The Economic Value of Forecasts for Optimal Curtailment Strategies to Comply with Ramp Rate Rules

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***Abstract* — We present a method to calculate the economic value of forecasts, based on the use of forecasts to optimize curtailment strategies in scenarios with a ramp rate rule. We consider how and when to limit PV power output in order to comply with a ramp rate rule to avoid penalties, but also calculate how curtailment will reduce revenue from energy yields. This framework provides a way to assess the value of forecasts.**

***Index Terms* — Curtailment, Intermittency, Forecasting.**

I. INTRODUCTION

How valuable are short-term forecasts of photovoltaic (PV) power? A number of forecasting technologies and providers are now available to operators of PV power plants, and these forecasts are predicted to reduce the costs associated with solar power variability [1]. PV power can vary quite rapidly due to passing clouds. Changes in output over the course of one minute as large as 70% of a PV power plant's AC-capacity have been observed for utility scale (multi MW) PV power plants in several locations [2]-[4]. This variability can lead to mismatches in supply and demand, and potentially raise the cost of integrating solar power plants into the electric grid. Forecasts can help utilities or power plant operators prepare for ramps in PV power.

However, quantifying the usefulness of these forecasting services, particularly for utilities, is still ambiguous. Previous studies have calculated the economic value of forecasts using many methods, and none are well-established. Some studies base forecast value on the cost of reserve generators needed to compensate for intermittency [5, 6]. A study on solar thermal power plants values day-ahead irradiance forecasts within a market framework where plants are penalized for not meeting their hourly demand schedule [7].

The value of short-term forecasts is dependent on grid stability costs due to PV variability. However, the methods for calculating these grid stability costs are not well-established. Levelized cost, which is the most widely-used metric of valuing electricity, does not consider the wide fluctuations in the market prices of electricity supplied by intermittent sources [8]. Gowrisankan, et al., estimates these grid stability costs by considering the extent to which the variability matches with demand, the extent that PV power is forecastable, and the costs of building backup generation required to maintain system reliability [5].

In this paper we propose a simple framework for assessing the value of forecasts. We assess the value of forecasts within the framework of a ramp rate rule (RRR) [9, 10]. We consider curtailment schedules informed by forecasts, that minimize RRR violations. Then, we estimate total revenue for a plant operator in terms of the income from MWh yields minus penalties (fines) due to RRR violations.

Using data from four different PV plants in southern Arizona and several different types of forecasts: an ideal forecast (available retrospectively), a series of WRF forecasts, a modified persistence model forecast, and a novel forecast based on a network of irradiance sensors, we assess the value of each forecast.

