Research Article

From Firm Solar Power Forecasts to Firm Solar Power Generation

An effective path to ultra-high renewable penetration

A New York Case Study

Richard Perez [1,*], Marc Perez [2] Sergey Kivalov[3], James Schlemmer[4], John Dise[5], Thomas E. Hoff[6], Agata Swierc[7], Patrick keelin[8], Marco Pierro[9] & Cristina Cornaro[10]

[1] University at Albany, ASRC; rperez@albany.edu
[2] Clean Power Research; marcp@cleanpower.com
[3] University at Albany, ASRC; skivalov@albany.edu
[4] University at Albany, ASRC; jschlemmer@albany.edu
[5] Clean Power Research; johndise@cleanpower.com
[6] Clean Power Research; tomhoff@cleanpower.com
[7] Clean Power Research; aswierc@cleanpower.com
[8] Clean Power Research; pkeelin@cleanpower.com
[9] University of Rome Tor Vergata; marco.pierro@gmail.com
[10] University of Rome Tor Vergata; cornaro@uniroma2.it
* Correspondence: rperez@albany.edu; Tel.: +33-518-573-1714

Abstract: We introduce firm solar forecasts as a strategy to operate optimally overbuilt solar power plants in conjunction with optimally sized storage systems so as to make up for any power prediction errors, hence entirely remove load balancing uncertainty emanating from grid-connected solar fleets. A central part of this strategy is plant overbuilding that we term implicit storage. We show that strategy, while economically justifiable on its own account, is an effective entry step to least-cost ultra-high solar penetration where firm power generation will be a prerequisite. We demonstrate that in absence of an implicit storage strategy, ultra-high solar penetration would be vastly more expensive. Using the New York Independent System Operator (NYISO) as a case study, we determine current and future cost of firm forecasts for a comprehensive set of scenarios in each ISO electrical region, comparing centralized vs. decentralized production and assessing load flexibility's impact. We simulate the growth of the strategy from firm forecast to firm power generation. We conclude that ultra-high solar penetration enabled by the present strategy, whereby solar would firmly supply the entire NYISO load, could be achieved locally at electricity production costs comparable to current NYISO wholesale market prices.

Keywords: Firm power generation; Energy storage; Irradiance forecasts; Implicit storage; Grid integration; ultra-high RE penetration

1. Introduction

Solar Forecasts: From minutes-ahead to days ahead, solar forecasts have become integral to utility operations as solar power generation (chiefly PV) penetrates power grids. The models underlying these forecasts are becoming more refined [1-7]. Probabilistic forecasts in particular, that complement deterministic forecasts with expected condition-specific probability ranges, are increasingly applied operationally as these integrate effectively with current grid management practice [8-13]. The underlying reason for solar forecasts is the intermittent nature of the non-

dispatchable solar resource. Accurately anticipating future solar production can minimize load imbalances, hence the size of reserve margins and spot-market electricity price spikes. Penalties that are often levied on large solar producers are intended to reflect the cost of these solar-induced load imbalances. These penalties represent an economic measure of forecast accuracy. However, this measure can vary substantially from one service area to the next and often reflects regulatory decisions that may change over time and that are not always directly traceable to tangible operational costs. A recent publication by Antonanzas et al. attests of the influence of market structures on the apparent economic accuracy of solar forecasts [15].

Introducing Firm Power forecasts: The aim of firm power forecasts is to bypass the standard [probabilistic] forecast paradigm and to remove grid operator uncertainty. Of course, the forecast models themselves are not error-free, but the production of a PV plant or a fleet of plants can be guaranteed operationally by adding physical hardware and controls to these plants, namely: energy storage to make up for over-forecasts, and plant overbuilding to safely curtail output in cases of under-forecasts. Operational controls take real-time action on storage dispatch or curtailment to reconcile actual and predicted production so that the output seen by the grid exactly amounts to the predicted output. The cost of achieving firm forecasts is the cost of the optimally minimized hardware (storage and additional PV) needed for the task.

We recently showed that this cost also constituted a new, robust and repeatable forecast model error metric [16, 17] that may be more reflective of operational grid imbalance costs than prevailing error metrics such as MAE, RMSE or forecast skill, even as efforts to refine/standardize these prevailing metrics are actively pursued [18-21]. We showed, in particular that simple persistence models scored considerably better relative to other models when gauged with the new operational cost metric than when gauged with traditional metrics [17].

From firm forecasts to least-cost ultra-high penetration: While the firm forecast overbuild/curtail/storage strategy may be economically justifiable for eliminating PV supply-side uncertainty, its most important value lies in opening a logistical door to massive PV penetration at the lowest possible cost. As outlined in a new IEA-PVPS Task 16 activity [22], grid-connected PV, either dispersed or centralized, has developed and grown at the margin of a core of dispatchable and baseload conventional generation. The challenge ahead is to move PV beyond this marginal position and the reliance on conventional generation. The transformation of intermittent variable solar power generation into ***firm, effectively dispatchable, power generation*** is a prerequisite to the gradual displacement of the underlying conventional generation core.

In a recent series of publications and reports [24-26], we have demonstrated that the least costly way to transform PV from intermittent to effectively dispatchable was to apply a strategy analogous to that described above for firm forecasting but on a larger scale. PV plant overbuilding and proactive curtailment can sufficiently reduce storage requirements to reach economically acceptable firm renewable power generation. Applying storage alone without overbuilding and proactively spilling excess PV would be prohibitively expensive. Figure 1 from [24] illustrates the relationship between overbuilding and the LCOE of firm power generation.

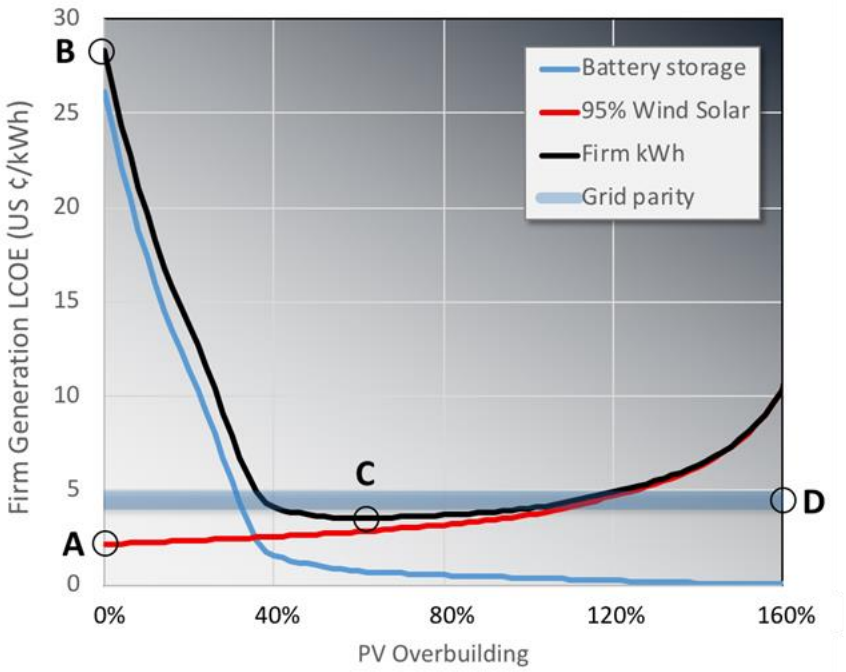

Figure 1. Influence of PV overbuilding on firm power generation LCOE. While unconstrained PV (A) is inexpensive (apparently below grid parity), firming PV to meet demand 24/365 with storage alone (B) is unrealistically expensive. Overbuilding PV fleets reduces storage requirements to the point (C) where firm PV power generation can achieve true grid parity (D). Source [24]

As presented by Pierro et al. [26, 27] for the Italian power grid, the entry-level firm forecast strategy based on storage and optimized overbuilding/curtailment can be gradually expanded over time, following enabling technologies' cost decrease and TSO's learning curves, to meet more stringent requirements, until meeting demand 24/365 becomes realistically achievable economically without reliance on conventional resources.

Implicit storage: We recently introduced the term "implicit storage" to designate the overbuilt/ curtailable part of PV. This overbuilt part enables operational curtailment without loss of planned production. It acts as a catalyst to storage, allowing storage to achieve its objective, i.e., transforming intermittent PV into a firm, effectively dispatchable resource, but at a considerably reduced cost. In the following sections, we will use the implicit storage term interchangeably with overbuild/curtail.

2. Methods

2.1 New York Independent System Operator (NYISO) Case study

NYISO manages the State of New York's transmission power grid. We use load data from this transmission system operator (TSO) as experimental support to present and contrast the costs of initially achieving firm forecasts, and of ultimately achieving firm power generation capable of entirely displacing existing conventional generation.

NYISO includes eleven electrical regions labelled A through K (Figure 2). For each electrical region, we analyze firm forecasts and firm power generation from the standpoint of either single PV plants at the region's center or homogeneously distributed PV fleets. We also consider the case of a distributed fleet for the entire NYISO territory.

The case study spans the year 2016, for which we acquired NYISO's regional historical hourly load data.

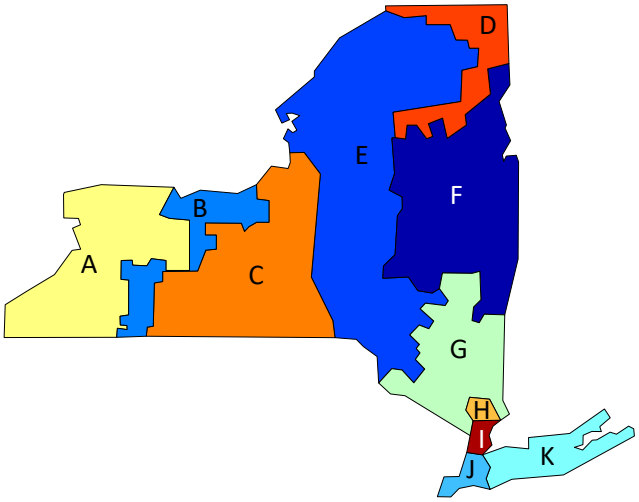

Figure 2. NYISO Electrical regions map

2.2 Firm Power Forecasts

The underlying forecast model we apply for this investigation is the SUNY model [28] that is served operationally by Clean Power Research under the trade name SolarAnywhere [29]. This model is an optimized blend of satellite-derived cloud motion forecasts and several global and regional numerical weather prediction (NWP) models [30-33].

The actual irradiances used to benchmark forecasts consist SolarAnywhere satellite-derived historical irradiances [34]. We have shown that using satellite-derived irradiances was acceptable, if not in some cases preferable, to evaluate forecast model performance, yielding error metrics comparable to ground measurements [35]. In a recent article [36] we reported on a detailed analysis of the appropriateness of satellite data for forecast validations. We showed that, while satellite data may be a suboptimal reference for single points' short-term dynamics, they are appropriate for the type of transmission grid-integration issues addressed in this article, especially as the footprint evolves from individual plants to regionally distributed PV fleets.

We calculate the real and implicit storage requirements, as well as the corresponding capital cost premiums, and levelized energy production costs (LCOE[1]s) for one, three and 24 hours-ahead forecasts. These requirements are a function of:

- The capital costs of PV and storage. We consider two scenarios: (1) a present/near-future scenario with PV at $1,000/kWptc and storage at $200/kWh and, (2) a future scenario at the 20 years horizon with PV at $400/kWptc and storage at $50/kWh [37].
- The round-trip efficiency of storage. We assume 90%.
- Whether storage can be recharged at night during off hours. We make this assumption here, whereby storage can be recharged at night at a conservatively 'generic' cost of $0.15/kWh.
- The amount of flexibility allowed by the TSOs to deem forecasts firm. We consider two scenarios. (1) 0% flexibility, i.e., the output seen by the grid must be equal to the forecast. (2) 2.5% flexibility, i.e., the output seen by the grid may differ from the forecast by an

[1] In addition to the capital cost (CAPEX) of PV and storage, LCOEs are also a function of the considered life cycle – we assume 30 years – the operation and maintenance costs (OPEX) of PV and storage – we assume respectively 1% per year for PV and 0.1% per full cycle for storage – as well as Weighted Average Cost of Capital (WACC). For the latter, we selected 4% as representative of the utility industry [25]

amount exceeding at most 25 Watts per installed kW. (3) 5% flexibility, where differences between actual and predicted generation must be below 50 Watts per installed PV kW.

For a given time horizon, location, and PV fleet configuration, the cost of firm forecasts is obtained by extracting the lowest life-cycle cost combination of storage, overbuilding and nighttime recharge expenses sufficient to meet the firm forecast requirements.

2.3 Firm Power Generation

At the other end of the spectrum, we calculate storage and implicit storage requirements to firmly supply the demand of each individual NYISO region, or the state in its entirety. We apply the Clean Power Research Clean Power Transformation (CPT) model to derive the optimum combination of real and implicit storage leading to the lowest possible firm generation cost [24, 25].

Operational inputs are analogous to firm power forecasts, with some key differences:

- The target output is not the forecast, but the [regional] NYISO load.
- Since the objective is to supply demand 24/7 at high-penetration, there is no external battery recharge possibility at night or in off-hours. Storage can only be recharged when renewable production exceeds demand.
- We also consider flexibility defined not in terms of forecast guaranties, but in terms of the fraction of energy allowed from an external, non-renewable sources. This external source could be supply-side, e.g., from legacy or new natural gas units, and/or demand-side from load management. We consider flexibility levels of 0%, 2.5% and 5%.
- Unlike for forecasts where the target load (i.e., the forecast production) is largely independent of PV configuration, meeting a target load shape depends on PV configuration. We selected a fixed 30o tilt south-facing array geometry.

2.4 Evolving Penetration strategy

Between the "light-duty" requirements of firm forecasts, and the "heavy-duty" requirements of 100%-ready firm power generation, we evaluate intermediate steps at 10%, 25% and 50% levels of PV grid energy penetration. The corresponding target load profiles evolve from day-ahead forecast production to grid demand commensurately with the degree of penetration. These evolving load shape targets on a yearly and daily basis are illustrated in Figure 3.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 July 2020 doi:10.20944/preprints202007.0088.v1

Peer-reviewed version available at Energies 2020, 13, 4489; doi:10.3390/en13174489

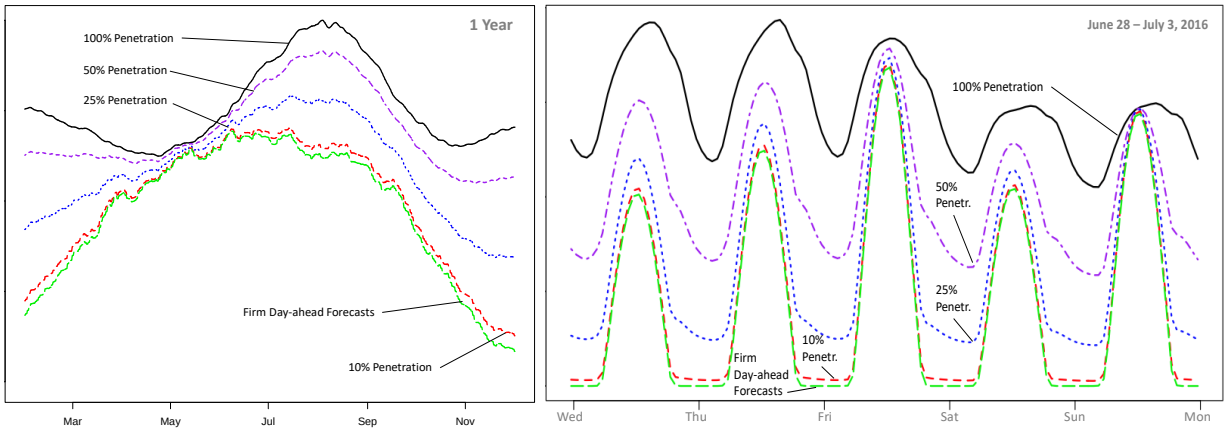

Figure 3: Evolution of yearly (left) and daily (right) target load shape from firm forecasts to firm power generation. Notes: (1) for visual clarity, the yearly load shape presented in this figure was smoothed using a 60-day running mean to remove day-to-day variability; (2) The y-axis scales are nominal and were selected for visual clarity to better distinguish between load shapes.

3. Results

3.1 Firm forecasts

Tables 1, 2 and 3 reports the nominal amount of storage, PV overbuilding, incremental capital costs, and plant/fleet LCOEs to achieve firm forecasts for all investigated scenarios: NYISO-wide, region-specific, 0% and 2.5% flexibility, current and future technology costs, centralized PV plants and distributed fleets. Table 1 pertains to one hour-ahead forecast, Table 2 to three hours-ahead forecasts, and Table 3 to 24 hours-ahead forecasts.

