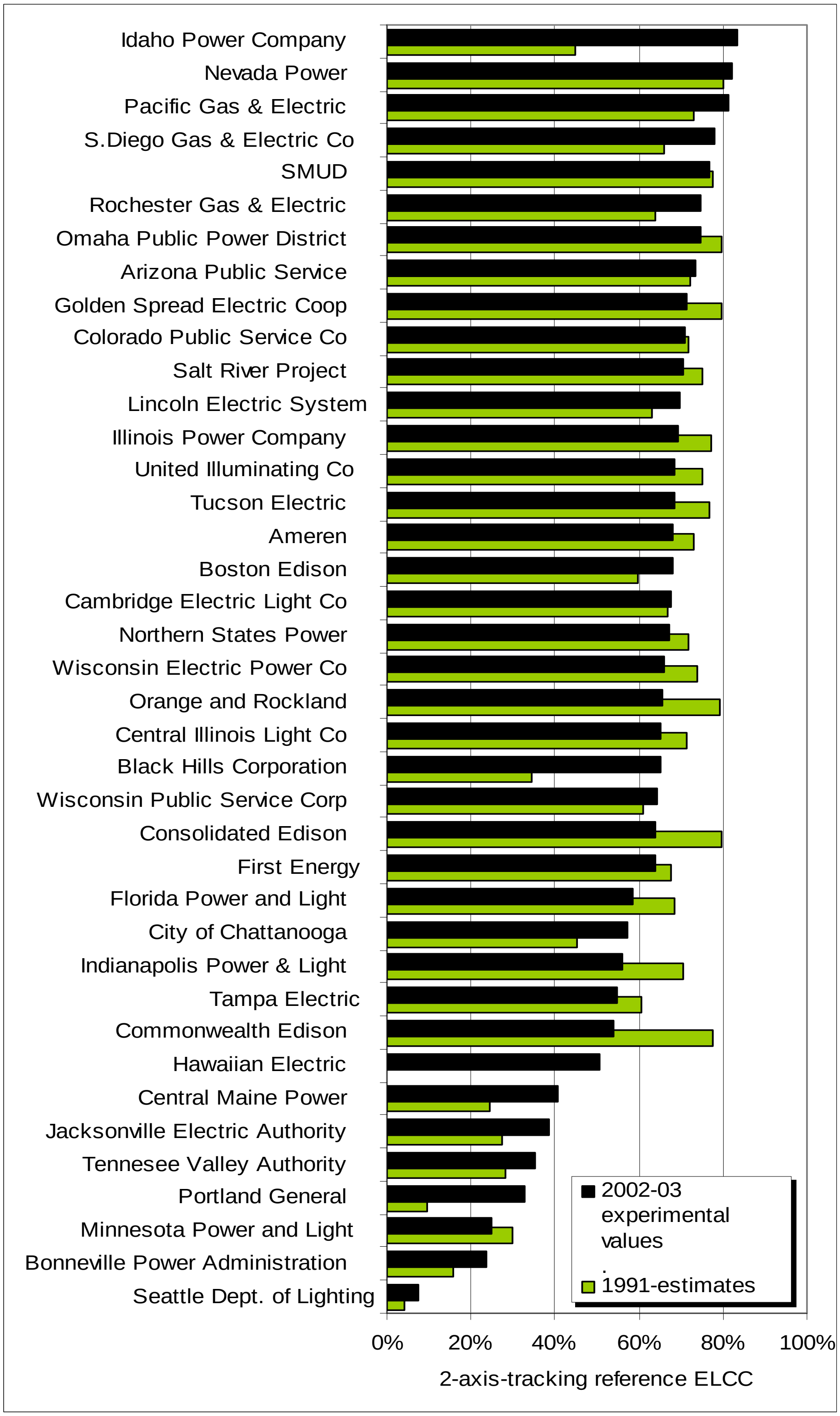

Figure 1: Experimentally derived reference ELCC (2-axis tracking, low grid penetration) compared against earlier estimates from the original study (Perez et al., 1996)

results indicate that the SWP ratio remains a strong predictor of ELCC, justifying following step.