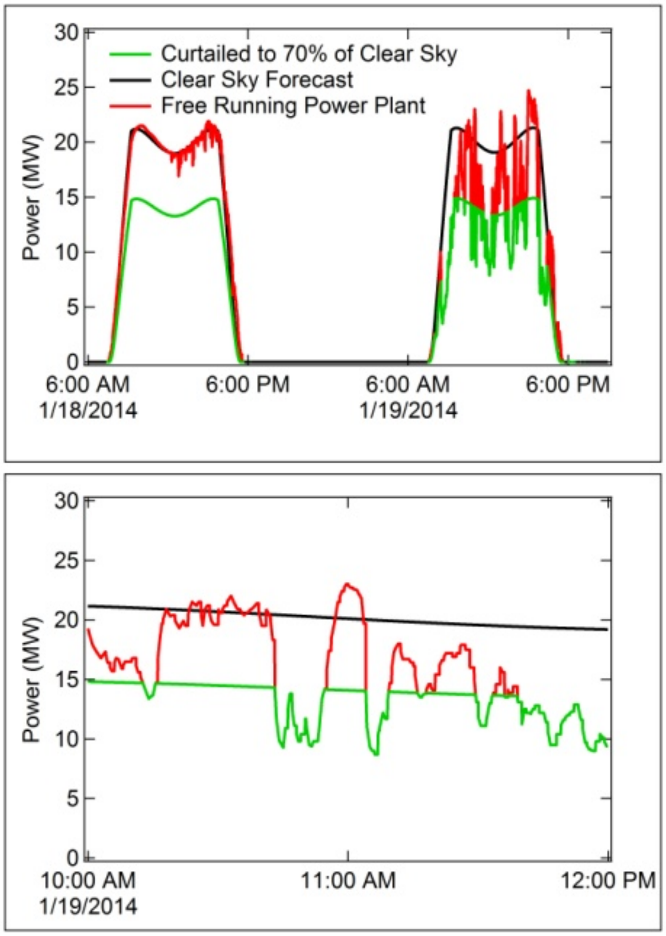

Fig 1. Two days of curtailment to 70% of clear sky prediction. The lower image details a particulary variable two hours on the second day. Compared to the free running system there is decrease in both total energy production and RRR violations. The optimum curtailment in this scheme will depend strongly upon the cost of violating the ramp rate rule.

Several previous studies of ramp rate rules have investigated the occurrence of ramp rate rule violations for free-running PV systems [3] or PV + battery hybrid systems [4,11]. Studies of curtailment have also been undertaken [10].

II. RAMP RATE RULES

Let us define the ramp rate rule (RRR) as 10% of nominal AC power plant capacity per minute on a rolling basis. A violation of the RRR is anytime that power output from the plant is changed by more than 10% of AC nameplate as compared to output 60 seconds earlier. Our studies of RRR violations examine two metrics. First, during a period of study the total number of seconds in violation of the RRR is counted. Second, for each second in violation, the amount of power by which the plant is violation is integrated to express a total energy of violation.

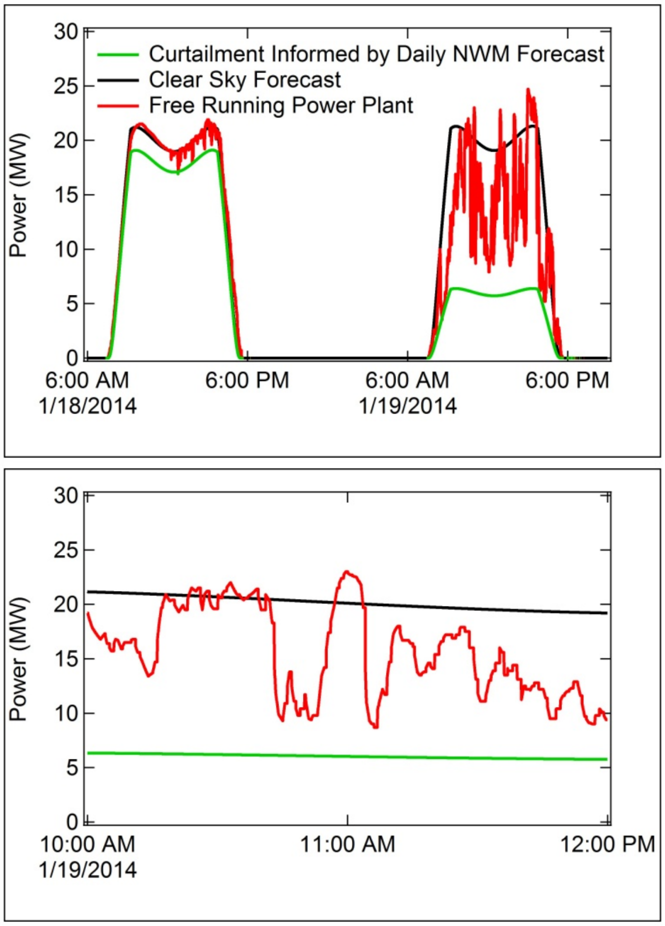

Fig 2 Curtailment to a variable percentage of clear sky prediction using numerical weather models to predict daily variability. The 19th of January was predicted to be highly variable and thus strongly curtailed to 20% of the clear sky prediction.

To determine maximum penalty for RRR violations we initially consider the avoided cost of an energy storage solution (ESS) such as a battery system. We then assume that the final output from the power plant will be ramp rate controlled through a combination of curtailment and energy storage. The energy storage system will be sized according to the effectiveness of the curtailment scheme. For a free running power plant an appropriate ESS is suggested to be 50% the PV power plant nominal output [4]. A perfect curtailment method will require an ESS of size zero and a free running power plant will require a full size ESS. By integrating the RRR violations over the course of a month and comparing this to the free running system we identify the size of the required ESS expressed as a ratio between zero and one.