Table 1. One hour-ahead forecasts

	1 Hour forecasts	Current technology cost: PV @ $1,000/kW, storage @ $200/kWh												Future technology cost: PV @ $400/kW, storage @ $50/kWh											
		no flexibility				2.5% flexibility				5% flexibility				no flexibility				2.5% flexibility				5% flexibility			
	Electrical region	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh
homogeneously dispersed fleets	Entire NYISO	111	0.29	0%	4.83	29	0.19	0%	4.48	1	0.07	0%	4.35	62	0.72	0%	2.01	12	0.19	0%	1.79	1	0.07	0%	1.74
	Region A	149	0.39	0%	5.00	68	0.28	0%	4.65	30	0.19	0%	4.48	79	0.98	0%	2.09	37	0.39	0%	1.90	13	0.19	0%	1.80
	Region B	167	0.47	1%	5.08	88	0.40	0%	4.73	40	0.23	0%	4.52	75	0.72	1%	2.06	34	0.40	0%	1.89	17	0.23	0%	1.81
	Region C	168	0.41	3%	5.08	84	0.38	0%	4.71	37	0.24	0%	4.51	69	0.78	0%	2.04	35	0.40	0%	1.89	14	0.24	0%	1.80
	Region D	148	0.36	0%	5.00	72	0.29	0%	4.66	32	0.21	0%	4.49	68	0.81	0%	2.04	35	0.29	1%	1.89	13	0.21	0%	1.80
	Region E	130	0.33	0%	4.92	49	0.24	0%	4.56	11	0.13	0%	4.40	72	0.86	0%	2.05	23	0.24	0%	1.84	3	0.13	0%	1.75
	Region F	152	0.37	1%	5.01	68	0.29	0%	4.65	23	0.17	0%	4.45	78	0.86	1%	2.08	33	0.50	0%	1.88	9	0.17	0%	1.78
	Region G	160	0.38	1%	5.05	70	0.26	0%	4.65	27	0.15	0%	4.47	77	0.80	1%	2.08	35	0.35	0%	1.89	14	0.21	0%	1.80
	Region H	214	0.51	6%	5.28	169	0.42	0%	5.09	118	0.45	0%	4.86	98	0.97	2%	2.17	73	0.81	2%	2.06	60	0.71	2%	2.00
	Region I	205	0.71	1%	5.24	178	0.64	0%	5.12	135	0.55	0%	4.94	89	0.89	1%	2.13	75	0.66	3%	2.07	62	0.87	0%	2.01
	Region J	218	0.54	1%	5.30	156	0.55	0%	5.03	116	0.51	0%	4.85	100	0.83	3%	2.18	67	0.65	2%	2.03	50	0.64	0%	1.96
	Region K	203	0.52	5%	5.23	140	0.54	0%	4.96	85	0.40	0%	4.72	89	0.72	3%	2.13	58	0.45	3%	1.99	36	0.39	0%	1.89
Individual locations	Region A	403	1.34	7%	6.11	364	1.15	9%	5.93	306	1.25	0%	5.68	156	1.70	4%	2.42	135	1.54	5%	2.33	118	1.06	9%	2.25
	Region B	293	0.81	6%	5.62	233	0.78	4%	5.36	187	0.68	0%	5.16	130	0.96	4%	2.31	91	0.78	4%	2.14	84	0.82	4%	2.11
	Region C	384	1.52	3%	6.02	322	1.28	3%	5.75	266	1.05	0%	5.51	139	1.52	3%	2.34	111	1.39	2%	2.22	95	1.09	3%	2.15
	Region D	344	1.09	4%	5.85	276	0.98	5%	5.55	241	0.94	0%	5.40	140	1.24	7%	2.35	100	0.98	5%	2.17	98	0.85	8%	2.16
	Region E	283	0.80	4%	5.58	231	0.71	5%	5.35	174	0.64	0%	5.11	136	0.76	8%	2.33	92	0.78	4%	2.14	80	0.68	5%	2.09
	Region F	334	0.82	3%	5.80	267	0.84	0%	5.51	211	0.77	0%	5.27	130	1.43	3%	2.31	114	1.13	5%	2.23	98	0.89	6%	2.17
	Region G	358	0.91	3%	5.91	282	0.85	0%	5.58	216	0.76	0%	5.29	147	1.53	4%	2.38	127	1.36	5%	2.29	114	1.10	7%	2.24
	Region H	480	1.71	2%	6.44	400	1.59	0%	6.09	343	1.46	0%	5.84	188	2.26	5%	2.56	165	2.09	6%	2.46	137	1.44	0%	2.34
	Region I	338	0.87	6%	5.82	262	0.94	3%	5.49	209	0.74	0%	5.26	127	1.59	1%	2.29	98	1.03	3%	2.17	85	0.76	5%	2.11
	Region J	353	1.17	2%	5.88	293	1.08	2%	5.63	256	1.01	0%	5.46	143	1.16	6%	2.36	110	1.05	5%	2.22	87	1.01	3%	2.12
	Region K	460	1.56	-1%	6.35	388	1.48	0%	6.04	341	1.39	0%	5.83	224	1.45	5%	2.71	174	1.36	4%	2.50	143	1.33	1%	2.36

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 July 2020 doi:10.20944/preprints202007.0088.v1

Peer-reviewed version available at Energies 2020, 13, 4489; doi:10.3390/en13174489

Table 2. Three hours ahead forecasts

	3 Hour forecasts	Current technology cost: PV @ $1,000/kW, storage @ $200/kWh												Future technology cost: PV @ $400/kW, storage @ $50/kWh											
		no flexibility				2.5% flexibility				5% flexibility				no flexibility				2.5% flexibility				5% flexibility			
	Electrical region	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh
homogeneously dispersed fleets	Entire NYISO	259	0.50	5%	5.48	152	0.46	1%	5.01	84	0.40	0%	4.71	153	0.47	6%	2.41	77	0.47	1%	2.08	35	0.40	0%	1.76
	Region A	367	1.01	0%	5.95	253	0.89	0%	5.45	186	0.78	0%	5.16	199	3.08	0%	2.61	120	1.87	0%	2.26	72	1.09	0%	1.71
	Region B	398	1.26	0%	6.08	290	1.12	0%	5.61	231	0.98	0%	5.36	193	2.04	5%	2.58	128	1.24	3%	2.30	90	1.02	0%	1.84
	Region C	379	1.16	0%	6.00	279	1.03	0%	5.56	212	0.90	0%	5.27	193	2.15	4%	2.58	124	1.76	0%	2.28	78	1.25	0%	1.82
	Region D	375	0.98	0%	5.98	248	0.78	0%	5.43	155	0.58	0%	5.02	171	1.74	4%	2.48	115	1.32	0%	2.24	74	0.83	0%	1.82
	Region E	310	0.71	1%	5.70	190	0.62	0%	5.18	120	0.51	0%	4.87	172	1.58	5%	2.49	105	1.06	1%	2.20	56	0.81	0%	1.79
	Region F	333	0.76	0%	5.80	209	0.60	0%	5.26	133	0.49	0%	4.93	189	1.39	10%	2.56	125	1.06	3%	2.29	70	0.60	0%	1.81
	Region G	392	0.97	3%	6.05	266	0.83	0%	5.51	169	0.63	0%	5.08	194	1.96	6%	2.59	133	1.16	5%	2.32	86	0.64	0%	1.71
	Region H	442	1.37	6%	6.27	362	1.27	0%	5.93	280	1.05	0%	5.57	179	1.67	5%	2.52	151	1.48	6%	2.40	123	1.48	1%	1.71
	Region I	478	1.44	6%	6.43	387	1.35	0%	6.03	303	1.13	0%	5.67	196	2.52	2%	2.59	160	2.04	3%	2.43	132	1.72	3%	1.71
	Region J	454	1.31	3%	6.33	355	1.17	0%	5.89	272	0.97	0%	5.53	196	2.14	5%	2.59	161	1.65	7%	2.44	132	1.27	8%	1.71
	Region K	407	1.28	3%	6.12	322	1.08	0%	5.75	247	0.96	0%	5.42	173	1.58	7%	2.49	129	0.98	10%	2.30	109	0.92	1%	1.71
Individual locations	Region A	498	1.37	4%	6.52	424	1.33	0%	6.19	346	1.19	0%	5.85	260	2.22	13%	2.87	173	2.06	0%	2.49	126	1.64	2%	1.71
	Region B	474	1.11	5%	6.41	377	1.10	0%	5.99	298	1.03	0%	5.65	221	1.78	9%	2.70	163	1.51	5%	2.45	120	1.28	4%	1.71
	Region C	536	1.41	0%	6.68	429	1.30	0%	6.22	349	1.20	0%	5.87	240	2.49	1%	2.79	179	2.07	2%	2.52	151	1.11	10%	1.71
	Region D	512	1.35	0%	6.58	392	1.15	0%	6.05	301	0.97	0%	5.66	230	1.89	12%	2.74	182	1.65	10%	2.53	137	1.28	8%	1.71
	Region E	465	1.36	4%	6.37	383	1.08	8%	6.02	321	1.07	0%	5.75	234	1.25	15%	2.76	172	1.39	3%	2.49	120	1.67	0%	1.71
	Region F	491	1.18	3%	6.49	385	1.12	0%	6.02	300	0.96	0%	5.66	269	1.42	15%	2.91	211	1.15	3%	2.66	157	1.07	4%	1.94
	Region G	538	1.43	1%	6.69	426	1.31	0%	6.20	345	1.14	0%	5.85	251	3.23	5%	2.83	200	2.48	6%	2.61	168	1.77	9%	1.95
	Region H	579	1.82	0%	6.87	484	1.68	0%	6.45	412	1.54	0%	6.14	232	2.75	5%	2.75	202	1.99	10%	2.62	179	1.58	13%	1.97
	Region I	493	1.47	3%	6.49	401	1.28	2%	6.09	321	1.08	0%	5.75	228	3.12	2%	2.73	183	2.17	5%	2.54	153	1.28	0%	1.93
	Region J	498	1.39	2%	6.52	428	1.31	2%	6.21	366	1.26	0%	5.94	226	1.89	11%	2.72	183	1.57	11%	2.54	157	1.19	11%	1.71
	Region K	594	1.64	5%	6.93	509	1.70	0%	6.56	435	1.56	0%	6.24	304	1.71	27%	3.06	255	1.52	7%	2.85	210	1.50	2%	2.01

Table 3. Twenty four hours ahead forecasts

	24 Hour forecasts	Current technology cost: PV @ $1,000/kW, storage @ $200/kWh												Future technology cost: PV @ $400/kW, storage @ $50/kWh											
		no flexibility				2.5% flexibility				5% flexibility				no flexibility				2.5% flexibility				5% flexibility			
	Electrical region	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh
homogeneously dispersed fleets	Entire NYISO	412	0.99	2%	6.14	261	0.82	0%	5.49	161	0.62	0%	5.05	216	1.87	9%	2.68	136	1.07	5%	2.33	77	0.71	1%	1.79
	Region A	602	1.36	16%	6.97	462	1.31	10%	6.36	369	1.39	0%	4.35	251	3.49	2%	2.83	184	2.38	3%	2.54	141	1.82	3%	1.72
	Region B	602	1.44	12%	6.97	467	1.46	3%	6.38	355	1.36	0%	5.89	269	3.04	5%	2.91	189	2.34	4%	2.56	140	1.67	4%	1.84
	Region C	582	1.54	5%	6.88	431	1.41	0%	6.23	312	1.17	0%	5.71	255	2.77	6%	2.85	175	2.04	4%	2.50	134	1.66	3%	1.84
	Region D	535	1.27	3%	6.68	387	1.08	0%	6.03	274	0.93	0%	5.54	246	2.72	6%	2.81	186	1.91	7%	2.55	134	1.59	2%	1.84
	Region E	470	1.01	8%	6.40	326	0.87	3%	5.77	214	0.76	0%	5.28	226	1.99	8%	2.73	157	1.33	6%	2.42	100	1.03	0%	1.81
	Region F	567	1.53	8%	6.82	416	1.39	1%	6.16	300	1.20	0%	5.66	262	2.22	12%	2.88	195	1.37	6%	2.59	130	1.26	-2%	1.83
	Region G	577	1.70	12%	6.86	484	1.37	13%	6.46	385	1.39	1%	4.35	249	1.65	14%	2.82	190	1.62	10%	2.57	151	1.36	9%	1.72
	Region H	734	2.47	13%	7.54	649	2.17	14%	7.17	580	2.01	9%	4.35	278	2.83	9%	2.95	234	2.47	10%	2.76	203	2.18	11%	1.72
	Region I	664	2.36	9%	7.24	592	2.04	11%	6.93	532	1.80	12%	4.35	257	2.51	8%	2.86	220	2.04	11%	2.70	190	1.80	12%	1.72
	Region J	735	2.76	9%	7.55	632	2.34	10%	7.10	548	2.01	10%	4.35	267	2.76	9%	2.90	219	2.41	9%	2.69	186	2.01	10%	1.72
	Region K	699	2.66	9%	7.39	590	2.21	10%	6.92	533	1.95	11%	4.35	247	2.66	9%	2.81	198	2.21	10%	2.60	174	2.02	10%	1.72
Individual locations	Region A	696	1.43	22%	7.38	584	1.50	12%	6.89	480	1.42	0%	4.35	285	3.97	3%	2.98	237	2.85	6%	2.77	192	1.89	9%	1.72
	Region B	706	1.79	4%	7.42	566	1.61	0%	6.81	442	1.40	0%	4.35	324	3.28	12%	3.15	245	2.99	4%	2.80	174	2.11	2%	1.72
	Region C	761	2.14	1%	7.66	641	2.03	0%	7.14	536	1.85	0%	4.35	310	3.50	7%	3.09	238	2.82	5%	2.77	191	2.48	3%	1.72
	Region D	616	1.51	3%	7.03	492	1.33	2%	6.49	388	1.19	0%	4.35	265	2.40	12%	2.89	213	1.83	12%	2.67	167	1.29	12%	1.72
	Region E	626	1.41	6%	7.07	500	1.41	-2%	6.52	392	1.23	0%	4.35	306	3.39	7%	3.07	233	2.20	9%	2.75	174	1.60	8%	1.72
	Region F	797	2.43	8%	7.82	651	2.30	0%	7.18	533	2.00	0%	6.67	350	2.83	20%	3.26	283	2.39	18%	2.97	238	2.45	1%	1.92
	Region G	733	2.43	2%	7.54	605	2.00	6%	6.98	512	1.57	12%	6.58	298	2.93	11%	3.04	247	2.26	13%	2.81	199	1.52	15%	1.89
	Region H	770	2.47	16%	7.70	676	2.17	16%	7.29	602	2.08	8%	6.97	283	3.31	7%	2.97	239	2.69	9%	2.78	206	2.30	10%	1.90
	Region I	743	2.19	18%	7.58	646	2.01	16%	7.16	556	1.84	13%	6.77	270	3.07	6%	2.91	233	2.48	9%	2.75	197	1.96	11%	1.89
	Region J	788	2.95	10%	7.78	671	2.45	11%	7.27	562	1.97	0%	4.35	285	2.95	10%	2.98	237	2.45	11%	2.77	199	1.97	12%	1.72
	Region K	882	2.74	5%	8.19	758	2.64	-2%	7.65	650	2.40	0%	7.18	369	2.60	29%	3.35	322	2.53	29%	3.14	292	2.46	29%	1.97

The results presented in Tables 1-3 are, of course, dependent on the accuracy of the underlying forecast model. Figure 4 provides a measure of how these results would be affected, if, instead of the state-of-the-art SUNY (SolarAnywhere) forecast model, we had applied less performant models, namely smart persistence [38], GFS [31], and ECMWF [30] – note that the last two models are internal components of the SUNY model. The quantity plotted in Figure 4 is the mean firm forecast cost premium per nominal PV kW across all scenarios analyzed. Full detailed results for these other forecast models are provided in Appendix A.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 July 2020 doi:10.20944/preprints202007.0088.v1

Peer-reviewed version available at Energies 2020, 13, 4489; doi:10.3390/en13174489

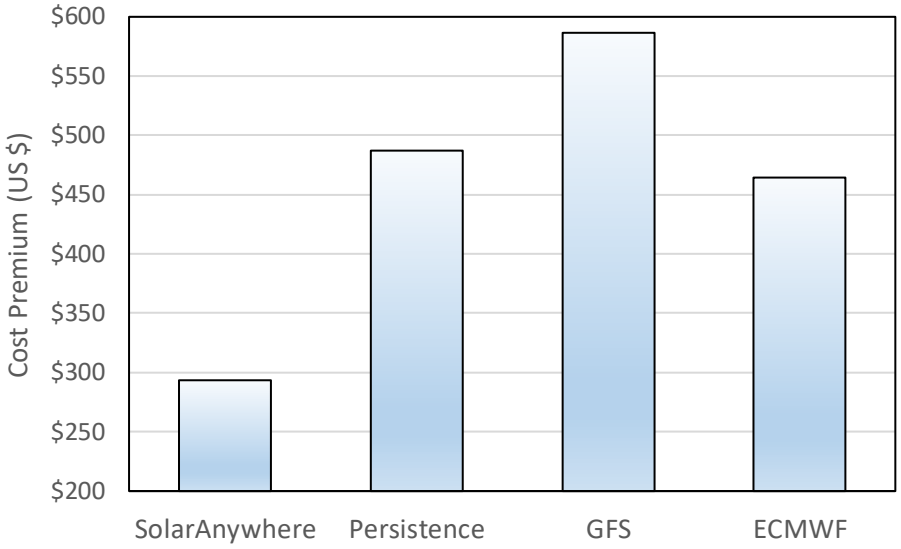

Figure 4: Comparing firm forecast cost premium per nominal KW as a function of forecast model. Displayed costs represent a mean for all scenarios and time horizons analyzed.

3.2 Firm power generation

Table 4 is analogous to Table 1-3, but with a firm load target equal to NYISO load shapes instead of forecast PV production. Table 5 reports the same results but achieved without implicit storage – i.e., no overbuilding and no PV output curtailment. These two tables correspond respectively to point C and point B in Figure 1.