The fourth step consisted of taking the 500+ utility gridded data from the original study and to update the map by layering the 2002-2003 interpolated map of differences between the earlier period and the current period derived for the 39 selected utilities.

Finally, the resulting gridded map was processed into statewide averages. Table 2 summarizes ELCCs observed for each state, and each PV-geometry/Load-penetration scenario. A subset of these results is provided graphically in Fig. 4, while figure 5 provides a state-by-state ranking for each selected geometry at low grid penetration while also providing information on statewide ranges for the reference ELCC.

3. DISCUSSION

The main conclusions reached in the original study remain valid: PV's effective capacity is significant – and considerably higher than PV's capacity factor – for much of the United States.

The utility-specific results presented in Fig. 1 indicate that utilities in the southwestern US exhibit the highest values, followed by Central US utilities and mid-Atlantic utilities. The lowest ELCCs are found in the North Pacific coast, the northern fringes of the Great Lakes and New England, and to a lesser extent, Florida. Overall, the national trends noted in the original study are conserved, but some regional changes are noteworthy. The upper northeast and central northwest exhibit strong ELCC increases – see for instance Idaho Power Company, Rochester Gas and Electric, Central Maine Power and Portland General -- while some erosion is noted in the large eastern metropolitan utilities – such as New York's Consolidated Edison. Although still speculative, the reasons for these changes could include, on the one hand a tendency for the northernmost utilities towards higher summer loads fueled by increased air conditioning deployment and warmer summers, and on the other, the implementation of effective peak load mitigation strategies in places like the New York metro area, offsetting the highest demands indirectly driven by the sun. The use of a more accurate, higher resolution hourly solar resource model (instead of an interpolated 3-hourly model as in the original study) may have also contributed to more conservative results in the eastern climates by better capturing transient cloudiness at critical times.

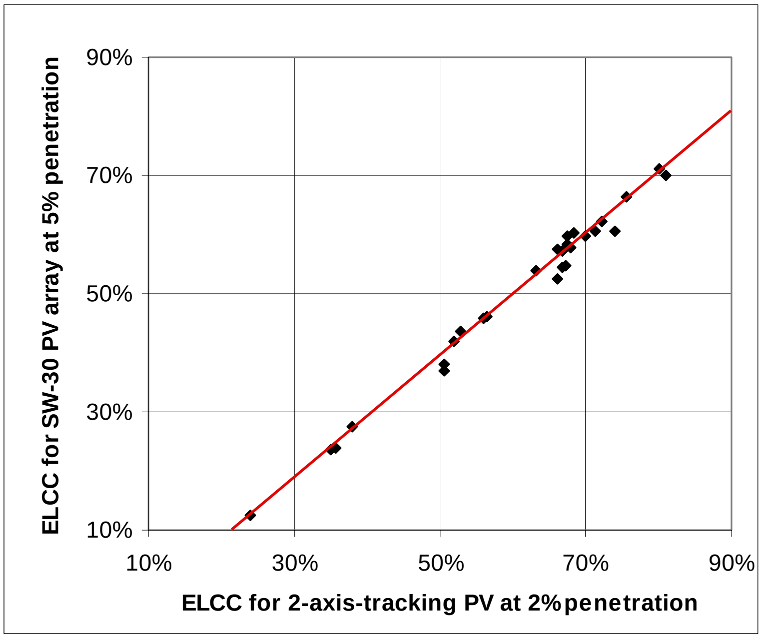

Figure 2: Observed ELCC at 5% penetration for a fixed southwest-facing array vs. reference 2-axis tracking, low penetration ELCC

