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Potential Impact of Solar Energy Penetration on PJM Electricity Market

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***Abstract*—Renewable energy resources, such as wind and solar, have become important parts of today's generating resource mix. Along with them, these resources also bring their inherent characteristics of variability and uncertainty. Hence, resource planners must be adaptable to accommodate these resources in conducting resource planning. Understanding their impact on the electric grid must be prior and critical. In this paper, we have studied the potential impact of solar energy penetration in a particular location of PJM electricity market. Key economic and system variables that were analyzed include system production cost, market prices (average zonal prices), congestion (both hours and dollars), and transmission losses. We find that significant penetration of solar energy resources can produce system-wide economic benefits in the respective transmission areas as well as the entire system.**

***Index Terms*—Economic analysis, electricity market, renewable energy, solar penetration.**

NOMENCLATURE

A. Sets and Indices

T Total study period in hours $t \in T$.

B. Economic Parameters

BC_i Bid curve of generator i.

CC_{ik} Congestion cost between bus k and bus i.

EC_i Emission cost of generator i.

FC_i Fuel cost of generator i.

NL_i No load cost of generator i.

OM_i O&M cost of generator i.

PC_i Production cost of generator i.

ST_i Startup cost of generator i.

SD_i Shut down cost of generator i.

C. Variables

F_l Real power flow on line l.

LMP_k Hourly LMP at bus k.

LMP_i Hourly LMP at generator bus i.

LMP_{ref} Hourly LMP at reference bus.

ML_i Marginal loss factor at bus i.

P_D Total real power load.

P_i Real power produced at generator i.

P_L Total real power loss.

SP_{xy} Shadow price of constraint x in contingency y.

SF_{xyi} Shift factor for real load at bus i on constraint x in contingency y.

D. Constants

a_i, b_i, and c_i Coefficients of bid curve for generator i.

$F_l^{\max}$ Maximum real power flow limit of line l.

$P_i^{\min}$ Minimum real power limit of generator i.

$P_i^{\max}$ Maximum real power limit of generator i.

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Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

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I. INTRODUCTION

THE RENEWABLE energy resources, such as wind and solar, have been proposed and developed in the U.S. due to mandatory state legislation on renewable energy requirements standards (RES) and influence of potential climate change policies at the federal level. For this reason, renewable energy resources will take more important roles in resource planning in both traditional standalone utility and organized multilateral market environments. Variability and uncertainty are inherent characteristics of renewable energy resources. This poses significant challenges to the system planners and operators.

Different states have different RES targets and goals. The RES requirements for states with RES mandate fall between 4% and 30% of electricity which must be generated from renewable sources by a specified date. As of August 2010 [1], 29 states plus the District of Columbia have renewable standards, while additional seven states have renewable portfolio goals. For example, California has renewable energy mandate that 33% of energy be generated from renewable energy by 2020. Similarly, New York State requires 29% by 2015 and Pennsylvania requires about 18% by 2021, including non-renewable alternative resources.

Development and penetration of wind energy has been significant due to its decreasing cost and federally supported production tax credit. Wind resources have become more economically competitive compared with conventional resources. However, the cost of solar energy, particularly fixed cost, has been prohibitively high to have large penetration into the electric grid. Recently, U.S. government set out a goal of doubling its renewable energy generation capacity from wind, solar, and geothermal resources by 2012 [2]. It also plans to halve the cost of solar energy by 2015, leading a way to make the solar energy more competitive with electricity from other resources in the electric grid.

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Consequently, in the near future, the solar energy can have significant potential to penetrate into the power grid and electricity market areas. Solar energy penetration will more likely be in smaller, gradual, and incremental scale, such as rooftop applications, installed at residential, commercial, and industrial buildings.

The key feature of these resources, including certain hydro resources, is their "intermittency" or "non-dispatchability." In the case of hydro resources, except runoff river type, the release of water can be controlled, hence dispatchable. Since wind and solar energy resources depend on the availability of wind and solar energy, these resources are generally non-dispatchable. In other words, these resources generate power *only when* there is wind blowing or sun shining, not when the system operators call them to do so. Hence, it is more challenging to incorporate these resources into the system planning and operation. As a consequence, the system planners and operators, including electricity market operators, have been concerned with the potential impact of penetration, especially the large amount, of renewable energy resources in their operating areas.