Table 4. Firm power generation with implicit storage

	Firm Power Gen	Current cost: PV @ 1,000/kW, storage @ $200/kWh												Future cost: PV @ 400/kW, storage @ $50/kWh											
		no flexibility				*2.5% flexibility*				*5% flexibility*				no flexibility				2.5% flexibility				5% flexibility			
	Electrical region	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh
homogeneously dispersed fleets	Entire NYISO	3299	6.7	197%	19.33	2062	4.4	118%	14.17	1654	3.7	92%	12.17	1107	6.8	192%	6.68	683	4.8	111%	5.47	541	4.2	83%	4.85
	Region A	4390	5.6	328%	24.32	2630	4.5	174%	16.89	2143	3.5	145%	14.40	1581	6.6	313%	8.87	900	5.2	161%	6.52	734	4.1	132%	5.74
	Region B	4313	7.3	285%	24.26	2634	4.6	171%	16.94	2141	3.6	142%	14.46	1505	7.3	285%	8.57	898	5.1	160%	6.52	731	4.1	132%	5.76
	Region C	4541	10.4	245%	25.97	2626	4.9	164%	17.12	2153	4.0	136%	14.67	1503	10.4	245%	8.76	877	5.6	149%	6.54	719	4.8	120%	5.78
	Region D	4088	8.2	245%	23.25	2881	5.5	179%	18.06	2411	4.7	148%	15.65	1376	8.3	241%	7.99	975	6.0	169%	6.90	810	5.1	139%	6.12
	Region E	4209	7.7	267%	23.76	2630	5.1	161%	16.99	2181	4.3	132%	14.72	1434	9.0	245%	8.29	886	5.8	149%	6.54	732	4.7	125%	5.83
	Region F	4001	10.8	184%	22.75	2273	5.2	122%	15.07	1863	4.5	96%	13.03	1276	10.8	184%	7.48	733	6.0	109%	5.71	594	5.1	85%	5.08
	Region G	3417	10.2	138%	19.31	2031	6.3	78%	13.65	1689	4.6	76%	11.86	1049	10.9	126%	6.24	624	6.3	77%	5.08	519	5.3	64%	4.62
	Region H	3541	11.8	118%	19.55	2119	6.5	81%	13.80	1759	5.1	75%	12.02	1063	11.8	118%	6.17	641	6.9	74%	5.16	534	5.8	61%	4.71
	Region I	3026	11.4	74%	17.30	1984	6.1	75%	12.98	1625	5.1	61%	11.35	868	11.4	74%	5.34	581	7.5	52%	4.82	470	6.0	42%	4.38
	Region J	3043	10.6	92%	17.29	1964	6.4	68%	12.93	1586	5.2	55%	11.17	875	12.6	61%	5.42	565	7.3	50%	4.70	457	6.0	40%	4.24
	Region K	2898	10.8	74%	16.38	1823	6.1	61%	12.16	1524	5.0	51%	10.81	836	10.8	74%	5.09	538	6.4	54%	4.52	446	5.7	40%	4.25
Individual locations	Entire NYISO	4215	10.2	217%	24.65	2352	5.2	132%	16.02	1941	4.2	111%	13.85	1385	12.0	197%	8.35	773	5.6	124%	6.06	640	4.6	102%	5.42
	Region A	4396	6.2	315%	24.91	2768	4.5	186%	17.80	2249	3.7	151%	15.13	1570	6.4	313%	8.98	951	5.2	173%	6.85	772	4.3	139%	5.99
	Region B	4081	7.8	253%	23.57	2592	4.7	165%	16.95	2137	3.8	137%	14.61	1400	7.8	253%	8.22	878	5.4	152%	6.53	712	5.0	115%	5.77
	Region C	4607	7.4	313%	25.84	2691	5.4	160%	17.50	2222	4.4	134%	15.07	1589	7.5	304%	9.04	889	6.2	145%	6.59	742	5.0	123%	5.90
	Region D	4210	8.8	245%	24.41	2893	5.3	183%	18.47	2451	4.2	160%	16.08	1381	9.0	233%	8.22	990	5.7	176%	7.04	828	5.4	140%	6.32
	Region E	6099	22.5	160%	35.11	2725	5.6	160%	17.86	2241	4.4	136%	15.32	1765	22.5	160%	10.50	897	6.6	142%	6.75	737	5.7	113%	6.01
	Region F	4171	11.6	185%	23.04	2325	5.7	119%	15.00	1906	4.8	94%	12.96	1321	11.6	185%	7.52	736	6.5	103%	5.63	597	5.6	80%	5.01
	Region G	3898	9.9	192%	20.94	2140	6.2	90%	13.90	1753	4.9	77%	12.01	1160	13.5	121%	6.70	652	6.7	79%	5.15	534	5.8	61%	4.65
	Region H	3420	11.0	121%	19.00	2148	6.3	89%	13.90	1788	5.1	77%	12.15	1036	11.0	121%	6.06	655	7.2	74%	5.21	545	6.0	62%	4.76
	Region I	2942	11.0	74%	16.86	1982	6.2	74%	12.92	1617	5.2	59%	11.30	847	11.0	74%	5.23	594	6.6	66%	4.77	468	6.0	42%	4.36
	Region J	3153	11.6	83%	17.89	1944	6.6	62%	12.91	1580	5.0	58%	11.25	893	13.0	61%	5.52	560	7.2	50%	4.69	455	6.1	38%	4.24
	Region K	3171	9.6	125%	17.40	1887	6.3	63%	12.51	1578	5.1	56%	11.09	939	11.9	86%	5.57	559	6.6	57%	4.64	466	5.6	46%	4.35

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 July 2020 doi:10.20944/preprints202007.0088.v1

Peer-reviewed version available at *Energies* **2020**, *13*, 4489; doi:10.3390/en13174489

Table 5. Firm power generation w/o implicit storage

	Firm Power Gen	Current cost: PV @ 1,000/kW, storage @ $200/kWh												Future cost: PV @ 400/kW, storage @ $50/kWh											
		no flexibility				*2.5% flexibility*				*5% flexibility*				no flexibility				2.5% flexibility				5% flexibility			
	Electrical region	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh
homogeneously dispersed fleets	Entire NYISO	42757	213.8	0%	220	37535	187.7	0%	189	32037	160.2	0%	158	10689	213.8	0%	56	9384	187.7	0%	49	8009	160.2	0%	41
	Region A	52591	263.0	0%	275	48166	240.8	0%	247	43508	217.5	0%	218	13148	263.0	0%	70	12042	240.8	0%	63	10877	217.5	0%	56
	Region B	51671	258.4	0%	271	47068	235.3	0%	242	42227	211.1	0%	212	12918	258.4	0%	68	11767	235.3	0%	62	10557	211.1	0%	54
	Region C	52172	260.9	0%	275	47712	238.6	0%	247	43017	215.1	0%	217	13043	260.9	0%	70	11928	238.6	0%	63	10754	215.1	0%	56
	Region D	60504	302.5	0%	314	56277	281.4	0%	286	51914	259.6	0%	257	15126	302.5	0%	79	14069	281.4	0%	73	12979	259.6	0%	66
	Region E	55382	276.9	0%	288	50794	254.0	0%	259	46033	230.2	0%	229	13845	276.9	0%	73	12699	254.0	0%	66	11508	230.2	0%	59
	Region F	45056	225.3	0%	229	39866	199.3	0%	199	34420	172.1	0%	168	11264	225.3	0%	58	9966	199.3	0%	51	8605	172.1	0%	43
	Region G	35207	176.0	0%	172	29625	148.1	0%	143	25758	128.8	0%	122	8802	176.0	0%	44	7406	148.1	0%	37	6440	128.8	0%	32
	Region H	37090	185.4	0%	177	31515	157.6	0%	148	26945	134.7	0%	124	9272	185.4	0%	45	7879	157.6	0%	38	6736	134.7	0%	32
	Region I	31524	157.6	0%	149	28667	143.3	0%	133	27941	139.7	0%	127	7881	157.6	0%	38	7167	143.3	0%	35	6985	139.7	0%	33
	Region J	29700	148.5	0%	141	26802	134.0	0%	125	26952	134.8	0%	123	7425	148.5	0%	36	6700	134.0	0%	32	6738	134.8	0%	32
	Region K	32438	162.2	0%	150	29746	148.7	0%	136	30915	154.6	0%	137	8109	162.2	0%	38	7436	148.7	0%	35	7729	154.6	0%	36
Individual locations	Entire NYISO	45194	226.0	0%	240	40565	202.8	0%	212	35693	178.5	0%	182	11298	226.0	0%	61	10141	202.8	0%	54	8923	178.5	0%	47
	Region A	52287	261.4	0%	279	47942	239.7	0%	251	43522	217.6	0%	222	13072	261.4	0%	70	11985	239.7	0%	64	10881	217.6	0%	57
	Region B	49154	245.8	0%	260	44589	222.9	0%	232	39783	198.9	0%	202	12288	245.8	0%	66	11147	222.9	0%	59	9946	198.9	0%	52
	Region C	53964	269.8	0%	286	49517	247.6	0%	257	44835	224.2	0%	227	13491	269.8	0%	72	12379	247.6	0%	65	11209	224.2	0%	58
	Region D	59102	295.5	0%	314	55050	275.2	0%	286	50784	253.9	0%	257	14776	295.5	0%	79	13762	275.2	0%	73	12696	253.9	0%	66
	Region E	52808	264.0	0%	282	48348	241.7	0%	253	43697	218.5	0%	223	13202	264.0	0%	71	12087	241.7	0%	64	10924	218.5	0%	57
	Region F	43974	219.9	0%	219	38660	193.3	0%	189	33372	166.9	0%	159	10994	219.9	0%	55	9665	193.3	0%	48	8343	166.9	0%	41
	Region G	33974	169.9	0%	164	28323	141.6	0%	135	26046	130.2	0%	121	8493	169.9	0%	42	7081	141.6	0%	35	6511	130.2	0%	32
	Region H	37211	186.1	0%	178	31648	158.2	0%	149	26951	134.8	0%	124	9303	186.1	0%	45	7912	158.2	0%	39	6738	134.8	0%	32
	Region I	31266	156.3	0%	148	28495	142.5	0%	132	27956	139.8	0%	127	7817	156.3	0%	37	7124	142.5	0%	34	6989	139.8	0%	33
	Region J	30548	152.7	0%	145	27833	139.2	0%	130	27441	137.2	0%	125	7637	152.7	0%	37	6958	139.2	0%	34	6860	137.2	0%	33
	Region K	32991	165.0	0%	154	30325	151.6	0%	139	30896	154.5	0%	138	8248	165.0	0%	39	7581	151.6	0%	36	7724	154.5	0%	36

In the most favorable future case – $400/kW PV, $50/kWh storage & 5% energy flexibility – the firm 24/365 PV generation LCOE for all NYISO regions would range from 4.2 to 6.3 ¢/kWh. These power generation numbers are comparable to current wholesale NYISO Location Based Market Prices (LBMPs) [39]. Furthermore, as was shown in our investigation of the MISO power grid [24, 25], these pure PV numbers could probably be reduced by 25%-30% when optimally blending wind generation. While the analysis of this renewables blending is out of the scope of the current paper, it will nevertheless constitute a pertinent follow-on, given New York's unique offshore wind resource potential [40].

A significant observation, comparing Tables 4 and 5 is the nearly ten-fold difference between scenarios applying implicit storage and scenarios avoiding curtailment. Required storage quantities and bottom-line electricity production costs would be one order of magnitude larger without provisioning PV overbuilding and operational curtailment. Of course, this difference depends on the assumed relative costs of PV and storage. Here we have assumed $400/kW for PV & $50/kWh for storage for the future scenario. The PV estimate is likely a robust estimate since PV technology will increasingly represent a smaller part of a PV plant's cost compared to structural outlays. Our storage estimate however, while optimistically sourced from NREL predictions [37] could be considered as too conservative by some, considering recent future flow battery ultra-low cost claims [41]. Figure 5 provides a sensibility analysis for assumed storage cost impact on implicit storage levels and LCOE bottom lines. This shows that the tenfold difference observed under current assumptions could be moderately reduced if ultra-low cost storage targets were to materialize, but that implicit storage would remain a crucial element to achieving lowest possible production costs.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 July 2020 doi:10.20944/preprints202007.0088.v1

Peer-reviewed version available at Energies 2020, 13, 4489; doi:10.3390/en13174489

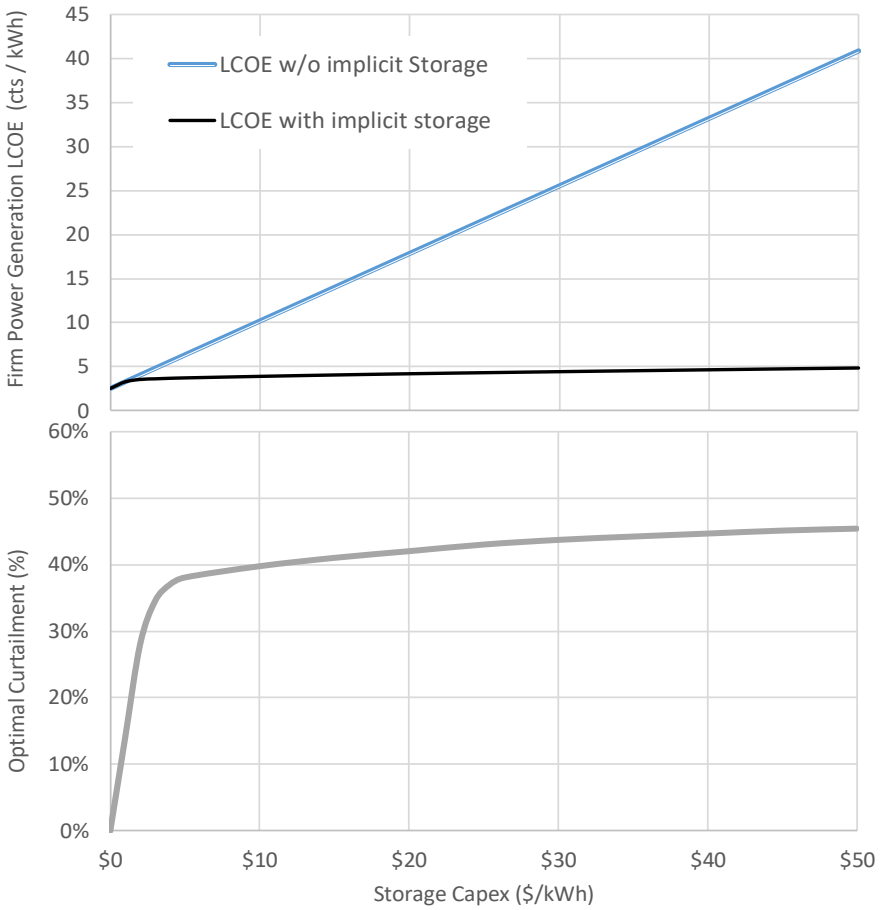

Figure 5: Comparing LCOE with and without implicit storage (top), and optimum level of proactive curtailment (bottom) as a function of future storage costs. Note: this illustrative example if for the future NYISO-wide scenario @ 5% flexibility.

3.3 Evolving Penetration

Tables 6, 7 and 8 report results for firm power generation logistics at 10%, 25% and 50% penetration. Target load shapes (see Figure 3) for these evolving penetration levels are defined as a blend between day-ahead forecasts and NYISO load shapes proportional to the degree of penetration.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 July 2020 doi:10.20944/preprints202007.0088.v1

Peer-reviewed version available at Energies 2020, 13, 4489; doi:10.3390/en13174489

Table 6. Firm generation at 10% penetration

	Firm Power Gen	Current cost: PV @ 1,000/kW, storage @ $200/kWh												Future cost: PV @ 400/kW, storage @ $50/kWh											
		no flexibility				2.5% flexibility				5% flexibility				no flexibility				2.5% flexibility				5% flexibility			
	Electrical region	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh
homogeneously dispersed fleets	Entire NYISO	936	4.4	5%	8.93	541	1.6	23%	7.00	428	0.8	26%	6.28	242	4.4	5%	2.90	151	2.0	13%	2.74	135	1.0	21%	2.59
	Region A	1074	4.5	17%	9.75	594	1.6	28%	7.44	455	1.1	24%	6.64	293	4.5	17%	3.20	167	2.0	17%	2.93	143	1.2	21%	2.75
	Region B	1064	4.8	10%	9.74	618	1.7	29%	7.49	477	1.1	25%	6.71	282	4.8	10%	3.16	203	1.6	31%	2.99	140	1.6	15%	2.72
	Region C	1081	4.9	10%	9.91	623	2.0	22%	7.67	500	1.2	26%	6.87	286	4.9	10%	3.20	178	2.2	17%	2.98	156	1.3	22%	2.81
	Region D	1261	5.8	10%	10.68	661	2.4	19%	7.81	541	1.4	27%	7.00	331	5.8	10%	3.38	192	2.4	18%	3.04	168	1.5	23%	2.87
	Region E	1146	4.6	23%	10.02	613	2.1	20%	7.54	488	1.2	24%	6.76	310	5.4	10%	3.28	170	2.8	8%	2.92	138	1.9	10%	2.75
	Region F	1173	5.6	5%	10.03	658	2.5	17%	7.66	526	1.6	20%	6.84	301	5.6	5%	3.17	183	2.6	14%	2.97	155	1.8	17%	2.79
	Region G	1244	5.7	10%	9.89	645	2.1	23%	7.23	506	1.6	18%	6.48	318	5.7	8%	3.10	184	2.3	17%	2.85	147	1.8	15%	2.65
	Region H	1214	5.5	11%	9.50	674	2.1	25%	7.15	523	1.5	22%	6.36	319	5.5	11%	3.03	189	2.5	17%	2.80	157	1.6	19%	2.61
	Region I	1226	5.4	14%	9.44	691	2.2	25%	7.17	539	1.4	26%	6.35	327	5.4	14%	3.02	186	2.9	10%	2.77	158	1.7	18%	2.60
	Region J	1244	5.3	18%	9.51	691	2.3	23%	7.20	545	1.4	26%	6.38	340	5.5	17%	3.08	186	2.9	10%	2.77	159	1.7	19%	2.61
	Region K	1196	4.8	23%	9.05	716	2.3	26%	7.07	535	1.6	21%	6.19	331	4.9	21%	2.96	199	2.7	17%	2.69	157	1.8	17%	2.49
Individual locations	Entire NYISO	1202	4.7	26%	10.47	717	2.8	17%	8.24	576	1.9	20%	7.40	327	5.4	14%	3.42	199	2.9	14%	3.12	160	2.4	10%	2.91
	Region A	1113	4.7	17%	10.14	630	2.2	19%	7.85	510	1.3	25%	7.07	303	4.7	17%	3.31	183	2.3	17%	3.08	156	1.5	20%	2.91
	Region B	1068	4.3	21%	9.78	642	2.2	21%	7.79	512	1.5	22%	6.99	296	4.6	17%	3.25	176	2.9	8%	2.95	152	1.7	17%	2.84
	Region C	1089	4.9	10%	9.98	673	2.6	15%	8.01	573	1.5	28%	7.26	288	4.9	10%	3.22	186	2.9	10%	3.06	174	1.7	23%	2.94
	Region D	1253	5.7	10%	10.88	721	2.5	22%	8.28	594	1.7	26%	7.46	329	5.7	10%	3.45	202	2.7	17%	3.18	168	2.5	10%	2.99
	Region E	1424	5.2	38%	11.58	744	2.7	21%	8.45	602	2.0	21%	7.56	374	6.6	10%	3.70	207	2.9	15%	3.24	175	2.1	17%	3.03
	Region F	1230	5.7	8%	10.05	722	2.8	17%	7.79	578	1.8	22%	6.94	320	5.7	8%	3.18	194	3.0	10%	2.95	167	2.0	17%	2.81
	Region G	1228	5.9	5%	9.73	692	2.5	19%	7.40	544	1.8	18%	6.60	315	5.9	5%	3.06	185	2.9	10%	2.86	154	2.0	13%	2.67
	Region H	1223	5.6	11%	9.56	673	2.2	23%	7.18	530	1.6	21%	6.42	322	5.6	11%	3.04	190	2.5	17%	2.81	155	1.8	17%	2.62
	Region I	1233	5.3	17%	9.42	689	2.3	23%	7.16	537	1.5	23%	6.34	333	5.3	16%	3.03	187	2.9	10%	2.77	160	1.7	19%	2.60
	Region J	1241	5.3	18%	9.52	701	2.7	17%	7.30	551	1.7	22%	6.46	337	5.4	17%	3.07	195	2.8	14%	2.81	160	1.9	17%	2.63
	Region K	1242	4.9	27%	9.31	741	2.4	26%	7.25	560	1.7	22%	6.38	351	4.9	27%	3.06	206	2.8	17%	2.77	156	2.3	10%	2.53