TABLE 1
Fitted relationships between reference ELCC (2 % penetration, 2-axis tracking) and other ELCCs

penetration - geometry	slope	intercept	R	Std. error
5% - 2axis	1.05	-0.07	1.00	1.2%
10% - 2axis	1.04	-0.13	0.97	2.9%
15% - 2axis	0.95	-0.15	0.95	3.9%
20% - 2axis	0.83	-0.14	0.92	4.2%
2% - horizontal	0.89	-0.08	0.94	3.8%
5% - horizontal	0.88	-0.10	0.95	3.3%
10% - horizontal	0.84	-0.13	0.96	2.9%
15% - horizontal	0.78	-0.14	0.95	2.9%
20% - horizontal	0.70	-0.13	0.94	2.9%
2% - S30	0.86	-0.04	0.93	4.1%
5% - S30	0.86	-0.07	0.94	3.7%
10% - S30	0.81	-0.10	0.94	3.4%
15% - S30	0.73	-0.10	0.94	3.2%
20% - S30	0.64	-0.10	0.93	3.0%
2% - SW30	1.10	-0.14	0.97	3.2%
5% - SW30	1.10	-0.17	0.98	2.5%
10% - SW30	1.05	-0.20	0.98	2.4%
15% - SW30	0.95	-0.20	0.97	2.9%
20% - SW30	0.84	-0.18	0.95	3.2%

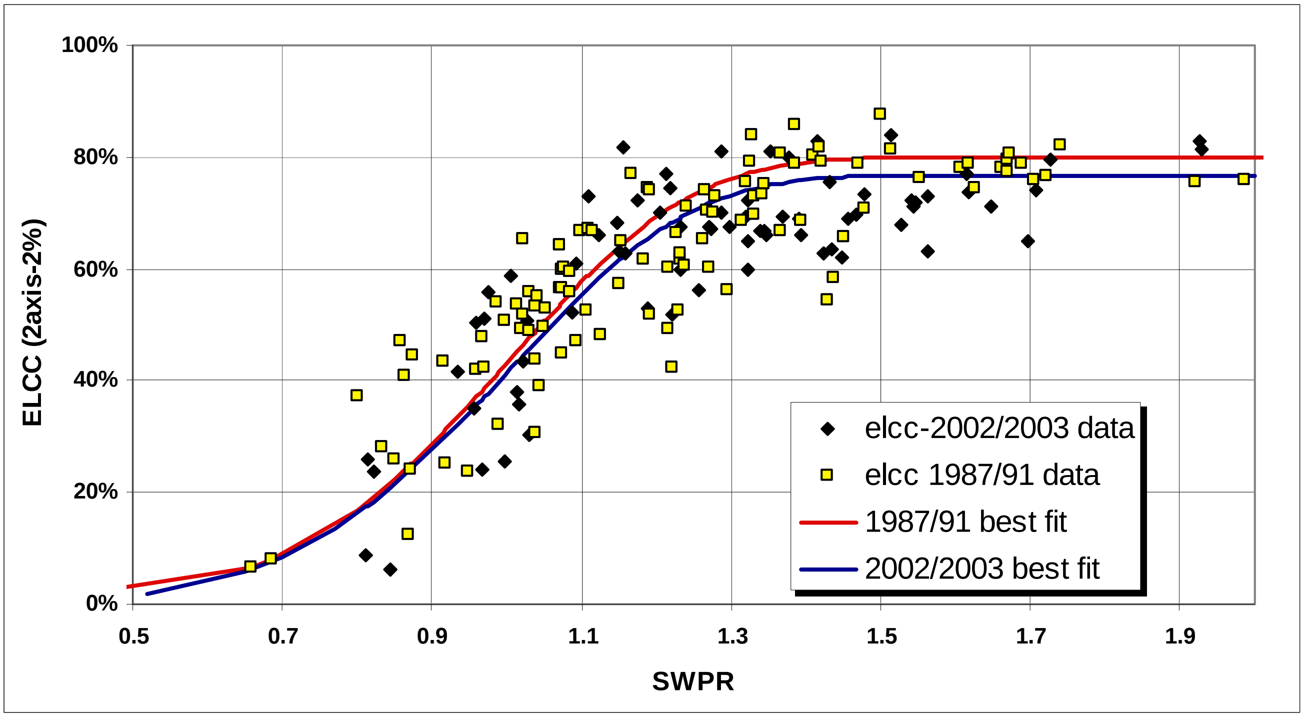

Figure 3: Reference ELCC as a function of Summer-to-Winter Peak Load Ratio

Statewide averages in Table 2 should be considered in the context of sometimes large statewide min-max ranges. High ranges may be characteristic of sparse experimental points – i.e., high statistical uncertainty (e.g., North Dakota), but more often, they represent different trends within a given State. For instance, the 40-70% range in New York State represents the different demand patterns of upstate's ~ rural utilities which are still nearly winter peaking vs. city utilities (New York City, Rochester) which are strongly summer peaking.