To determine the cost of a full size ESS we include capital expenses, operation and maintenance costs, and interest payments. This is estimated to be approximately 20% of the revenue from the power plant. To calculate the appropriate penalty for RRR violations we first multiply the required size ratio of the ESS by 0.20 and deduct the result as percentage from the power plant yield. Justifications for this 20% figure can be developed in several ways, for example (a.) an operator may buy the ESS system, (b.) outsource RRR mitigation to a third party, or (c.) pay the off-taker utility a reduced rate to deal with the ramps. The exact justification is not the point of this paper. In fact, the true cost of RRR violations may depend on both location and time. In this paper we will simply use this 20% cost as an assumption, and report how curtailment schedules informed by forecasts can then have a resulting value. We note that the analysis method for directly comparing different forecasts would work for any base cost of the hypothetical ESS.

III. AVOIDED RRR COSTS AS PROXY FOR VALUE OF FORECASTS

There is a growing consensus that forecasts of solar power have some economic value. However, a metric for estimating this value has not yet been agreed upon. We have attempted to answer this question by creating a metric to simplify this macro-economic problem into a tractable micro-economic problem. It uses an external constraint that makes the problem of exactly how to use forecasts into a simpler optimization problem, and from this approach we can report a resulting value for forecasts. One primary motivation for this approach is that it allows for a direct comparison between various forecasting methods and technologies.

A direct summary example of this metric is now considered. Suppose a 1 MW photovoltaic power plant is operated in the southwestern desert of the United States. The plant uses common silicon technology with conventional inverters and is mounted on single axis tracker (SAT) hardware. This plant will typically produce approximately 2200 MWh per year. At the going rate in the region for renewably produced energy of $80 per MWh, the annual revenue for the plant operator will be around $176,000. However, our research suggests that during a year of free running operation the plant will be in violation of our RRR approximately 400,000 seconds (4% of

TABLE I

CURTAILMENT TO A FIXED PERCENTAGE OF SPA PREDICTED OUTPUT FOR JANUARY THROUGH APRIL 2014

Limitation (% of SPA)	Number of Seconds in Violation	Total Energy Production (MWh)	Integrated RRR violations (MWh)	Revenue from Energy Production (K$)	Penalties from RRR Violations	Net Revenue	Value Index
10	0	380	0	38	0	38	11
20	4	754	0	75	0.002	75	22
30	224	1121	0.04	112	0.10	112	33
40	2124	1477	0.38	148	0.94	147	44
50	9282	1819	1.8	182	4.3	178	53
60	21622	2149	4.7	215	10	204	61
70	39852	2465	9.1	246	20	227	67
80	62112	2766	15	277	31	245	73
90	87202	3045	22	305	45	260	77
100	111446	3276	28	327	58	270	80.2
free running	129340	3368	33	337	67	269	80

daylight hours) and require the off-taker to supply about 30 MWh of supplementary energy to correct ramp rate violations. If we assume the cost for very high response rate spinning reserve power is a very low $8 per hour per MW and the operator must supply this service during all daylight hours then the cost to correct RRR violations is about 20% of the gross revenue from the sale of energy, which is in line with estimated cost of a chemical battery ESS. To simply put it: as an ansatz we assume that the cost of RRR violations is approximately 10 cents per second of violation per MW of power plant capacity.

The value of a forecast can be found then by using the forecast to preemptively curtail output from the power plant in anticipation of imminent events which will violate the RRR. Such curtailment reduces the total energy output and thus reduces the gross revenue; however, it may also reduce the RRR violation expenses and thus potentially increase the net revenue. These changes in net revenue are then the basis of comparison between the various forecasting methods as well as other operational protocols designed to reduce to RRR violations which we will consider. A single metric developed to capture both the resultant energy production in MWh and the decrease in RRR violations is the Value Index (VI). The VI describes net revenue for a power plant as a percentage of revenue in cases where the penalty for violating RRR is zero. Thus the VI of a free running system is set to 80, with the ansatz that the true cost of RRR violations is 20% of the gross revenue. If the cost of RRR violations is determined to be lower, the VI of the free running system should be correspondingly increased.