Table 7. Firm generation at 25% penetration

	Firm Power Gen	Current cost: PV @ 1,000/kW, storage @ $200/kWh												Future cost: PV @ 400/kW, storage @ $50/kWh											
		no flexibility				2.5% flexibility				5% flexibility				no flexibility				2.5% flexibility				5% flexibility			
	Electrical region	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh
homogeneously dispersed fleets	Entire NYISO	1813	3.6	109%	12.53	1014	2.6	50%	9.21	810	2.1	40%	8.56	596	3.8	101%	4.39	316	3.0	42%	3.55	249	3.1	23%	3.40
	Region A	2345	3.7	160%	15.14	1234	2.5	74%	10.31	983	2.6	46%	9.37	817	3.7	158%	5.44	408	3.1	63%	4.00	312	3.1	40%	3.60
	Region B	2385	3.9	160%	15.34	1279	2.6	76%	10.56	1032	2.2	59%	9.31	823	4.0	156%	5.47	416	3.3	63%	4.08	321	3.0	42%	3.67
	Region C	2479	5.8	132%	16.19	1251	2.8	69%	10.55	1006	2.6	49%	9.31	787	6.3	118%	5.46	405	3.2	61%	4.05	314	3.2	39%	3.66
	Region D	2221	5.1	120%	14.71	1319	3.2	68%	10.73	1095	3.0	49%	9.69	735	5.1	120%	5.10	425	3.5	63%	4.09	340	3.6	40%	3.75
	Region E	2559	4.8	160%	16.15	1421	3.1	79%	11.27	1147	2.7	61%	9.89	865	5.0	154%	5.67	467	3.4	74%	4.36	364	3.3	50%	3.93
	Region F	2263	5.9	109%	14.66	1177	3.3	51%	9.93	979	2.9	39%	9.20	709	6.0	102%	4.90	358	4.0	40%	3.74	293	3.5	30%	3.50
	Region G	1915	6.1	70%	12.65	1079	3.5	37%	9.15	902	3.4	23%	8.70	564	7.3	50%	4.15	320	3.9	31%	3.45	260	3.4	23%	3.59
	Region H	2302	7.6	77%	14.08	1311	4.1	50%	10.04	1081	3.3	42%	8.99	690	7.9	74%	4.57	391	4.5	41%	3.80	318	3.8	33%	3.60
	Region I	1748	7.2	31%	11.72	1047	3.8	29%	8.80	861	3.7	13%	8.28	484	7.2	31%	3.69	294	4.1	22%	3.30	234	3.7	13%	3.37
	Region J	1721	6.3	46%	11.51	1006	3.6	29%	8.67	818	3.4	14%	8.32	482	7.8	23%	3.72	279	3.9	21%	3.30	225	3.8	9%	3.47
	Region K	1731	6.2	50%	11.28	1055	3.6	33%	8.75	866	3.3	21%	8.12	507	6.2	49%	3.67	309	3.7	31%	3.39	243	3.6	15%	3.39
Individual locations	Entire NYISO	2347	5.8	119%	15.69	1257	3.1	63%	10.67	1057	3.1	45%	9.71	765	5.8	119%	5.37	392	3.6	53%	4.01	318	3.6	34%	3.74
	Region A	2417	4.1	160%	15.79	1355	2.6	84%	11.05	1062	3.1	44%	9.75	845	4.1	160%	5.68	445	3.3	70%	4.27	329	3.4	40%	3.78
	Region B	2336	5.1	132%	15.48	1301	2.6	78%	10.76	1031	2.8	47%	9.49	769	5.2	128%	5.34	418	3.5	61%	4.14	319	3.2	40%	3.71
	Region C	2457	4.3	160%	15.88	1301	3.2	67%	10.85	1074	3.0	48%	9.69	835	4.3	155%	5.60	417	3.4	61%	4.12	333	3.5	40%	3.79
	Region D	2280	4.8	132%	15.26	1390	3.2	75%	11.28	1157	3.4	47%	10.17	752	4.9	127%	5.28	450	3.6	67%	4.29	359	3.5	46%	3.91
	Region E	3703	14.0	90%	23.11	1535	3.4	85%	12.08	1261	3.4	58%	10.71	1061	14.0	90%	7.04	499	3.9	76%	4.62	390	3.8	50%	4.15
	Region F	2258	6.5	96%	14.39	1218	3.7	48%	9.92	1038	3.2	39%	9.13	706	6.9	90%	4.81	362	4.1	40%	3.69	305	3.9	28%	3.48
	Region G	2108	6.3	84%	13.30	1118	3.8	36%	9.22	936	3.5	23%	8.77	603	8.1	50%	4.29	327	4.1	30%	3.43	264	3.9	17%	3.53
	Region H	2207	7.7	66%	13.75	1293	3.9	51%	9.96	1071	3.2	43%	8.96	651	7.7	66%	4.42	387	4.4	42%	3.78	314	3.8	31%	3.60
	Region I	1676	6.8	32%	11.35	1055	3.5	36%	8.81	853	3.6	14%	8.22	467	6.8	32%	3.60	304	3.8	28%	3.35	234	3.6	14%	3.37
	Region J	1769	6.8	40%	11.80	994	4.0	19%	8.78	809	2.8	24%	8.60	488	7.9	23%	3.75	273	4.2	16%	3.25	230	4.0	8%	3.67
	Region K	1872	5.6	74%	11.84	1112	3.5	41%	8.99	926	2.7	38%	8.48	576	5.7	73%	3.95	315	4.0	29%	3.58	268	3.2	27%	3.68

Table 8. Firm generation at 50% penetration

	Firm Power Gen	Current cost: PV @ 1,000/kW, storage @ $200/kWh												Future cost: PV @ 400/kW, storage @ $50/kWh											
		no flexibility				2.5% flexibility				5% flexibility				no flexibility				2.5% flexibility				5% flexibility			
	Electrical region	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh
homogeneously dispersed fleets	Entire NYISO	2778	5.8	162%	16.98	1681	3.6	97%	12.35	1326	3.1	71%	10.65	939	6.0	160%	5.93	554	3.9	90%	4.79	425	3.5	62%	4.25
	Region A	3687	4.7	275%	21.12	2124	3.6	141%	14.50	1709	2.8	114%	12.40	1332	4.8	274%	7.72	730	4.1	132%	5.63	578	3.6	100%	4.95
	Region B	3686	6.2	245%	21.35	2149	3.7	141%	14.63	1736	3.0	114%	12.56	1279	6.2	242%	7.55	720	4.9	119%	5.65	576	4.1	93%	5.00
	Region C	3826	9.3	197%	22.66	2130	4.1	132%	14.75	1723	3.3	107%	12.65	1252	9.3	197%	7.61	711	4.5	121%	5.66	575	3.9	95%	5.02
	Region D	3440	7.2	199%	20.31	2323	4.5	142%	15.43	1897	3.8	114%	13.28	1163	7.5	197%	7.04	784	4.9	135%	5.92	631	4.2	105%	5.22
	Region E	3652	6.8	229%	21.21	2210	4.4	133%	15.00	1798	3.6	109%	12.93	1244	7.1	222%	7.39	743	4.7	126%	5.78	599	3.9	101%	5.14
	Region F	3423	9.1	160%	20.04	1872	4.5	97%	13.19	1508	3.8	74%	11.39	1086	9.2	156%	6.62	596	5.2	84%	5.00	474	4.2	66%	4.45
	Region G	2911	8.5	120%	17.02	1684	5.2	64%	12.02	1375	4.0	57%	10.47	889	9.7	101%	5.55	514	5.3	62%	4.50	420	4.4	50%	4.10
	Region H	3129	10.4	105%	17.73	1836	5.7	69%	12.50	1512	4.3	65%	10.88	939	10.4	105%	5.64	554	6.2	62%	4.70	454	5.0	51%	4.28
	Region I	2609	10.0	61%	15.47	1640	5.1	62%	11.40	1325	4.3	47%	10.00	717	10.3	51%	4.71	473	6.2	41%	4.23	381	5.0	33%	3.88
	Region J	2603	9.2	77%	15.37	1597	5.2	57%	11.23	1279	4.4	41%	9.87	745	10.9	50%	4.86	455	6.3	36%	4.12	363	4.9	30%	3.83
	Region K	2493	9.4	61%	14.64	1545	5.2	50%	10.90	1285	4.1	47%	9.80	716	9.4	61%	4.58	452	5.5	44%	4.08	369	5.1	29%	3.83
Individual locations	Entire NYISO	3654	8.4	197%	21.88	1947	4.1	112%	14.00	1606	3.7	86%	12.27	1175	8.8	184%	7.29	642	4.5	105%	5.34	517	4.2	76%	4.78
	Region A	3726	5.3	266%	21.79	2248	3.6	153%	15.30	1813	3.1	119%	13.11	1320	6.8	245%	7.89	771	4.6	135%	5.94	612	3.8	105%	5.19
	Region B	3491	6.9	211%	20.84	2120	3.8	136%	14.68	1746	3.3	109%	12.78	1190	6.9	211%	7.26	708	4.9	116%	5.67	572	4.2	90%	5.03
	Region C	3828	6.4	255%	22.25	2186	4.3	132%	15.07	1804	3.6	109%	13.08	1348	7.3	245%	7.98	722	5.1	116%	5.71	593	4.3	95%	5.13
	Region D	3502	7.6	198%	21.10	2371	4.4	150%	15.94	1970	3.4	128%	13.81	1173	7.7	197%	7.25	803	5.0	139%	6.12	659	4.5	109%	5.44
	Region E	5295	19.9	132%	31.12	2303	4.7	136%	15.79	1887	3.8	114%	13.62	1521	19.9	132%	9.32	762	5.4	123%	6.02	609	4.9	91%	5.33
	Region F	3555	9.8	160%	20.22	1896	5.0	90%	13.07	1554	4.3	70%	11.39	1117	9.9	156%	6.62	597	5.5	81%	4.91	479	4.7	61%	4.40
	Region G	3307	8.5	160%	18.39	1752	5.4	67%	12.17	1438	4.3	58%	10.62	974	11.8	96%	5.90	534	5.6	63%	4.54	425	5.0	44%	4.10
	Region H	3005	9.8	106%	17.18	1851	5.5	74%	12.55	1520	4.4	65%	10.94	910	9.8	106%	5.51	563	6.2	63%	4.74	458	5.2	50%	4.30
	Region I	2525	9.6	61%	15.04	1630	5.2	59%	11.34	1321	4.3	46%	9.96	723	9.6	61%	4.70	472	6.1	41%	4.22	381	4.8	35%	3.86
	Region J	2693	10.0	69%	15.87	1575	5.4	50%	11.21	1276	4.3	42%	9.86	759	11.2	50%	4.93	451	6.1	36%	4.10	361	5.0	27%	3.83
	Region K	2704	8.4	102%	15.43	1607	5.3	55%	11.22	1321	4.4	44%	9.94	817	9.1	90%	5.00	470	5.8	45%	4.16	386	4.9	35%	3.91

Figures 6 illustrates the impact of flexibility and grid penetration – hence of load shape requirements – on storage and overbuilding in the case of NYISO-wide distributed PV generation.

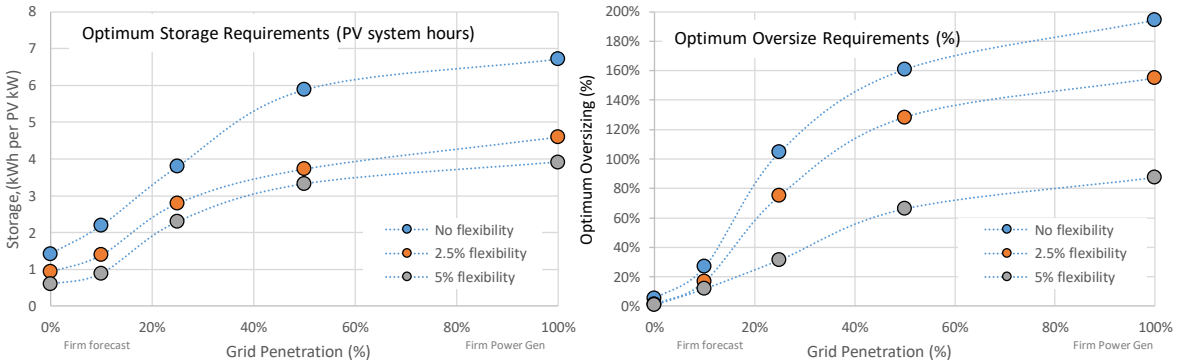

Figure 6: Physical storage (left) and implicit storage (right) optimum requirements as a function of penetration and flexibility. Note: these illustrative plots are for the entire NYISO and represent a mean of current and future cost scenarios.

As we had observed for the MISO and Italy studies [25, 27] a small amount of demand flexibility, from e.g., limited natural gas generation, goes a long way in reducing both true and implicit storage requirements. Most importantly for the present investigation, the trends show that firm forecast real and implicit storage requirements represent only a small fraction of firm power generation's requirements. This signifies (1) that in a future high PV penetration context, there will be ample storage and implicit storage available on power grids to address any production forecast uncertainty; and (2) that firm forecasts constitute a smart logistical entry step to building a future firm PV generation resource.

Figure 7 translates Figure 6's hardware requirements into operational electricity production LCOEs. The solid horizontal line represents the electricity production LCOE that would be unconstrained by any firmness requirements, i.e., the cost basis of present-day power purchase agreements (PPAs). Importantly, the small incremental cost to insure firm day-ahead forecasts – although this may be economically justifiable on the basis of current load balancing economics – makes it a sensible and effective entry step to a least-cost firm PV power generation strategy. The value of such strategy becomes fully apparent in Figure 8 where we compare firm production LCOEs with and without implicit storage. While the difference remains small when looking at firm forecasts (at low PV penetration), this grows exponentially, up to ten-fold, when very high penetration will demand firm power generation. This observation implies that the sooner implicit storage strategies are put in place, the easier it will be to evolve towards a lowest cost final objective.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 July 2020 doi:10.20944/preprints202007.0088.v1

Peer-reviewed version available at Energies 2020, 13, 4489; doi:10.3390/en13174489

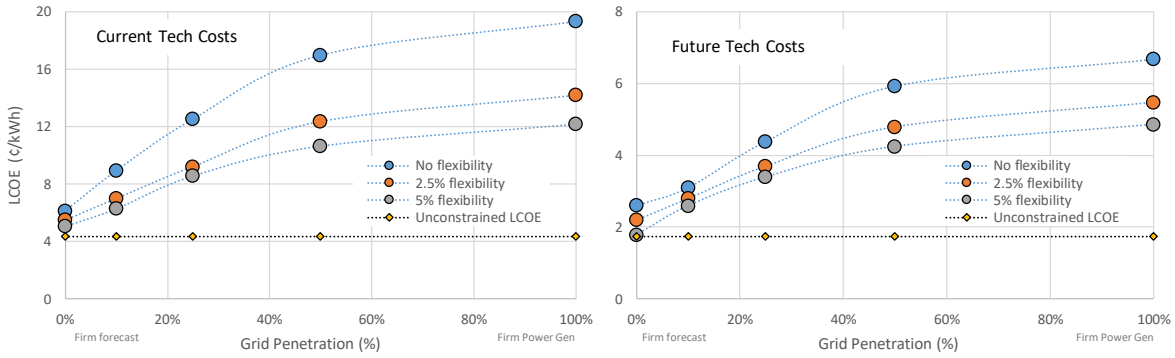

Figure 7: Evolution of firm PV generation LCOE from low penetration firm forecast requirements to high penetration firm power generation requirements, compared to unconstrained PV generation LCOE, at current (left) and future (right) technology costs. Note: these illustrative plots are for the entire NYISO.