The present study provides considerably more insight on the effects of geometry and penetration. With fixed optimized PV arrays, the national average for ELCC at low penetration is nearly 55%, reaching 65%+ in the best cases. ELCC erodes down to ~ 35% nationwide at 20% penetration reaching 45% in the best cases.

Finally, it is important to remark that ELCCs can be increased to nearly 100% -- i.e., firm power equivalence -- with modest amounts of storage and/or load control, even at significant levels of penetration. Considering New York City's ConEdison for instance, and considering a 15% load penetration with optimized fixed array, the ELCC of PV could be increased from 40% to 100% with 2.5 hours worth of storage and/or load control capability. The total amount of load control needed year-around to guaranty 100% ELCC would 23,000 MWh. Accomplishing the same load reduction without the benefit of PV would require nearly six times more load control. The use of load control and storage to provide firm capacity equivalence in the context of demand reduction programs is the focus of a follow-on phase of this work.

4. ACKNOWLEDGEMENT

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TABLE 2
Statewide ELCCs

Geometry	2 axis tracking					Horizontal					South 30° tilt					Southwest 30° tilt				
Penetration	2%	5%	10%	15%	20%	2%	5%	10%	15%	20%	2%	5%	10%	15%	20%	2%	5%	10%	15%	20%
Arkansas	71%	68%	61%	53%	45%	55%	52%	47%	42%	37%	57%	54%	47%	41%	36%	65%	61%	55%	48%	41%
Alabama	69%	66%	59%	51%	44%	54%	51%	46%	40%	36%	56%	52%	46%	40%	35%	63%	59%	53%	46%	40%
Arizona	71%	68%	61%	53%	45%	55%	52%	47%	42%	37%	57%	54%	47%	41%	36%	65%	61%	55%	48%	41%
California	75%	72%	65%	57%	48%	59%	56%	51%	45%	40%	61%	57%	51%	44%	38%	69%	66%	59%	52%	45%
Colorado	66%	63%	56%	48%	41%	51%	48%	43%	38%	33%	53%	50%	44%	38%	33%	59%	56%	50%	43%	37%
Connecticut	62%	58%	51%	44%	37%	47%	44%	39%	34%	30%	49%	46%	40%	34%	30%	54%	50%	44%	38%	33%
Delaware	62%	58%	51%	44%	38%	47%	44%	40%	35%	30%	50%	46%	40%	35%	30%	55%	51%	45%	39%	34%
Florida	57%	53%	46%	40%	34%	43%	40%	35%	31%	27%	46%	42%	36%	31%	27%	49%	46%	40%	35%	30%
Georgia	69%	65%	58%	50%	43%	53%	50%	45%	40%	35%	55%	52%	46%	39%	34%	62%	59%	52%	45%	39%
Hawaii	51%	47%	40%	34%	28%	42%	39%	34%	30%	26%	41%	38%	32%	27%	23%	43%	40%	34%	29%	25%
Idaho	67%	62%	55%	47%	40%	50%	47%	42%	37%	32%	53%	49%	43%	37%	32%	58%	54%	47%	41%	35%
Illinois	70%	66%	59%	51%	44%	54%	51%	46%	41%	36%	56%	53%	46%	40%	35%	63%	59%	53%	46%	40%
Indiana	64%	60%	53%	46%	39%	49%	46%	41%	36%	32%	51%	48%	42%	36%	31%	57%	53%	47%	41%	35%
Iowa	73%	69%	62%	54%	46%	57%	54%	48%	43%	38%	59%	55%	49%	42%	37%	66%	63%	56%	49%	42%
Kansas	75%	72%	65%	57%	48%	59%	56%	50%	45%	40%	61%	57%	51%	44%	38%	69%	66%	59%	51%	44%
Kentucky	53%	49%	42%	36%	30%	39%	37%	32%	28%	24%	42%	39%	33%	28%	24%	45%	42%	36%	31%	26%
Louisianna	71%	68%	61%	53%	45%	55%	53%	47%	42%	37%	58%	54%	48%	41%	36%	65%	61%	55%	48%	41%