IV. FORECAST-INFORMED CURTAILMENT

Forecasting technologies for PV power have been developed in several ways [1]. We consider 5 different forecast methods and operational protocols to enable curtailment experiments in this paper.

Each forecast method informs a different curtailment algorithm. We then investigate the consequences of such curtailment on energy yields (MWh) and RRR violations. The economic valuation accounts for revenue from MWh and fines due to RRR violations. Each method is assigned a value index which represents the net revenue from the power plant as compared to situation in which the cost for RRR violations was zero. Our forecast methods include:

1) A solar position algorithm (SPA) is used to predict a clear sky output of a system for each time step. Power output is modeled to be a combination of both direct normal and diffuse irradiance projected onto either fixed tilt panels or in the case of single axis trackers, a plane that tracks the sun as best it can with a single degree of freedom along a north south line tangent to the ground. Further refinements include consideration of row spacing and typical season temperatures. The SPA value may be used without further weather forecast by continuously curtailing the system to a fixed percentage of clear-sky output. Additionally, the SPA model becomes an input into other forecast functions.

TABLE II

GROSS REVENUE UNDER VARIOUS CURTAILMENT SCHEMES JANUARY TO APRIL 2014

Limitation method	Number of Seconds in Violation	Total Energy Production (MWh)	Integrated RRR violations (MWh)	Revenue from Energy Production (K$)	Penalties from RRR Violations (K$)	Net Revenue (K$)	Value Index
Free Running	129340	3368	33	337	67	269	80
Ideal	0	3314	0	331	0	331	98
Easy up	56144	3343	13	334	28	306	90
Daily NWM	75262	3131	19	313	38	275	82
3 Hr NWM	78362	3063	19	306	40	266	79
80 % of SPA	62112	2766	15	277	31	245	73

2) Numerical Weather Model (NWM) forecasts made with 4 different WRF runs 12 to 24 hours in advance. These may be applied to a system in several ways. We consider two methods: a) Each day the system is curtailed to percentage of SPA model. A daily curtailment schedule is calculated based upon the expected insolation for each day, b) Alternatively, each day is divided into 3 hour blocks and a daily curtailment schedule is generated with separate curtailments for each time block.

3) A spatial network of irradiance sensors [12,13] which produce short-term forecasts of power output, used in an attempt to proactively curtail just-in-time (JIT) before a RRR violating event occurs. The irradiance sensor network is a fleet of inexpensive GHI sensors reporting real-time irradiance via a commercial cellular network to a central control system. In combination with NWM of cloud height along with wind speed at cloud height, this data is used to predict changes in GHI at the PV plant. A number of such sensors are deployed in the vicinity of the University of Arizona Science and Tech Park, where Tucson Electric Power (TEP) has sited 22 MW of PV power, among 6 different PV plant installations. The sensor network is used to predict power output 5-15 minutes in advance for selected sites at the Tech Park. Sensors sufficient to provide early warnings to a 5 MW fixed tilt plant were operational in late January, making analysis of this method only possible for February through April.

4) An easy-up protocol, in which power is not permitted to increase faster than allowed by the current RRR. This is a form of persistence.

5) Ideal (retrospective) forecasts which are used to execute exactly JIT curtailment accompanied by easy-up increases in output with the result that no RRR violations occur, and power is never curtailed more than is necessary to satisfy the RRR.