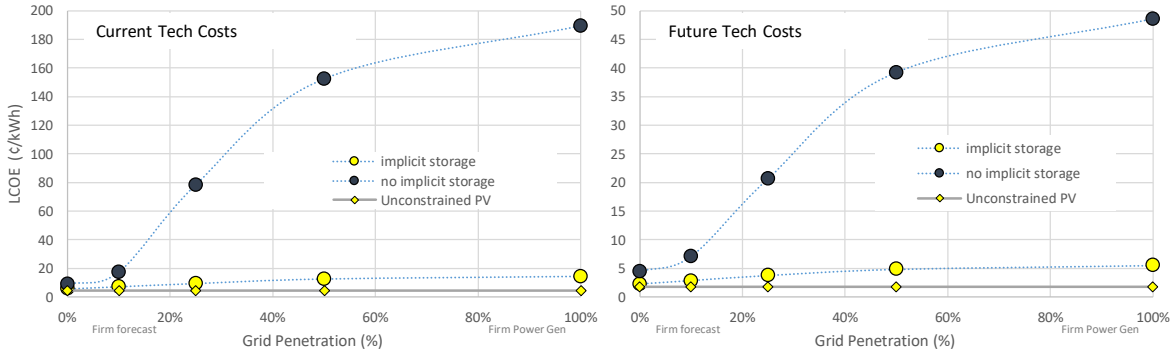

Figure 8: Comparing firm power generation LCOE with and without an implicit storage strategy. Note: this illustrative example is for NYISO-wide at 2.5% flexibility.

3.4 Regional and Fleet Configuration Trends

The breadth of scenarios analyzed reveals interesting trends that will inform resource regional deployment and PV fleet configuration choices.

Influence of electrical region size: We define the firm LCOE premium as the difference between firm LCOE and unconstrained LCOE for a given scenario. In Figure 9, we plot this firm LCOE premium for homogenously distributed PV fleets as a function of regional surface area. When the firmness requirement is for firm forecasts (i.e., low penetration in the context of this study), the trends indicate a decrease of the premium as a function of regional size (i.e., generating footprint size). The trend is most pronounced for the shortest-term forecasts. This finding is consistent with prior studies, including studies from the authors [35] showing that forecast accuracy improves as a function of the generating footprint. In other words, short-term weather-averaging is effective and results in smaller operational costs to firm-up large regional forecasts compared to small region's forecasts.

Importantly, this region-size trend disappears when the objective is firm power generation. This is because short-term weather averaging is less important than other factors in providing load shape firmness, namely seasonal resource trends and overall resource capacity factor.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 July 2020 doi:10.20944/preprints202007.0088.v1

Peer-reviewed version available at Energies 2020, 13, 4489; doi:10.3390/en13174489

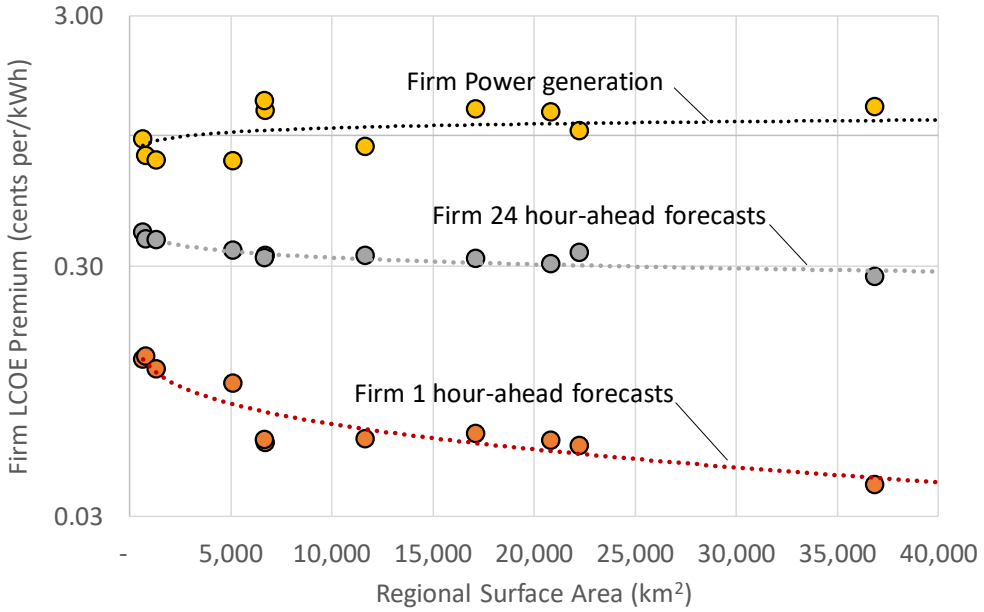

Figure 9: Firm LCOE premium as a function of electrical region size and firm load target.

Influence of the solar resource: Figure 10 is analogous to Figure 9, but replaces the X-axis by the solar resource's capacity factor.

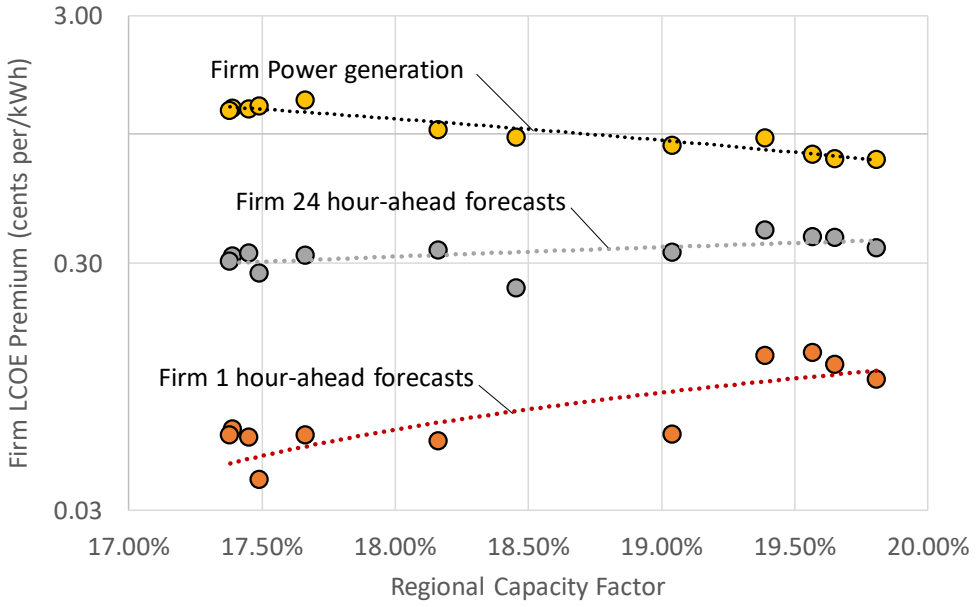

Figure 10: Firm LCOE premium as a function of regional capacity factor and firm load target.

The most important observation in Figure 10 is that the high-penetration's firm power generation costs, while not influenced by the generating footprint as noted above in Figure 9, are influenced by the solar resource. As would be expected, the higher the solar resource (quantified here by the PV capacity factor) the least costly the task of transforming unconstrained power generation into firm power generation. Delivering firm forecasts, on the other hand, is less influenced by the solar resource – note that the positive forecast trends apparent in Figure 10 are a reflection of region

size: indeed the smaller regions (see Figure 2) are located in the southern part of the state and benefit from a higher capacity factor as shown in Figure 11.

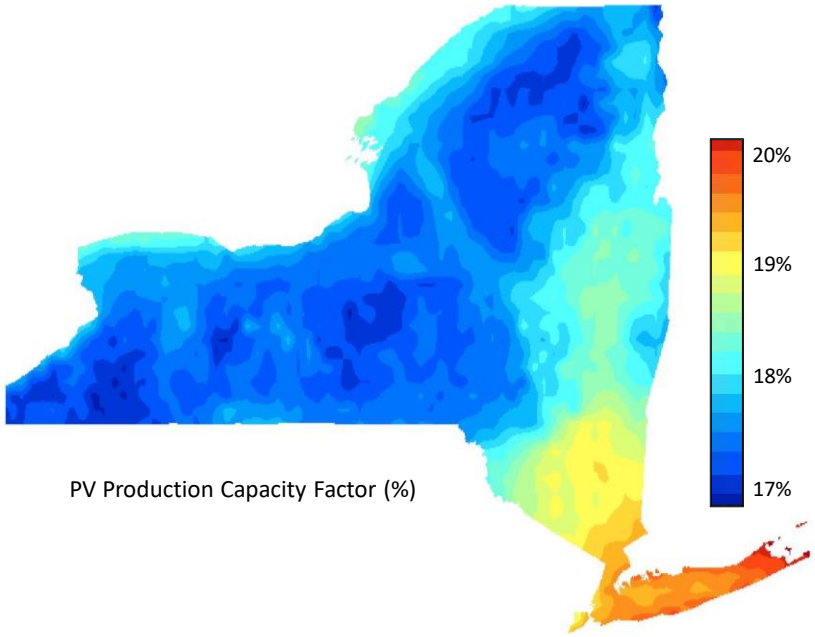

Figure 11: New York State Solar Resource – Annual PV Production Capacity Factor.

NYISO-Wide vs. single electric region strategy: We defined the regional penalty as the ratio between the mean regional firm generation LCOE and the firm LCOE for the entire NYISO, minus one. In Figure 12, we plotted this regional penalty across all scenarios considering homogenously dispersed PV fleets.

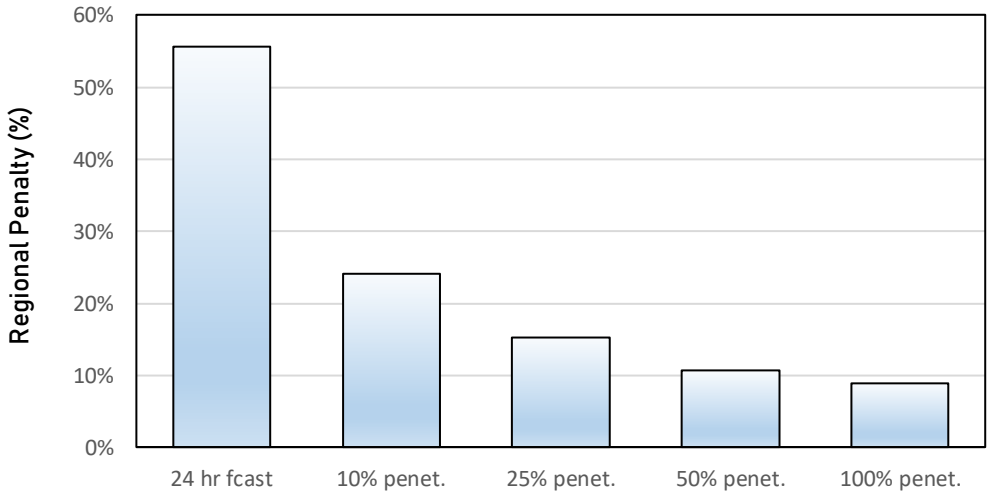

Figure 12: Regional penalty as a function of penetration and firmness requirements from 24-hours-ahead forecasts to firm power generation.

Consistently with the geographical trends observed in Figure 9, a statewide forecast balancing strategy would be considerably more cost-effective than region-specific strategies. However, this statewide advantage reduces significantly when firmness requirements evolve from forecast production to demand load shape. Weather-averaging (hence geographic dispersion) is important to

reduce weather-induced forecast errors. At high penetration, however, the driving factor for cost is multi-day/seasonal variability [24] where weather (hence the importance of weather averaging) has a comparatively lesser impact. This result is very important because it suggests that firm power generation could, if needed, be achieved within each electrical region at only a small premium compared to a NYISO-wide strategy that would have to rely on a strong transmission backbone.

Centralized power plants vs. distributed fleets' strategy: Figure 13 is analogous to Figure 12, but compares the penalty of centralized vs homogeneously dispersed generation premium within each region. The trend is reminiscent of the above NYISO-vs-region trend, because the driving factors are essentially the same: Weather-averaging is important to minimize forecast errors, hence the cost of producing firm forecasts, but other factors, chiefly seasonal trends, become dominant as penetration increase. This result is logistically important because it suggest that a few strategically located large plants and/or clusters of urban/suburban-sited systems within each region could supply the bulk of firm power requirements, without having to insure a perfectly homogeneous supply.

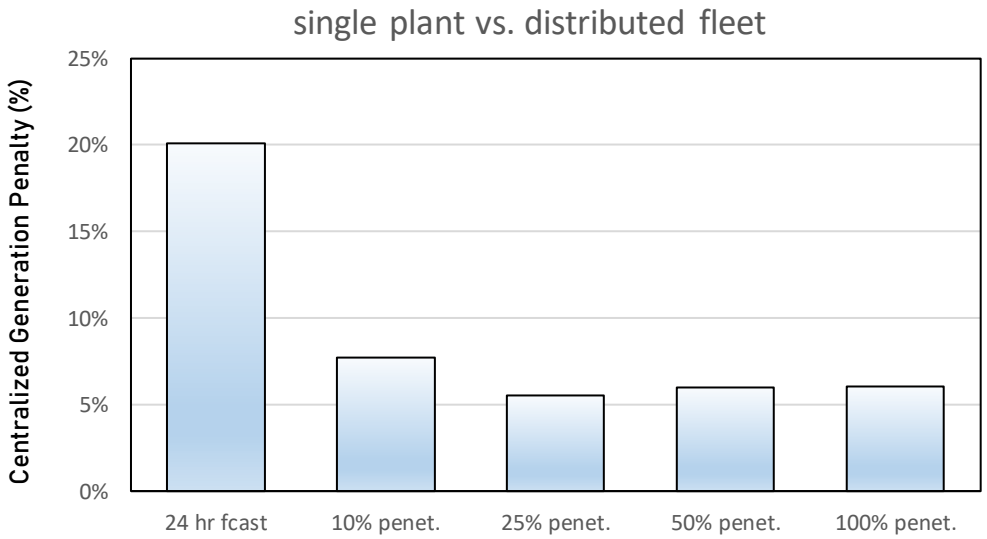

Figure 13: Centralized generation LCOE premium as a function of firmness requirements from 24-hours forecasts to firm power generation.

5. Conclusions

We presented a firm solar forecast strategy articulated around optimized physical and implicit storage (aka overbuilding solar resource) as an operational alternative to standard practice exploiting probabilistic forecast models to integrate solar resources into power grids. We showed that this strategy could entirely remove load-balancing uncertainty emanating from variable renewable resources such as solar at a modest operational cost premium. Most importantly, we showed that the firm forecast strategy was an effective entry step to least-cost ultra-high solar penetration where production firmness will be a prerequisite because achieving firmness in the absence of an implicit storage-enabled strategy could be unrealistically expensive.

Using the New York Independent System Operator as a case study, we showed that this ultra-high solar penetration future where solar would firmly supply the entire load shape could be achieved at electricity production costs commensurate with current New York's wholesale market

electricity prices. We also pointed out that applying an implicit storage strategy to an optimal mix of solar with wind would likely result in production cost targets below current New York's wholesale prices.

Interestingly, we showed that while geographic dispersion had a significant impact on the cost of firm forecasts, its impact diminished considerably when the objective evolved from firm forecasts to firm power generation. This is because weather-driven short-term fluctuations driving forecast models' uncertainty (hence the cost of transforming these forecasts into firm forecasts) can be reduced with geographic dispersion by exploiting the well-documented smoothing effect [42]. These short-term fluctuations play less of a role compared to other factors such as seasonal variability when the objective evolves to meeting a given load shape. We noted that this observation had important implications. In particular, it suggests that large-scale geographic dispersion, implying strong transmission capabilities, would not be an absolute prerequisite to ultra-high penetration economics whereby locally resilient solutions contained in electrical sub-regions could be considered at a modest cost premium.