Massachussetts	56%	52%	45%	39%	33%	42%	39%	34%	30%	26%	45%	41%	35%	30%	26%	48%	45%	39%	33%	29%
Maryland	60%	56%	49%	42%	36%	46%	43%	38%	33%	29%	48%	45%	39%	33%	29%	52%	49%	43%	37%	32%
Maine	28%	23%	16%	12%	10%	17%	15%	11%	8%	7%	21%	17%	13%	10%	8%	17%	14%	10%	7%	6%
Michigan	65%	61%	54%	47%	40%	49%	47%	42%	37%	32%	52%	48%	42%	37%	32%	57%	54%	48%	41%	36%
Minnesota	46%	42%	35%	29%	24%	33%	30%	26%	22%	19%	36%	32%	27%	23%	20%	37%	34%	28%	24%	20%
Missouri	72%	69%	62%	54%	46%	56%	54%	48%	43%	38%	59%	55%	49%	42%	37%	66%	63%	56%	49%	42%
Mississipi	71%	68%	61%	53%	45%	55%	52%	47%	42%	37%	57%	54%	47%	41%	36%	64%	61%	54%	48%	41%
Montana	73%	71%	65%	57%	49%	58%	56%	51%	45%	40%	60%	57%	51%	44%	39%	69%	66%	60%	53%	46%
North carolina	56%	52%	45%	39%	33%	42%	39%	34%	30%	26%	45%	41%	35%	30%	26%	48%	45%	39%	33%	29%
North Dakota	49%	45%	38%	32%	27%	36%	33%	29%	25%	22%	39%	35%	30%	26%	22%	41%	37%	32%	27%	23%
Nebraska	74%	71%	64%	56%	48%	58%	55%	50%	44%	39%	60%	57%	50%	44%	38%	68%	65%	58%	51%	44%
New Hampshire	43%	38%	31%	26%	22%	30%	27%	23%	20%	17%	33%	30%	25%	21%	18%	33%	30%	25%	21%	17%
New Jersey	64%	60%	53%	46%	39%	49%	46%	41%	36%	31%	51%	48%	41%	36%	31%	56%	53%	47%	40%	35%
New Mexico	62%	58%	51%	44%	37%	47%	44%	39%	35%	30%	50%	46%	40%	35%	30%	55%	51%	45%	39%	33%
Nevada	59%	55%	48%	41%	35%	45%	42%	37%	32%	28%	47%	44%	38%	33%	28%	51%	48%	42%	36%	31%
New York	53%	48%	40%	34%	28%	38%	35%	30%	26%	22%	41%	37%	32%	27%	23%	43%	39%	33%	28%	24%
Ohio	63%	59%	52%	45%	38%	48%	45%	40%	35%	31%	50%	47%	41%	35%	30%	55%	52%	46%	40%	34%
Oklahoma	68%	64%	57%	49%	42%	52%	49%	44%	39%	34%	54%	51%	45%	39%	34%	61%	57%	51%	44%	38%
oregon	42%	38%	31%	25%	21%	30%	27%	23%	19%	16%	33%	29%	24%	20%	17%	33%	29%	24%	20%	17%
Pennsylvania	53%	48%	41%	34%	29%	38%	35%	31%	27%	23%	41%	38%	32%	27%	23%	43%	40%	34%	29%	25%
Rhodes Island	64%	61%	54%	46%	39%	49%	46%	41%	36%	32%	52%	48%	42%	36%	31%	57%	54%	48%	41%	35%
South Carolian	57%	53%	47%	40%	34%	43%	40%	35%	31%	27%	46%	42%	36%	31%	27%	49%	46%	40%	35%	30%
Southe dakota	59%	55%	48%	41%	35%	44%	41%	37%	32%	28%	47%	43%	38%	32%	28%	51%	48%	42%	36%	31%
Tennesseee	51%	47%	40%	34%	28%	37%	35%	30%	26%	23%	40%	37%	31%	27%	23%	42%	39%	34%	29%	24%
Texas	64%	60%	53%	46%	39%	49%	46%	41%	36%	32%	51%	48%	42%	36%	31%	56%	53%	47%	41%	35%
Utah	42%	37%	30%	25%	21%	29%	27%	22%	19%	16%	32%	29%	24%	20%	17%	32%	29%	24%	20%	17%
Virginia	57%	53%	46%	39%	33%	43%	40%	35%	31%	27%	45%	42%	36%	31%	27%	49%	46%	40%	34%	29%
Vermont	46%	42%	35%	29%	24%	33%	30%	26%	22%	19%	36%	33%	27%	23%	20%	37%	33%	28%	23%	20%
Washington	17%	12%	7%	5%	4%	8%	6%	5%	4%	3%	11%	8%	6%	4%	4%	7%	6%	4%	4%	3%
Wisconsin	59%	55%	48%	41%	35%	44%	41%	37%	32%	28%	47%	43%	37%	32%	28%	51%	47%	42%	36%	31%
West Virginia	51%	47%	40%	33%	28%	37%	34%	30%	26%	23%	40%	36%	31%	26%	23%	42%	39%	33%	28%	24%
Wyomming	44%	39%	32%	27%	22%	31%	28%	24%	20%	18%	34%	30%	25%	21%	18%	34%	31%	26%	21%	18%