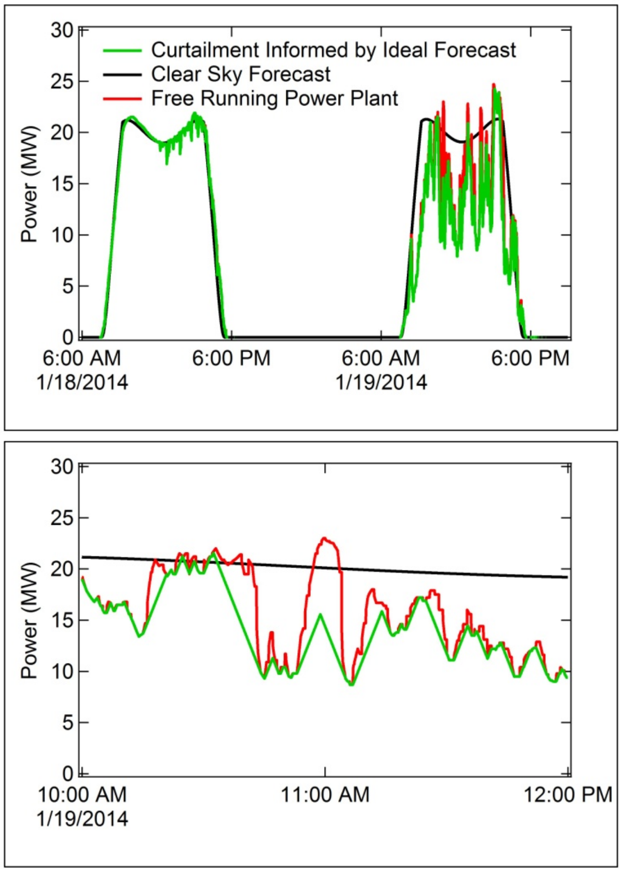

Fig 3. Curtailment based on a ideal forecast which only reduces power output the absolute minimum to avoid RRR violations.

TABLE III

SUMMARY OF VALUE INDEX FOR VARIOUS CURTAILMENT SCHEMES BY MONTH

Method	January	February	March	April
Free Running	80	80	80	80
WRF 1-day	81.8	84.8	82.2	81.6
Irradiance Network		88.1	88.1	88.8
Easy-up	90.2	90.2	90.1	90.4
Irradiance Network + Easy up		91.2	91.2	92.0
Ideal (Easy up + Easy down)	98.8	97.7	97.3	97.6

These forecasts are listed in the order from most simple to most perfect. At one extreme, we may design curtailment schemes based on no forecast. For example, if we had 10 MW of PV panels, but only allowed the inverter to output 2 MW of power at maximum, then it would be curtailed most of the daylight hours. This results in many hours of flat line output, which naturally suppresses fluctuations unless the available sunlight falls below 0.2 sun. At the other extreme we can understand the upper limit in value for a forecast by considering an ideal forecast achieved through a retrospective analysis of the output of a free-running PV power plant.

For forecast (1), we simply curtail the output at all times to a fraction, e.g. 70%, of the output that would be predicted with an SPA and a cloud-free sky. The power plants studied for Figures 1-3 and Tables 1-2 include 25 MW single axis tracking plant and a 5 MW fixed tilt system. Both are installed near Tucson, Arizona [14]. Separate forecasts are generated for each. Fig. 1 and Table 1 show the result of using this model for fixed amounts of curtailment as a percentage of SPA models. Table 3 includes results from the irradiance sensor network which became operational for February and is located near the 5 MW power plant.

V. DISCUSSION

Table 1 summarizes the results of hypothetically curtailing the studied system for the months of January through April 2014 using various percentage of the SPA prediction. This produces lower net revenue at most levels of curtailment under the proposed pricing of RRR violations. When the power plant is limited to exactly the SPA model a small increase in revenue is projected. On cloudy days it is commonly observed that the cloud edge enhancement effect increases output of the modules above a clear sky profile. This may be observed in Fig. 1 by comparing the free running output to the SPA model for January 19th. The nature of the cloud enhancement is to be very temporary and frequently results in RRR violations, thus limiting output to 100% of the SPA model, which has a trivial impact on energy production but reduces RRR violations.