Appendix

TABLE A1. One hour-ahead firm forecasts results applying smart persistence

	1 Hour forecasts	Current technology cost: PV @ $1,000/kW, storage @ $200/kWh												Future technology cost: PV @ $400/kW, storage @ $50/kWh											
		no flexibility				2.5% flexibility				5% flexibility				no flexibility				2.5% flexibility				5% flexibility			
	Electrical region	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh
homogeneously dispersed fleets	Entire NYISO	201	0.61	4%	5.22	140	0.41	4%	4.96	92	0.38	0%	4.75	75	0.92	1%	2.07	53	0.47	3%	1.97	35	0.31	2%	1.89
	Region A	226	0.73	4%	5.33	188	0.60	4%	5.17	134	0.56	-2%	4.93	94	0.73	4%	2.15	71	0.64	4%	2.05	60	0.64	3%	2.00
	Region B	236	0.84	3%	5.37	194	0.71	3%	5.20	161	0.67	-2%	5.05	91	0.84	3%	2.14	70	0.71	3%	2.05	60	0.78	1%	2.00
	Region C	259	0.75	6%	5.48	194	0.61	5%	5.20	154	0.59	0%	5.02	93	1.09	2%	2.14	70	0.83	2%	2.04	56	0.64	2%	1.98
	Region D	228	0.60	6%	5.34	156	0.47	4%	5.03	119	0.42	2%	4.87	87	1.16	1%	2.12	60	0.53	3%	2.00	44	0.42	2%	1.93
	Region E	224	0.65	5%	5.32	165	0.42	6%	5.07	117	0.38	2%	4.86	81	1.03	1%	2.09	62	0.68	2%	2.01	47	0.38	2%	1.94
	Region F	228	0.36	10%	5.34	169	0.39	5%	5.09	110	0.34	1%	4.83	100	1.20	2%	2.18	71	0.53	5%	2.05	51	0.29	3%	1.96
	Region G	208	0.42	7%	5.26	155	0.39	5%	5.03	113	0.36	0%	4.84	86	0.71	3%	2.11	67	0.39	5%	2.03	56	0.56	2%	1.98
	Region H	300	0.77	3%	5.65	249	0.66	3%	5.43	197	0.61	0%	5.21	106	1.29	2%	2.20	97	1.00	4%	2.16	87	0.71	6%	2.12
	Region I	261	0.87	4%	5.49	225	0.76	3%	5.33	200	0.72	2%	5.22	107	0.87	4%	2.20	91	0.71	5%	2.13	80	0.74	4%	2.09
	Region J	225	0.69	4%	5.33	189	0.58	3%	5.17	156	0.50	3%	5.03	96	0.69	4%	2.16	80	0.53	5%	2.09	61	0.59	2%	2.01
	Region K	229	0.66	5%	5.35	194	0.46	4%	5.19	148	0.44	0%	4.99	97	0.77	4%	2.16	84	0.72	5%	2.11	66	0.77	2%	2.03
Individual locations	Region A	291	0.88	6%	5.62	251	0.77	6%	5.44	224	0.70	2%	5.32	124	0.88	6%	2.28	100	0.88	5%	2.17	89	0.78	5%	2.13
	Region B	280	0.89	5%	5.57	245	0.73	5%	5.41	216	0.63	5%	5.29	113	0.98	4%	2.23	104	0.69	7%	2.19	91	0.88	2%	2.14
	Region C	279	0.76	7%	5.56	252	0.72	7%	5.45	235	0.62	8%	5.37	117	0.97	5%	2.25	98	1.16	3%	2.17	87	0.89	4%	2.12
	Region D	265	0.92	4%	5.50	234	0.88	3%	5.37	201	0.72	3%	5.22	101	1.03	3%	2.18	84	0.88	3%	2.11	74	0.72	3%	2.06
	Region E	305	0.75	9%	5.68	276	0.83	7%	5.55	246	0.84	0%	5.42	114	1.39	2%	2.24	104	1.05	4%	2.19	97	0.75	7%	2.16
	Region F	277	0.82	6%	5.55	259	0.56	5%	5.48	227	0.58	2%	5.34	115	0.90	5%	2.24	102	0.93	5%	2.18	96	0.82	6%	2.16
	Region G	291	0.95	5%	5.62	272	0.68	4%	5.53	226	0.64	0%	5.33	116	1.26	3%	2.24	104	1.09	4%	2.19	104	0.86	7%	2.19
	Region H	326	0.92	8%	5.77	280	0.76	3%	5.57	230	0.70	0%	5.35	116	1.45	2%	2.25	105	1.27	3%	2.20	97	1.19	3%	2.16
	Region I	291	1.02	4%	5.62	254	0.78	6%	5.45	230	0.70	5%	5.35	114	1.22	3%	2.24	100	0.87	5%	2.18	89	0.87	4%	2.13
	Region J	270	0.99	2%	5.52	234	0.74	5%	5.37	203	0.72	2%	5.23	104	1.01	3%	2.19	92	0.84	4%	2.14	74	0.83	2%	2.06
	Region K	289	0.70	9%	5.61	248	0.83	5%	5.43	229	0.67	4%	5.34	108	1.19	3%	2.21	94	0.83	5%	2.15	87	0.82	5%	2.12

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 July 2020 doi:10.20944/preprints202007.0088.v1

Peer-reviewed version available at Energies 2020, 13, 4489; doi:10.3390/en13174489

TABLE A2. One hour-ahead firm forecasts results applying GFS

	1 Hour forecasts	Current technology cost: PV @ $1,000/kW, storage @ $200/kWh												Future technology cost: PV @ $400/kW, storage @ $50/kWh											
		no flexibility				2.5% flexibility				5% flexibility				no flexibility				2.5% flexibility				5% flexibility			
	Electrical region	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh
homogeneously dispersed fleets	Entire NYISO	585	0.88	27%	6.89	472	0.74	23%	6.40	383	0.58	21%	6.02	278	2.01	26%	2.95	210	1.39	23%	2.65	164	0.63	25%	2.45
	Region A	733	1.62	15%	7.54	616	1.58	8%	7.03	512	1.51	3%	6.58	368	1.53	29%	3.34	292	3.93	12%	3.01	220	2.45	14%	2.70
	Region B	737	1.54	16%	7.55	616	1.55	6%	7.03	511	1.50	1%	6.57	383	1.38	29%	3.41	308	2.12	29%	3.08	246	2.22	20%	2.81
	Region C	690	1.14	25%	7.35	577	1.11	19%	6.86	480	1.05	15%	6.44	343	1.79	28%	3.23	270	1.53	26%	2.92	220	1.13	28%	2.70
	Region D	1164	3.19	28%	9.41	1016	3.01	21%	8.77	883	2.87	13%	8.19	472	6.27	23%	3.79	417	5.60	22%	3.55	356	2.48	28%	3.29
	Region E	757	1.37	29%	7.64	620	1.01	29%	7.05	517	0.87	25%	6.60	338	2.73	26%	3.21	277	1.77	29%	2.94	229	1.89	21%	2.74
	Region F	808	1.62	29%	7.86	692	1.62	17%	7.36	584	1.54	11%	6.89	388	4.04	29%	3.43	317	1.43	29%	3.12	265	1.28	29%	2.89
	Region G	794	1.94	24%	7.80	683	1.92	18%	7.32	604	1.75	17%	6.98	321	2.56	29%	3.13	270	1.95	29%	2.92	233	1.60	25%	2.75
	Region H	681	2.16	17%	7.31	612	1.85	17%	7.01	558	1.57	19%	6.78	252	2.20	18%	2.84	228	1.76	21%	2.73	207	1.48	22%	2.64
	Region I	663	2.03	15%	7.23	572	1.70	16%	6.84	510	1.34	19%	6.57	246	2.36	15%	2.81	217	1.78	18%	2.68	194	1.67	15%	2.59
	Region J	720	1.61	19%	7.48	631	1.47	17%	7.09	551	1.43	12%	6.75	242	3.19	10%	2.79	214	2.74	11%	2.67	207	2.41	14%	2.64
	Region K	672	2.03	21%	7.27	590	1.82	19%	6.92	518	1.66	16%	6.60	240	2.35	18%	2.78	201	2.39	13%	2.61	173	1.66	16%	2.49
Individual locations	Region A	1056	2.71	29%	8.94	977	2.52	29%	8.60	903	2.32	29%	8.28	421	4.93	23%	3.57	361	3.41	29%	3.31	342	3.34	29%	3.23
	Region B	935	2.43	16%	8.42	827	2.23	16%	7.95	738	2.04	16%	7.56	453	3.83	27%	3.71	376	3.41	24%	3.38	327	3.34	23%	3.16
	Region C	972	2.41	18%	8.58	838	2.34	7%	8.00	712	2.24	0%	7.45	426	3.69	29%	3.59	350	3.72	20%	3.26	305	3.18	20%	3.07
	Region D	1425	3.82	29%	10.55	1276	3.48	29%	9.90	1145	3.29	24%	9.33	594	8.43	29%	4.32	543	7.86	29%	4.10	486	7.03	27%	3.85
	Region E	829	1.83	27%	7.95	737	1.59	29%	7.56	671	1.40	29%	7.27	389	1.87	28%	3.43	323	1.75	28%	3.14	280	1.54	29%	2.96
	Region F	1027	2.47	28%	8.82	930	2.25	29%	8.40	846	2.26	20%	8.03	378	4.03	29%	3.38	326	3.26	29%	3.16	300	2.84	27%	3.05
	Region G	983	3.14	10%	8.63	887	2.96	15%	8.21	827	2.75	19%	7.95	381	3.85	26%	3.40	330	3.12	27%	3.18	290	2.76	25%	3.00
	Region H	805	2.49	14%	7.85	705	2.20	20%	7.41	658	2.02	20%	7.21	285	2.78	19%	2.98	250	2.20	21%	2.83	232	1.98	22%	2.75
	Region I	705	2.15	15%	7.42	635	1.87	16%	7.11	580	1.59	18%	6.87	268	2.90	15%	2.91	242	2.47	17%	2.79	223	2.08	19%	2.71
	Region J	819	3.18	13%	7.91	739	2.12	10%	7.56	660	2.10	1%	7.22	264	3.18	13%	2.89	250	2.94	15%	2.83	238	2.68	17%	2.78
	Region K	1129	3.37	22%	9.26	1024	3.14	19%	8.80	925	3.03	11%	8.37	476	3.20	29%	3.81	425	2.89	29%	3.59	381	2.59	29%	3.40

TABLE A3. One hour-ahead firm forecasts results applying ECMF

	1 Hour forecasts	Current technology cost: PV @ $1,000/kW, storage @ $200/kWh												Future technology cost: PV @ $400/kW, storage @ $50/kWh											
		no flexibility				2.5% flexibility				5% flexibility				no flexibility				2.5% flexibility				5% flexibility			
	Electrical region	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh
homogeneously dispersed fleets	Entire NYISO	522	1.22	7%	6.62	382	1.12	1%	6.01	274	1.00	0%	5.54	275	1.00	21%	2.93	193	0.95	12%	2.58	132	0.93	3%	2.31
	Region A	640	1.61	4%	7.13	492	1.44	0%	6.49	368	1.22	0%	5.95	339	1.38	24%	3.22	257	1.25	15%	2.86	189	1.13	6%	2.56
	Region B	629	1.60	5%	7.09	485	1.44	0%	6.46	363	1.22	0%	5.93	337	1.45	19%	3.21	252	1.29	13%	2.84	186	1.15	5%	2.55
	Region C	612	1.44	6%	7.01	472	1.34	0%	6.40	356	1.17	0%	5.90	330	1.16	27%	3.18	250	1.12	15%	2.83	185	1.06	6%	2.55
	Region D	749	1.59	25%	7.61	604	1.65	12%	6.98	479	1.69	0%	6.43	349	2.77	27%	3.26	278	2.24	25%	2.95	212	1.34	13%	2.66
	Region E	609	1.45	6%	7.00	464	1.36	0%	6.37	350	1.21	0%	5.87	325	1.24	21%	3.16	239	1.15	14%	2.78	173	1.11	5%	2.49
	Region F	587	1.11	16%	6.91	454	0.96	12%	6.33	344	0.86	7%	5.84	321	1.04	23%	3.14	237	0.92	14%	2.77	173	0.76	10%	2.49
	Region G	624	1.61	12%	7.06	502	1.44	7%	6.53	393	1.37	0%	6.06	304	1.46	21%	3.06	237	1.31	15%	2.77	185	1.27	4%	2.54
	Region H	697	2.41	2%	7.38	593	2.21	0%	6.93	508	2.01	0%	6.56	302	2.40	12%	3.06	249	2.15	9%	2.82	210	1.89	7%	2.65
	Region I	693	2.20	10%	7.37	594	2.17	0%	6.93	506	1.94	0%	6.55	298	2.30	13%	3.04	245	1.92	15%	2.81	214	1.69	16%	2.67
	Region J	585	1.79	4%	6.89	465	1.63	0%	6.37	375	1.40	0%	5.98	253	1.92	15%	2.84	211	1.56	17%	2.66	172	1.36	3%	2.49
	Region K	579	1.51	19%	6.87	479	1.62	2%	6.44	382	1.48	0%	6.01	233	2.36	10%	2.75	186	1.83	12%	2.55	156	1.24	10%	2.42
Individual locations	Region A	768	1.77	8%	7.69	633	1.57	6%	7.10	516	1.43	0%	6.59	428	4.62	27%	3.60	352	1.42	20%	3.27	283	1.30	12%	2.97
	Region B	755	1.97	7%	7.64	626	1.80	4%	7.07	512	1.69	0%	6.58	404	1.54	23%	3.50	325	1.45	17%	3.15	258	1.36	11%	2.86
	Region C	786	1.87	10%	7.77	653	1.65	8%	7.19	532	1.64	0%	6.66	418	1.97	25%	3.56	339	1.93	14%	3.21	273	1.77	10%	2.93
	Region D	791	1.85	20%	7.79	676	1.85	7%	7.29	570	1.84	0%	6.83	365	2.21	29%	3.33	302	1.63	29%	3.06	256	1.87	29%	2.85
	Region E	671	1.46	7%	7.27	554	1.42	1%	6.76	450	1.31	0%	6.31	400	1.32	18%	3.48	317	1.39	12%	3.12	254	1.26	12%	2.84
	Region F	732	1.90	10%	7.53	603	1.82	1%	6.97	482	1.63	0%	6.45	372	1.52	27%	3.36	304	1.38	21%	3.06	245	1.67	4%	2.81
	Region G	684	1.71	7%	7.33	565	1.51	4%	6.81	454	1.40	0%	6.33	330	3.33	13%	3.18	274	2.64	14%	2.93	228	1.92	16%	2.73
	Region H	749	2.20	8%	7.61	640	2.13	-2%	7.13	540	1.91	0%	6.70	317	2.71	16%	3.12	276	3.17	10%	2.94	237	2.74	10%	2.77
	Region I	700	2.38	9%	7.39	627	2.31	0%	7.08	542	2.09	0%	6.71	283	2.54	11%	2.97	237	2.12	12%	2.77	209	2.19	10%	2.65
	Region J	600	1.81	1%	6.96	483	1.61	0%	6.45	394	1.39	0%	6.06	275	2.20	15%	2.94	231	1.86	16%	2.74	194	1.35	3%	2.58
	Region K	686	2.17	9%	7.33	604	1.94	9%	6.98	532	1.91	0%	6.66	303	2.53	15%	3.06	255	1.87	14%	2.85	219	1.70	10%	2.69

TABLE A4. Three hours-ahead firm forecasts results applying smart persistence

	3 Hour forecasts	Current technology cost: PV @ $1,000/kW, storage @ $200/kWh												Future technology cost: PV @ $400/kW, storage @ $50/kWh											
		no flexibility				2.5% flexibility				5% flexibility				no flexibility				2.5% flexibility				5% flexibility			
	Electrical region	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh
homogeneously dispersed fleets	Entire NYISO	486	1.90	3%	6.46	435	1.73	3%	6.24	386	1.56	3%	6.03	182	2.09	2%	2.53	156	1.73	3%	2.42	134	1.56	3%	1.90
	Region A	584	2.30	4%	6.89	566	2.13	7%	6.81	538	2.11	0%	6.69	209	2.39	3%	2.65	184	2.61	1%	2.54	169	2.64	0%	1.71
	Region B	618	2.66	2%	7.04	589	2.51	3%	6.91	564	2.38	4%	6.80	208	2.66	2%	2.64	195	2.51	3%	2.59	183	2.38	4%	1.97
	Region C	676	2.78	4%	7.29	632	2.27	10%	7.10	597	2.09	12%	6.95	230	2.89	3%	2.74	213	2.70	4%	2.67	198	2.67	4%	1.99
	Region D	578	2.55	1%	6.86	496	2.12	2%	6.51	429	1.84	2%	6.22	184	2.69	0%	2.54	166	2.12	2%	2.46	142	1.84	2%	1.91
	Region E	581	2.64	0%	6.88	490	2.08	2%	6.48	429	1.83	2%	6.21	184	2.87	-1%	2.54	163	2.77	-2%	2.45	142	1.83	2%	1.92
	Region F	540	1.86	7%	6.70	477	1.65	7%	6.42	420	1.51	6%	6.18	195	2.38	2%	2.59	173	2.17	2%	2.49	153	1.78	3%	1.93
	Region G	496	1.52	8%	6.51	434	1.33	8%	6.24	381	1.16	7%	6.01	211	2.81	1%	2.66	182	2.42	1%	2.53	152	2.17	0%	1.71
	Region H	598	1.56	15%	6.95	558	1.69	12%	6.78	508	1.78	8%	6.56	247	3.40	2%	2.81	214	2.96	2%	2.67	183	2.72	1%	1.71
	Region I	595	2.25	5%	6.94	560	2.10	6%	6.79	523	1.99	6%	6.62	227	2.25	5%	2.73	196	2.61	2%	2.59	173	2.35	2%	1.71
	Region J	511	1.66	7%	6.57	469	1.56	7%	6.39	444	1.52	7%	6.28	215	1.76	6%	2.68	190	2.03	4%	2.57	171	1.91	4%	1.71
	Region K	555	2.08	5%	6.77	486	1.63	8%	6.46	417	1.50	6%	6.16	205	2.39	3%	2.63	181	2.03	4%	2.53	153	1.58	5%	1.71
Individual locations	Region A	708	2.93	4%	7.43	666	2.67	6%	7.25	640	2.24	12%	7.14	240	3.05	3%	2.78	228	2.92	4%	2.73	218	2.60	7%	1.71
	Region B	649	2.54	5%	7.17	602	2.31	6%	6.97	563	2.19	6%	6.80	238	3.64	0%	2.78	219	2.47	5%	2.69	197	2.30	5%	1.71
	Region C	669	2.75	4%	7.26	642	2.55	6%	7.14	625	2.47	7%	7.07	233	2.75	4%	2.75	223	2.55	6%	2.71	212	2.47	7%	1.71
	Region D	623	2.45	5%	7.06	575	2.28	5%	6.85	521	2.12	4%	6.62	224	2.60	4%	2.72	200	2.38	4%	2.61	179	2.12	4%	1.71
	Region E	666	2.96	1%	7.25	614	2.67	2%	7.02	563	2.33	4%	6.80	214	3.18	0%	2.67	201	2.67	2%	2.61	187	2.43	3%	1.71
	Region F	532	1.84	6%	6.66	482	1.74	5%	6.45	430	1.61	4%	6.22	204	2.36	2%	2.63	182	2.10	2%	2.53	158	1.77	2%	1.94
	Region G	594	1.86	10%	6.94	539	1.69	10%	6.69	506	1.56	11%	6.55	251	2.08	8%	2.83	225	1.69	10%	2.72	205	3.28	-1%	2.00
	Region H	779	1.92	7%	7.74	693	1.85	3%	7.36	611	1.75	2%	7.01	293	5.14	-1%	3.02	269	4.74	-1%	2.91	238	4.05	0%	2.05
	Region I	624	2.24	7%	7.06	575	2.18	6%	6.85	548	1.99	8%	6.73	246	2.24	7%	2.81	212	2.18	6%	2.66	201	2.11	7%	2.00
	Region J	576	2.06	6%	6.85	538	1.96	5%	6.69	499	1.85	5%	6.52	231	2.06	6%	2.75	210	2.04	6%	2.65	189	1.82	7%	1.71
	Region K	768	1.68	28%	7.69	748	2.64	13%	7.60	668	1.91	-2%	7.26	268	3.13	6%	2.90	254	3.08	7%	2.84	242	2.85	9%	2.06