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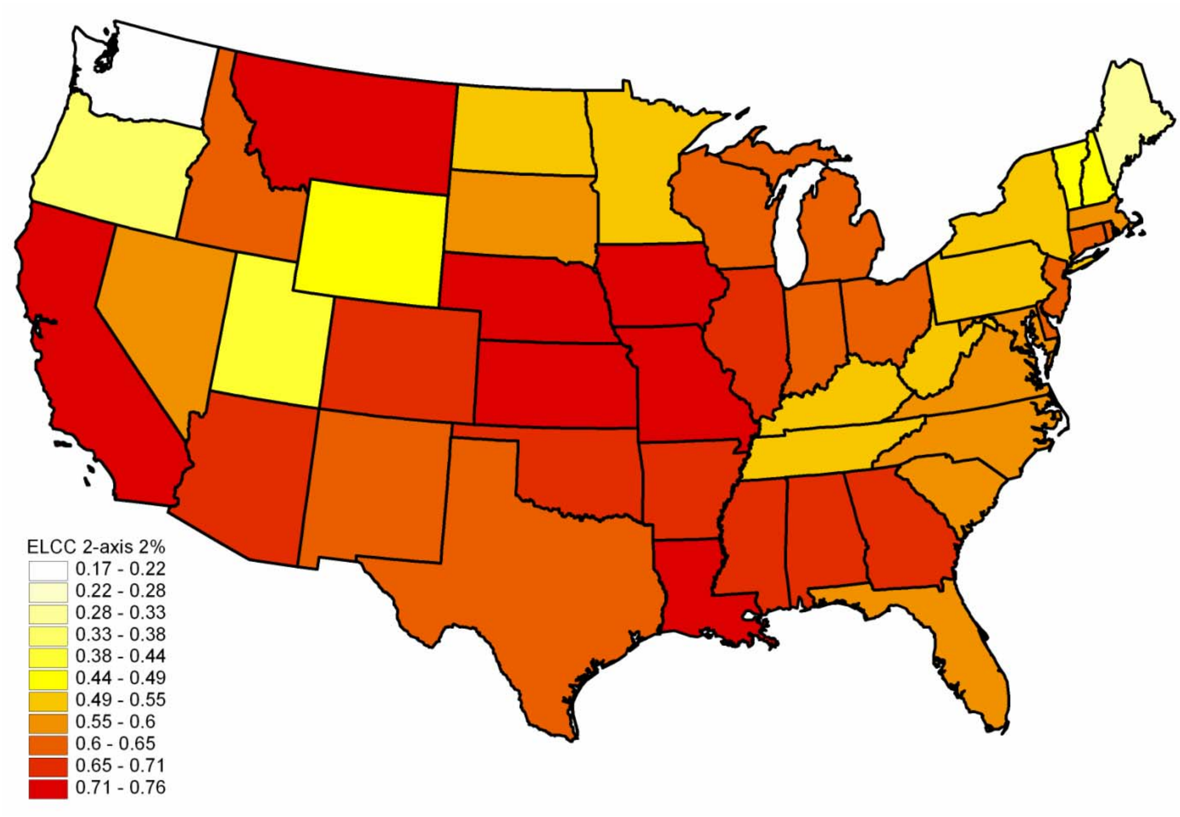