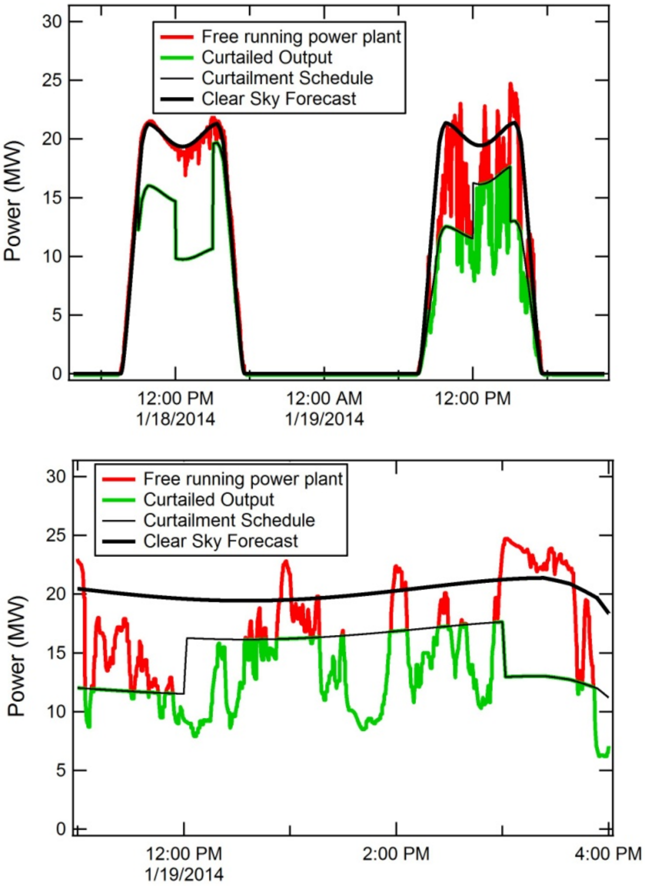

Fig 4. Intra-day curtailment scedules based on NWM. The transistions every 3 hours are slopped to not cause a RRR violation.

Table 1 is from data from a 5 MW fixed tilt site. The results are nearly identical for a 25 MW single axis tracking site. Interestingly, during the study period, the number of seconds in RRR violation for both sites was very close to 130K seconds, despite significant size, mounting differences and a geographic distance of about 20 miles between the sites.

Table 2 summarizes the result of each method of curtailment on the 5 MW system for the months of January through April 2014. We note that under most curtailment methods hypothetical revenue is increased as the reduction in RRR penalties outweighs the reduction in energy production.

The retrospective approach demonstrates an upper limit in value for a forecast. With curtailment informed by ideal forecasts, energy production drops by approximately 2% while entirely avoiding penalties for RRR violations, resulting in an increased value index of 18 points over the free running system. It produces the highest MWh output of a power plant which never commits a ramp violation by preemptively curtailing just in time to a safe level.

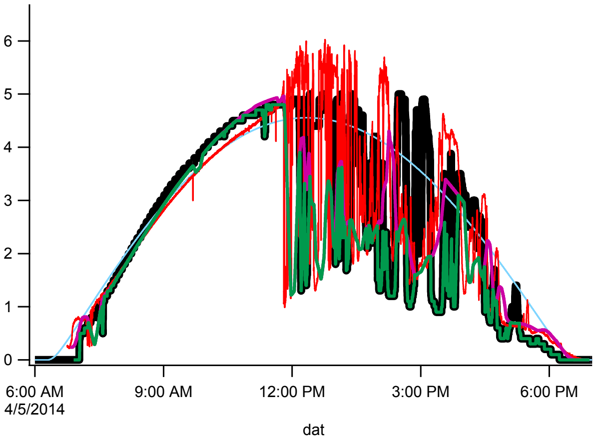

Fig 5. Various forecasts for a day in April 2014. The Fine red line represents free running output. The Cyan line represents the SPA model. Black and Green lines represent sensor network informed curtailment schedules.

The easy-up protocol, while not strictly a forecast methodology, is included for study in this paper as it notably will increase net revenue anytime the penalty associated with RRR violations is greater than 1% of gross revenue form a free running system. The implementation of the easy-up protocol is both trivial and results in a direct reduction of RRR violations by more than 50%. For this reason we compare the effectiveness of other forecasting and curtailment methods against the easy-up method. Additionally we find that the easy-up method is useful to combination with other strategies, especially the irradiance sensor network

Table 3 summarized monthly results from selected methods, listing only the Value Index as result. We find that the most profitable approach is to use the irradiance sensor network to trigger downward curtailments and use the easy-up protocol to control all upward ramps.

NWM and sensor network forecasts can increase gross revenue. There is a tradeoff between higher energy yields and still acceptable penalties due to RRR violations. The single most cost effective method to reduce RRR violations is to curtail increases in power output, limiting ramp up rates to meet a ramp rate rule. Using this at the baseline, we find that an irradiance sensor network can provide short term forecasts which further reduce RRR violations.

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