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 July 2020 doi:10.20944/preprints202007.0088.v1

Peer-reviewed version available at Energies 2020, 13, 4489; doi:10.3390/en13174489

TABLE A5. Three hours-ahead firm forecasts results applying GFS

	3 Hour forecasts	Current technology cost: PV @ $1,000/kW, storage @ $200/kWh												Future technology cost: PV @ $400/kW, storage @ $50/kWh											
		no flexibility				2.5% flexibility				5% flexibility				no flexibility				2.5% flexibility				5% flexibility			
	Electrical region	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh
homogeneously dispersed fleets	Entire NYISO	564	0.73	29%	6.81	462	0.56	27%	6.36	379	0.45	24%	6.00	271	1.74	28%	2.92	204	1.17	25%	2.63	160	0.50	26%	1.94
	Region A	787	1.83	20%	7.77	665	1.70	15%	7.24	557	1.64	7%	6.77	379	1.67	28%	3.39	302	1.53	24%	3.06	230	2.55	15%	1.71
	Region B	819	1.92	19%	7.91	700	1.80	15%	7.40	593	1.83	4%	6.93	391	2.32	29%	3.44	311	2.10	29%	3.09	248	2.18	21%	2.07
	Region C	751	1.60	22%	7.62	644	1.53	18%	7.15	545	1.64	3%	6.72	344	1.89	29%	3.24	271	1.43	29%	2.92	224	1.26	28%	2.03
	Region D	1150	3.09	29%	9.35	1005	2.92	22%	8.72	870	2.80	13%	8.13	467	6.12	24%	3.77	411	5.52	22%	3.53	354	2.43	27%	2.22
	Region E	751	1.36	29%	7.62	615	1.00	29%	7.03	512	0.82	26%	6.58	329	2.68	26%	3.17	272	1.83	28%	2.92	226	1.69	23%	2.03
	Region F	802	1.59	29%	7.84	690	1.53	21%	7.35	586	1.51	12%	6.90	389	1.61	29%	3.43	315	1.38	29%	3.11	262	1.21	29%	2.09
	Region G	818	1.97	26%	7.91	705	2.00	18%	7.42	627	1.74	20%	7.08	336	2.71	29%	3.20	286	1.99	29%	2.98	244	1.57	26%	1.71
	Region H	828	2.37	15%	7.95	722	2.09	15%	7.49	636	1.93	11%	7.12	291	3.05	19%	3.01	261	2.50	21%	2.87	234	2.00	23%	1.71
	Region I	735	2.46	15%	7.55	650	2.10	12%	7.18	576	1.80	11%	6.86	265	2.65	17%	2.89	238	2.11	20%	2.77	216	1.78	21%	1.71
	Region J	758	1.88	14%	7.65	667	1.81	9%	7.25	582	1.78	2%	6.88	258	3.24	13%	2.86	231	2.92	13%	2.74	220	2.53	16%	1.71
	Region K	693	2.27	19%	7.36	613	2.05	17%	7.02	559	1.77	18%	6.78	239	2.27	19%	2.78	200	2.22	15%	2.61	184	1.86	17%	1.71
Individual locations	Region A	1063	2.71	29%	8.97	982	2.52	29%	8.62	910	2.32	29%	8.31	418	4.32	28%	3.56	371	3.68	29%	3.35	347	3.47	29%	1.71
	Region B	977	2.66	15%	8.60	871	2.42	17%	8.14	785	2.17	20%	7.76	464	3.90	29%	3.76	383	3.41	26%	3.40	328	3.33	26%	1.71
	Region C	996	2.61	12%	8.68	863	2.40	8%	8.10	738	2.30	0%	7.56	447	4.59	26%	3.69	382	4.42	20%	3.40	338	3.90	20%	1.71
	Region D	1440	3.86	29%	10.61	1296	3.53	29%	9.99	1164	3.19	29%	9.41	592	8.19	29%	4.31	531	7.38	29%	4.05	478	6.70	29%	1.71
	Region E	826	1.83	28%	7.94	738	1.62	29%	7.56	673	1.40	29%	7.28	376	2.01	29%	3.38	316	1.86	29%	3.11	285	1.66	29%	1.71
	Region F	1021	2.52	29%	8.79	932	2.38	29%	8.40	872	2.24	29%	8.14	388	3.43	29%	3.43	345	3.01	29%	3.24	317	3.00	29%	2.16
	Region G	988	3.08	14%	8.65	893	2.90	15%	8.23	832	2.72	17%	7.97	398	3.93	29%	3.47	350	3.35	29%	3.26	308	2.80	29%	2.15
	Region H	831	2.50	15%	7.97	727	2.22	20%	7.51	684	1.95	25%	7.33	299	2.89	22%	3.04	261	2.14	25%	2.87	242	1.95	25%	2.06
	Region I	772	2.06	15%	7.71	681	1.78	16%	7.31	608	1.60	14%	6.99	286	3.13	17%	2.98	263	2.65	20%	2.88	251	2.51	21%	2.07
	Region J	842	2.25	13%	8.01	758	2.08	12%	7.65	675	2.06	0%	7.28	276	3.44	14%	2.94	260	3.00	17%	2.87	247	2.70	19%	1.71
	Region K	1153	3.30	28%	9.36	1049	3.14	22%	8.91	946	3.04	14%	8.47	488	3.28	29%	3.86	434	2.97	29%	3.63	389	2.67	29%	2.27

TABLE A6. Three hours-ahead firm forecasts results applying ECMF

	3 Hour forecasts	Current technology cost: PV @ $1,000/kW, storage @ $200/kWh												Future technology cost: PV @ $400/kW, storage @ $50/kWh											
		no flexibility				2.5% flexibility				5% flexibility				no flexibility				2.5% flexibility				5% flexibility			
	Electrical region	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh
homogeneously dispersed fleets	Entire NYISO	501	0.96	15%	6.53	367	0.83	10%	5.95	257	0.89	0%	5.47	265	0.85	21%	2.89	182	0.75	13%	2.53	122	0.70	6%	1.89
	Region A	641	1.62	3%	7.14	493	1.44	0%	6.49	370	1.22	0%	5.96	340	1.37	25%	3.22	259	1.24	16%	2.87	191	1.12	7%	1.71
	Region B	631	1.61	4%	7.09	487	1.44	0%	6.47	366	1.22	0%	5.94	339	1.43	21%	3.21	255	1.30	12%	2.85	188	1.14	6%	1.98
	Region C	593	1.43	3%	6.93	447	1.25	0%	6.29	326	1.01	0%	5.77	325	1.16	24%	3.16	243	1.04	14%	2.80	178	0.92	6%	1.97
	Region D	759	1.78	20%	7.65	615	1.76	10%	7.03	490	1.74	0%	6.48	334	2.55	26%	3.19	265	2.25	22%	2.89	212	1.97	16%	2.01
	Region E	563	0.86	21%	6.80	423	0.90	10%	6.19	306	0.90	1%	5.68	307	0.83	22%	3.07	222	0.75	15%	2.71	157	0.70	8%	1.94
	Region F	577	0.94	21%	6.86	450	0.89	14%	6.31	342	0.88	6%	5.84	310	0.91	22%	3.09	230	0.73	19%	2.74	168	0.69	12%	1.95
	Region G	620	1.65	11%	7.05	498	1.46	6%	6.52	389	1.37	0%	6.04	303	1.57	16%	3.06	234	1.33	14%	2.76	183	1.24	6%	1.71
	Region H	705	2.38	4%	7.42	602	2.23	-2%	6.97	512	2.01	0%	6.58	304	2.76	14%	3.06	252	2.21	14%	2.84	217	1.78	14%	1.71
	Region I	693	2.13	14%	7.37	588	2.16	0%	6.91	497	1.94	0%	6.51	286	2.20	14%	2.99	239	2.10	13%	2.78	210	1.87	14%	1.71
	Region J	575	1.76	4%	6.85	464	1.60	0%	6.37	373	1.38	0%	5.97	252	2.12	14%	2.83	211	1.47	10%	2.66	172	1.32	6%	1.71
	Region K	584	1.49	20%	6.89	480	1.62	2%	6.44	383	1.48	0%	6.02	231	2.49	9%	2.74	181	1.94	10%	2.53	155	1.56	12%	1.71
Individual locations	Region A	762	1.83	3%	7.66	621	1.61	1%	7.05	503	1.40	0%	6.54	423	4.65	26%	3.58	353	1.40	23%	3.27	285	1.29	13%	1.71
	Region B	733	1.86	8%	7.54	608	1.71	4%	7.00	495	1.55	1%	6.51	397	1.51	21%	3.47	319	1.42	15%	3.13	254	1.31	10%	1.71
	Region C	782	1.71	19%	7.75	666	1.64	11%	7.25	549	1.66	0%	6.74	410	1.52	26%	3.53	333	1.51	21%	3.19	272	1.69	11%	1.71
	Region D	785	1.81	22%	7.76	672	1.85	7%	7.27	562	1.77	0%	6.79	367	2.52	29%	3.34	295	1.97	29%	3.02	250	1.76	29%	1.71
	Region E	672	1.57	3%	7.27	545	1.43	0%	6.72	440	1.29	0%	6.27	398	1.33	22%	3.47	314	1.22	14%	3.11	246	1.12	8%	1.71
	Region F	672	1.63	6%	7.27	544	1.52	-2%	6.72	430	1.31	0%	6.22	358	1.77	29%	3.30	291	1.39	26%	3.01	229	1.24	6%	2.04
	Region G	664	1.67	6%	7.24	546	1.61	0%	6.73	449	1.42	0%	6.30	329	3.37	13%	3.17	271	2.63	14%	2.92	227	2.02	15%	2.04
	Region H	741	2.16	10%	7.58	636	2.10	0%	7.11	536	1.91	0%	6.68	310	2.80	15%	3.09	272	2.73	14%	2.93	245	2.43	15%	2.06
	Region I	701	2.35	10%	7.40	624	2.31	0%	7.06	536	2.09	0%	6.68	274	2.57	10%	2.93	236	2.41	10%	2.77	209	2.14	11%	2.01
	Region J	590	1.78	1%	6.92	477	1.60	0%	6.42	387	1.37	0%	6.03	271	2.22	15%	2.92	230	1.91	16%	2.74	189	1.33	3%	1.71
	Region K	695	2.13	11%	7.37	613	1.90	12%	7.02	533	1.91	0%	6.67	307	2.82	17%	3.08	256	1.90	12%	2.85	220	1.69	13%	2.03

TABLE A7. Twenty four hours-ahead firm forecasts results applying smart persistence

	24 Hour forecasts	Current technology cost: PV @ $1,000/kW, storage @ $200/kWh												Future technology cost: PV @ $400/kW, storage @ $50/kWh											
		no flexibility				2.5% flexibility				5% flexibility				no flexibility				2.5% flexibility				5% flexibility			
	Electrical region	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh
homogeneously dispersed fleets	Entire NYISO	1190	2.76	29%	9.53	1027	2.71	20%	8.82	884	2.71	10%	8.20	448	7.52	1%	3.69	386	6.51	1%	3.42	336	5.51	2%	2.01
	Region A	1483	4.35	13%	10.80	1314	4.23	5%	10.06	1155	4.09	0%	4.35	516	8.72	1%	3.98	473	7.90	2%	3.80	432	7.30	2%	1.72
	Region B	1494	4.48	9%	10.85	1319	4.37	0%	10.09	1159	4.11	0%	9.39	494	8.42	1%	3.89	462	7.77	2%	3.75	435	7.06	4%	2.09
	Region C	1448	4.13	16%	10.65	1267	4.06	4%	9.86	1106	3.88	0%	9.16	482	8.26	1%	3.84	445	7.46	2%	3.67	409	6.72	3%	2.07
	Region D	1390	3.62	24%	10.40	1221	3.51	16%	9.66	1066	3.41	8%	8.99	475	6.15	10%	3.81	396	5.50	7%	3.46	330	4.93	4%	2.00
	Region E	1350	3.67	27%	10.22	1180	3.65	14%	9.48	1028	3.54	6%	8.82	458	7.50	2%	3.73	391	6.40	2%	3.44	338	5.50	2%	2.01
	Region F	1269	2.93	29%	9.87	1104	2.68	26%	9.15	950	2.86	7%	8.48	449	8.02	-1%	3.69	395	6.89	0%	3.46	345	5.86	1%	2.02
	Region G	1287	3.19	10%	9.95	1109	2.98	6%	9.17	948	2.73	4%	4.35	445	7.40	1%	3.68	396	6.08	4%	3.46	346	4.84	7%	1.72
	Region H	1400	4.82	24%	10.44	1229	4.35	21%	9.70	1068	4.01	16%	4.35	461	7.20	3%	3.74	400	6.20	4%	3.48	353	5.00	7%	1.72
	Region I	1381	4.66	25%	10.36	1221	4.15	22%	9.66	1064	3.86	18%	4.35	486	8.50	0%	3.85	414	6.90	2%	3.54	355	5.05	7%	1.72
	Region J	1412	3.59	1%	10.49	1232	3.33	0%	9.71	1064	3.02	0%	4.35	501	9.16	-1%	3.92	451	7.46	3%	3.70	401	5.65	9%	1.72
	Region K	1527	3.99	14%	10.99	1351	3.85	6%	10.23	1190	3.67	0%	4.35	532	9.31	1%	4.05	455	8.15	1%	3.72	392	6.91	2%	1.72
Individual locations	Region A	1555	4.58	10%	11.11	1393	4.42	4%	10.41	1238	4.26	0%	4.35	570	9.78	1%	4.22	525	8.87	2%	4.02	482	8.03	3%	1.72
	Region B	1602	4.70	7%	11.32	1430	4.59	0%	10.57	1268	4.29	0%	4.35	515	8.77	1%	3.98	493	8.01	3%	3.88	462	7.36	4%	1.72
	Region C	1601	4.88	3%	11.31	1429	4.67	0%	10.56	1271	4.36	0%	4.35	529	9.24	0%	4.04	502	8.35	2%	3.93	478	7.65	4%	1.72
	Region D	1542	4.38	1%	11.06	1377	4.10	3%	10.34	1215	3.94	0%	4.35	545	7.57	10%	4.11	476	7.05	7%	3.81	414	6.53	4%	1.72
	Region E	1338	3.50	15%	10.17	1177	3.54	2%	9.47	1025	3.34	0%	4.35	471	8.39	-1%	3.79	438	7.61	0%	3.64	405	6.87	1%	1.72
	Region F	1450	3.54	23%	10.66	1284	3.39	15%	9.94	1125	3.26	6%	9.24	461	8.09	-1%	3.75	418	7.17	0%	3.56	375	6.12	2%	2.04
	Region G	1329	3.63	22%	10.13	1183	3.38	20%	9.49	1047	3.16	15%	8.90	412	6.85	0%	3.53	365	6.00	1%	3.33	329	5.14	3%	2.00
	Region H	1313	3.32	2%	10.06	1154	3.03	3%	9.37	1007	2.73	4%	8.73	464	7.80	1%	3.76	413	6.69	3%	3.54	362	5.56	5%	2.03
	Region I	1337	3.32	4%	10.16	1172	3.13	0%	9.45	1017	2.86	0%	8.77	489	8.26	1%	3.87	419	7.00	2%	3.56	355	5.37	5%	2.03
	Region J	1417	3.67	3%	10.51	1244	3.44	0%	9.76	1082	3.14	0%	4.35	513	8.78	1%	3.97	430	7.76	0%	3.61	364	6.44	1%	1.72
	Region K	1433	3.65	2%	10.59	1270	3.43	0%	9.87	1114	3.15	0%	9.20	515	9.33	0%	3.98	449	7.84	2%	3.69	392	6.69	3%	2.06

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 July 2020 doi:10.20944/preprints202007.0088.v1

Peer-reviewed version available at Energies 2020, 13, 4489; doi:10.3390/en13174489