Figure 4: State-wide reference 2-axis-tracking 2% penetration ELCC

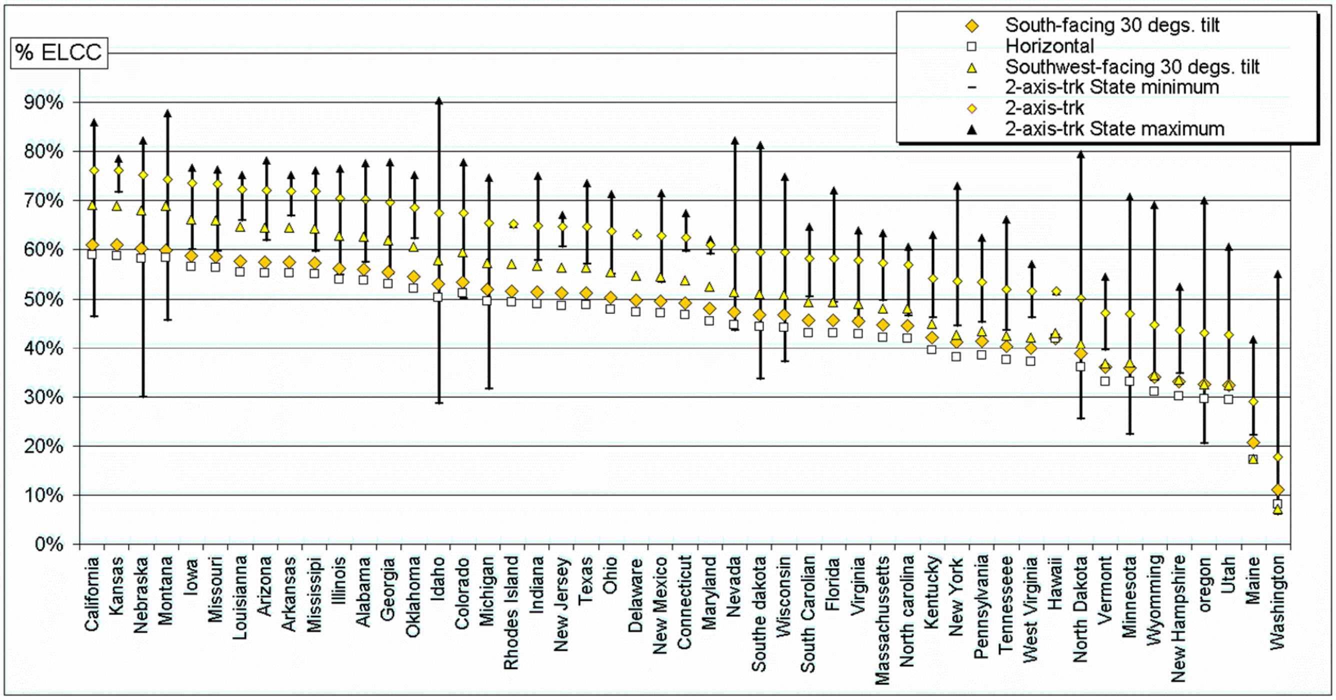

Figure 5: Low-penetration ELCCs per state including statewide range