TABLE A8. Twenty four hours-ahead firm forecasts results applying GFS

	24 Hour forecasts	Current technology cost: PV @ $1,000/kW, storage @ $200/kWh												Future technology cost: PV @ $400/kW, storage @ $50/kWh											
		no flexibility				2.5% flexibility				5% flexibility				no flexibility				2.5% flexibility				5% flexibility			
	Electrical region	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh
homogeneously dispersed fleets	Entire NYISO	584	1.13	20%	6.89	467	0.99	12%	6.38	356	0.83	9%	5.90	284	1.51	29%	2.97	214	0.94	21%	2.67	164	0.82	18%	1.86
	Region A	811	2.02	13%	7.88	671	1.84	9%	7.27	552	1.66	5%	4.35	411	1.69	27%	3.53	328	1.43	26%	3.17	252	3.49	7%	1.72
	Region B	758	1.66	17%	7.65	625	1.63	8%	7.07	510	1.40	8%	6.57	395	1.41	29%	3.46	315	1.34	22%	3.11	248	1.29	15%	1.93
	Region C	770	1.90	18%	7.70	644	1.70	17%	7.15	547	1.49	17%	6.73	368	2.19	28%	3.34	284	1.70	20%	2.97	221	1.49	17%	1.91
	Region D	825	1.56	28%	7.94	723	1.64	18%	7.50	615	1.61	10%	7.02	384	2.23	29%	3.41	319	2.09	29%	3.13	263	2.07	25%	1.95
	Region E	707	1.41	24%	7.42	604	1.10	27%	6.98	509	1.32	10%	6.56	341	1.40	29%	3.23	270	1.29	24%	2.91	209	1.40	19%	1.90
	Region F	731	1.22	29%	7.53	622	1.10	26%	7.06	526	1.12	15%	6.64	363	2.22	29%	3.32	291	1.74	29%	3.01	237	1.36	26%	1.92
	Region G	964	2.97	21%	8.54	852	2.77	17%	8.06	758	2.67	10%	4.35	379	3.15	29%	3.39	320	3.00	23%	3.13	276	2.32	24%	1.72
	Region H	961	3.56	16%	8.53	883	3.26	14%	8.19	815	2.92	15%	4.35	332	3.56	16%	3.18	303	3.24	17%	3.06	280	2.84	19%	1.72
	Region I	900	3.40	13%	8.26	823	3.05	13%	7.93	752	2.71	13%	4.35	307	3.87	10%	3.08	281	3.21	13%	2.96	259	2.66	16%	1.72
	Region J	889	2.98	21%	8.22	785	2.17	15%	7.77	692	2.01	12%	4.35	314	3.03	20%	3.10	279	2.63	21%	2.95	248	2.36	20%	1.72
	Region K	812	2.91	16%	7.88	719	2.48	17%	7.48	644	2.06	19%	4.35	279	2.91	16%	2.95	246	2.48	17%	2.81	220	2.14	18%	1.72
Individual locations	Region A	1097	3.20	21%	9.12	1002	2.92	24%	8.71	919	2.62	26%	4.35	448	5.38	19%	3.69	371	3.58	25%	3.35	331	2.82	28%	1.72
	Region B	904	2.32	7%	8.28	786	2.11	9%	7.77	693	1.87	14%	4.35	485	1.92	29%	3.85	400	2.26	21%	3.48	322	3.37	11%	1.72
	Region C	981	2.54	10%	8.62	856	2.37	7%	8.07	745	2.30	-2%	4.35	452	3.21	29%	3.70	374	3.10	28%	3.36	299	3.08	17%	1.72
	Region D	1271	3.36	23%	9.88	1152	3.29	14%	9.36	1041	3.20	7%	4.35	482	4.16	29%	3.84	419	3.87	29%	3.56	368	3.59	29%	1.72
	Region E	887	1.75	29%	8.21	790	1.56	29%	7.79	707	1.37	29%	4.35	398	2.51	29%	3.47	346	2.07	29%	3.25	306	1.72	29%	1.72
	Region F	1091	2.76	27%	9.09	975	2.56	21%	8.59	876	2.40	14%	8.16	437	3.75	29%	3.64	391	3.53	29%	3.44	352	3.17	29%	2.02
	Region G	996	2.93	13%	8.68	880	2.69	13%	8.18	802	2.46	17%	7.84	395	3.73	25%	3.46	342	3.06	25%	3.23	303	2.40	27%	1.98
	Region H	995	3.68	15%	8.68	909	3.38	13%	8.30	847	3.06	13%	8.03	343	3.72	17%	3.23	310	3.28	18%	3.09	290	2.94	20%	1.97
	Region I	937	3.34	17%	8.43	848	3.12	15%	8.04	793	2.80	17%	7.80	318	3.71	12%	3.12	290	3.12	15%	3.00	271	2.80	17%	1.95
	Region J	959	2.22	28%	8.52	858	1.97	28%	8.08	773	1.77	27%	4.35	356	3.27	25%	3.29	313	2.84	25%	3.10	279	2.53	24%	1.72
	Region K	1167	3.39	22%	9.43	1061	3.13	20%	8.97	960	3.00	13%	8.53	512	3.21	29%	3.97	456	2.91	29%	3.73	408	2.60	29%	2.07

TABLE A9. Twenty four hours-ahead firm forecasts results applying ECMF

	24 Hour forecasts	Current technology cost: PV @ $1,000/kW, storage @ $200/kWh												Future technology cost: PV @ $400/kW, storage @ $50/kWh											
		no flexibility				2.5% flexibility				5% flexibility				no flexibility				2.5% flexibility				5% flexibility			
	Electrical region	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh	Add'l $ per PVkW	Storage PV hrs	Over-sizing	LCOE ¢/kWh
homogeneously dispersed fleets	Entire NYISO	576	1.28	12%	6.85	437	1.22	4%	6.25	317	1.12	0%	5.73	295	1.00	26%	3.02	215	0.98	16%	2.67	151	0.94	7%	1.85
	Region A	754	1.96	12%	7.63	612	1.82	7%	7.01	498	1.67	4%	4.35	377	1.95	24%	3.38	285	1.73	17%	2.98	211	1.44	14%	1.72
	Region B	725	1.86	14%	7.50	589	1.79	7%	6.91	488	1.59	6%	6.47	353	1.56	26%	3.27	266	1.46	20%	2.90	203	1.39	14%	1.89
	Region C	661	1.50	7%	7.22	520	1.37	1%	6.61	392	1.20	0%	6.05	355	1.86	29%	3.29	271	1.60	18%	2.92	210	1.00	10%	1.90
	Region D	720	1.76	9%	7.48	577	1.66	2%	6.86	451	1.50	0%	6.31	366	3.54	21%	3.33	292	1.38	18%	3.01	225	1.30	10%	1.91
	Region E	668	1.64	8%	7.26	526	1.53	2%	6.64	402	1.38	0%	6.10	345	1.28	28%	3.24	263	1.26	17%	2.89	196	1.20	8%	1.89
	Region F	633	1.35	7%	7.10	484	1.17	3%	6.46	361	1.00	0%	5.92	348	1.16	29%	3.26	269	1.03	20%	2.91	203	0.92	10%	1.89
	Region G	700	1.89	13%	7.39	589	1.85	4%	6.91	486	1.77	0%	4.35	312	1.77	27%	3.10	257	1.45	26%	2.86	212	1.46	17%	1.72
	Region H	715	2.19	15%	7.46	640	2.14	3%	7.14	545	1.98	0%	4.35	293	2.21	17%	3.02	253	1.88	19%	2.84	223	1.71	19%	1.72
	Region I	634	1.77	6%	7.11	540	1.57	5%	6.70	458	1.59	0%	4.35	289	1.66	20%	3.00	249	1.42	22%	2.82	222	1.20	24%	1.72
	Region J	663	2.04	6%	7.23	570	1.96	0%	6.83	489	1.80	0%	4.35	265	2.04	17%	2.89	224	1.66	19%	2.72	196	1.47	19%	1.72
	Region K	729	2.61	13%	7.52	663	2.48	7%	7.23	590	2.44	0%	4.35	257	2.59	14%	2.86	222	2.35	15%	2.70	198	2.17	15%	1.72
Individual locations	Region A	916	2.48	10%	8.33	786	2.18	11%	7.77	672	2.04	7%	4.35	457	4.12	26%	3.73	375	3.03	27%	3.37	310	2.09	18%	1.72
	Region B	819	2.17	3%	7.91	690	2.00	0%	7.35	575	1.85	0%	4.35	408	3.40	29%	3.51	346	2.20	17%	3.25	289	1.98	14%	1.72
	Region C	808	1.97	3%	7.87	671	1.81	0%	7.27	550	1.60	0%	4.35	444	1.77	28%	3.67	359	1.89	18%	3.30	293	1.68	17%	1.72
	Region D	795	1.92	14%	7.81	672	1.84	4%	7.27	565	1.78	0%	4.35	380	2.52	29%	3.39	304	1.90	28%	3.06	248	1.50	29%	1.72
	Region E	758	1.74	6%	7.65	632	1.61	2%	7.10	519	1.46	0%	4.35	431	1.43	24%	3.62	351	1.47	18%	3.27	281	1.17	19%	1.72
	Region F	737	1.72	9%	7.56	617	1.66	3%	7.03	503	1.48	0%	6.54	408	2.53	29%	3.51	338	1.48	12%	3.21	274	1.30	10%	1.96
	Region G	773	2.09	9%	7.71	662	1.98	5%	7.23	569	1.96	0%	6.82	375	3.05	24%	3.37	315	2.46	24%	3.11	269	1.61	14%	1.95
	Region H	766	2.38	5%	7.68	664	2.25	0%	7.24	568	2.00	0%	6.82	314	2.82	16%	3.10	272	2.13	20%	2.92	245	1.64	24%	1.93
	Region I	655	1.90	15%	7.20	596	1.76	10%	6.94	517	1.73	0%	6.60	275	1.97	15%	2.94	243	1.66	18%	2.80	219	1.44	20%	1.91
	Region J	709	2.00	20%	7.43	610	1.94	0%	7.00	522	1.69	3%	4.35	286	2.06	19%	2.99	244	1.86	19%	2.80	213	1.45	21%	1.72
	Region K	876	2.76	23%	8.16	818	2.93	0%	7.91	730	2.77	0%	7.52	324	2.87	22%	3.15	290	2.58	24%	3.00	265	2.43	24%	1.95

References

1. Blaga, R., A. Sabadus, N. Stefu, C. Dughir, M. Paulescu, and V. Badescu, 2019. A current perspective on the accuracy of incoming solar energy forecasting. Progress in Energy and Combustion Science, Volume 70, 119-144.
2. Yang, D. J. Kleissl, CA Gueymard, HTC Pedro, CFM Coimbra, 2018. History and trends in solar irradiance and PV power forecasting: A preliminary assessment and review using text mining. Solar Energy 168, 60-1011.
3. Wang, P., R. Van Westrhenen, J. Fokke Meirink, S. van der Veen, and W. Knap (2019): Surface solar radiation forecasts by advecting cloud physical properties derived from Meteosat Second Generation observations. Solar Energy 177, pp. 47-58
4. Van der Meer1 D., D. Yang, J. Widén, and J. Munkhammar, (2020): Clear-sky index space-time trajectories from probabilistic solar forecasts: Comparing promising copulas featured. Journal of Renewable and Sustainable Energy 12.
5. Remund J., D. Klauser and S. Müller S. (2016): Shortest Term Solar Energy Forecast. In: Sayigh A. (eds) Renewable Energy in the Service of Mankind Vol II. Springer, Cham

6. Zhang X., Y, Li, S. Lu, H. Hamann, B.M. Hodge, and B. Lehman, (2019): A Solar Time Based Analog Ensemble Method for Regional Solar Power Forecasting. IEEE Transactions on Sustainable Energy. Volume: 10, Issue: 1
7. Perveen G., M. Rizwan, and N. Goel (2019): An ANFIS?based model for solar energy forecasting and its smart grid application. Engineering Reports Volume 1, Issue 5
8. Yang., D:, (2020): Reconciling solar forecasts: Probabilistic forecast reconciliation in a nonparametric framework. Solar Energy (In press -- available online 6 May 2020)
9. Panamtash, H., Q. Zhou, T. Hong, Z. Qu, & K. Davis, (2020): A copula-based Bayesian method for probabilistic solar power forecasting. Solar Energy 196, pp. 336-345
10. Lauret, P., M. David, and P. Pinson (2019): Verification of solar irradiance probabilistic forecasts Solar Energy 94, pp. 254-271
11. Bakker, K., K. Whan, W. Knap & M. Schmeits (2019): Comparison of statistical post-processing methods for probabilistic NWP forecasts of solar radiation. Solar Energy, pp. 138-150
12. Von Loeper, F., P. Schaumann, M. de Langlard, R. Hess, and V. Schmidt (2020) : Probabilistic prediction of solar power supply to distribution networks, using forecasts of global horizontal irradiation. Solar Energy 203 pp. 145-156
13. Verbois, H., A. Rusydi, A. Thiery, (2018): Probabilistic forecasting of day-ahead solar irradiance using quantile gradient boosting. Solar Energy, 173 pp. 313-327
14. Badosa J., E. Gobet, M. Grangereau, and D. Kim, (2018) Day-Ahead Probabilistic Forecast of Solar Irradiance: A Stochastic Differential Equation Approach. In: Drobinski P., Mougeot M., Picard D., Plougonven R., Tankov P. (eds) Renewable Energy: Forecasting and Risk Management. FRM 2017. Springer Proceedings in Mathematics & Statistics, vol 254. Springer, Cham
15. Antonanzas, J., O. Perpinan-Lamigueiro , R. Urraca , & F. Antonanzas-Torresa, (2020): Influence of electricity market structures on deterministic solar forecasting verification. Solar Energy (In press -- available online 25 April 2020)
16. Perez R., M. Perez, M. Pierro, J. Schlemmer, S. Kivalov, J. Dise, P. Keelin, M. Grammatico, A. Swierc, J. Ferreira, A. Foster, M. Putnam and T. Hoff, (2019): Operationally Perfect Solar Power Forecasts: A Scalable Strategy to Lowest-Cost Firm Solar Power Generation. Proc. 46th IEEE PV Specialists Conference (oral), Chicago, Il.
17. Perez R., M. Perez, M. Pierro, J. Schlemmer, S. Kivalov, J. Dise, P. Keelin, M. Grammatico, A. Swierc, J. Ferreira, A. Foster, M. Putnam and T. Hoff, (2019): Perfect Operational Solar Forecasts - a scalable strategy toward firm power generation. International Energy Agency Solar World Congress, Santiago, Chile
18. Yang, D., (2019): A guideline to solar forecasting research practice: Reproducible, operational, probabilistic or physically-based, ensemble, and skill (ROPES) Journal of Renewable and Sustainable Energy 11, 022701
19. Yang, D., S. Alessandrini , J. Antonanzas, F. Antonanzas-Torres, V. Badescu., H. G. Beyer, R. Blaga, J. Boland, J. M.Bright, C. Coimbra, M. David, Â. Friman, C. A.Gueymard, T. Hong, M. Kay, S. Killinger, J. Kleissl, P. Lauret, E. Lorenz, D. van der Meer, M. Paulescu, R. Perez, O. Perpiñán Lamigueiro, I. Peters, G. Reikard, D. Renné, Y. Saint-Drenan, Y. Shuai, R. Urraca, H. Verbois, F. Vignola, C. Voyant & J. Zhang, (2020): Verification of deterministic solar forecasts. Solar Energy (in press -- available online 18 May 2020)
20. Huertas, J. & M. Centeno Brito, (2019): Using Smart Persistence and Random Forests to Predict Photovoltaic Energy Production. Energies 2019, 12(1), 100
21. Hansen, Clifford & Holmgren, William & Tuohy, Aidan & Sharp, Justin & Lorenzo, Antonio & Boeman, Leland & Golnas, Anastasios. (2019). The Solar Forecast Arbiter: An Open Source Evaluation Framework for Solar Forecasting. 2452-2457. 10.1109/PVSC40753.2019.8980713.
22. International Energy Agency PVPS Task 16 - Solar Resource for High Penetration and Large Scale Applications. Activity 3.5: Firm Power Generation.
23. Perez, M., R. Perez, K. Rabago & M. Putnam, (2019): Overbuilding & curtailment: The cost-effective enablers of firm PV generation. Solar Energy 180, 412-422
24. Perez, M., R. Perez, K. Rabago & M. Putnam, (2019): Achieving 100% renewables: supply-shaping through curtailment. PVTECH Power Vol 19., May 2019. www.pv-tech.org
25. Perez, M. et al, (2020): Report: MISO-wide Solar Potential Analysis -- How do we achieve 100% renewables across the MISO region while not breaking the bank? http://mnsolarpathways.org/miso-spa/

26. Pierro M., R. Perez, M. Perez, D. Moser & Cristina Cornaro, (2020): Italian protocol for massive solar integration: imbalance mitigation strategies. Renewable Energy Journal, 153, pp. 725-739
27. Pierro M., R. Perez, M. Perez, D. Moser, M. Giacomo & Cristina Cornaro, (2019): Italian protocol for massive solar integration (part2): from solar imbalance mitigation to 24/365 solar power generation, (under peer review)
28. Perez, R., J. Schlemmer, S. Kivalov, J. Dise, P. Keelin, M. Grammatico, T. Hoff & A. Tuhoy, 2018. A New Version of the SUNY Solar Forecast Model: A Scalable Approach to Site-Specific Model Training. Proc. IEEE PV Specialists Conference (invited). WCPEC-7, Waikoloa, HI
29. SolarAnywhere URL
30. ECMWF, 2019. European Centre for Medium-Range Weather Forecasts
31. GFS, 2019. Global Forecast System - NOAA
32. HRRR, 2019. High-Resolution Rapid Refresh - NOAA
33. NDFD, 2019. National Digital Forecast Database - NOAA
34. SolarAnywhere historical data IEEE paper with latest model
35. Perez, R., J. Schlemmer, K. Hemker, Jr., S. Kivalov, A. Kankiewicz and J. Dise, 2016. Solar Energy Forecast Validation for Extended Areas & Economic Impact of Forecast Accuracy. In 43th IEEE PV Specialists Conference, 2016
36. Yang, D. and R. Perez 2019. Can we gauge forecasts using satellite-derived solar irradiance. Journal of Renewable and Sustainable Energy Journal of Renewable and Sustainable Energy 11, 023704; https://doi.org/10.1063/1.5087588
37. NREL (National Renewable Energy Laboratory), 2019. 2019 Annual Technology Baseline. Golden, CO: National Renewable Energy Laboratory.<http://www.nrel.gov/CPT model
38. Smart Persistence definition from IEA 2015. International Energy Agency, Solar Heating & Cooling Program, Task 46, Subtask C-1: Short-term solar forecasting.
39. https://www.nyiso.com/documents/20142/2223763/2018-State-of-the-Market-Report.pdf
40. New York State Offshore Wind Master Plan (2019): file:///Users/rperez/Downloads/Offshore-Wind-Master-Plan.pdf
41. E.g. https://formenergy.com/
42. Perez, R., M. David, T. Hoff, S. Kivalov, J. Kleissl, M. Jamaly, P. Lauret & M. Perez (2016): Spatial and Temporal Variability of Solar Energy . Foundations and Trends in Renewable Energy, Vol 1, Issue 1, pp. 1-44