The key questions that draw some attention recently include whether these intermittent resources are going to have some impact—positive and/or negative—on the system in terms of economic, reliability, and operation. Economic impact on the system includes observing and measuring the changes in the key economic variables such as system production cost, congestion, market prices, and others, with and without those energy resources.

Some studies [3], [4] have been conducted to understand better about the potential impact of wind energy penetration on the New York power market. While these studies were quite comprehensive, the key findings was that New York bulk power system can reliably accommodate at least 10% penetration, 3300 MW, of wind generation with only minor adjustments to its existing planning, operation, and reliability practices. The authors found that there is a $1.8/MW average reduction in spot prices in New York State for the simulated study year.

Recent studies [5]–[7] include an investigative study [7] on the operational impact of up to 35% energy penetration of wind, photovoltaics (PV), and concentrating solar power on the power system operated by the WestConnect group.[1] This paper shows that it is operationally feasible for WestConnect to accommodate 30% wind and 5% solar energy penetration, with recommended changes in a number of operational areas, including increased balancing area cooperation, increased utilization of transmission, and more coordinated commitment/dispatch of generation over wider regions.

California Independent System Operator (ISO) [8] has recently conducted a study[2] on integration of renewable resources which include wind, solar, small hydro, geothermal, and biomass/biogas. The study was done to understand the operational and market impact of meeting the requirement that 20% of all electricity supply come from eligible renewable resources by 2010, required by California's existing RES. The modeled renewable resource portfolio in the study includes 2246 MW of solar power in addition to other resources. Operational impact includes the load-following (up/down) and regulation (up/down) requirements by existing generation fleet. Key finding of the study was that the combination of (some amount of) wind and solar resources can lessen the operational requirements, as compared to wind resource alone because solar resources are ramping up when wind resources are ramping down, and vice versa. It also can lead to reduction in market clearing prices as well as displacement of energy from thermal (gas-fired) generation in both the daily off-peak and on-peak hours.

A review of literature showed that many of the previous work on solar energy fall into either technical (operation) or economics or combination of the two. Most of the work [9]–[12] on technical category searched for new methods—simulation and analytical—to estimate the solar energy output, with or without additional storage battery capacity so as to determine the optimal size of PV system. Some of these works [13]–[17] also evaluate the reliability of PV system which studies the loss-of-load probability of PV system based on various factors. Some recent works [18]–[22] extend technical work by including aspects of economic analysis into the PV system valuation.

However, most of these works were focused solely on standalone PV system and thus did not consider the impact on the larger system (larger utility area or larger regional transmission area) with the penetration of large amount of standalone PV resources. While there were some studies on the impact of wind energy resources on the electric grid and electricity market, no such study was done to understand the potential impact of solar energy penetration on a power grid, particularly, under an operating electricity market environment. In this respect, our paper has attempted to make some important contribution to fill that gap.

This paper is organized as follows. We describe the study background of solar energy penetration in Section II, the methodology and assumptions in Section III, the results in Section IV, and the conclusion and further discussion in Section V. We also provide, in the appendixes, a concise mathematical formulation of locational marginal pricing (LMP) methodology used in the market simulation method.

II. Study Background of Solar Energy Penetration

In this section, we provide a brief description of PJM electricity market and rationale for modeling solar energy penetration as load reduction.

A. PJM Electricity Market

PJM Interconnection is a RTO which operates the world's largest wholesale electricity market in a defined control area. It is also an experienced operator of successful wholesale electricity markets and is responsible for reliability of electric

[1]WestConnect includes group of utilities operating in Arizona, Colorado, Nevada, New Mexico, and Wyoming.

[2]Except this particular study, the author is not aware of any other relevant study, being conducted or been conducted at any other regional transmission organization (RTO)/ISOs.

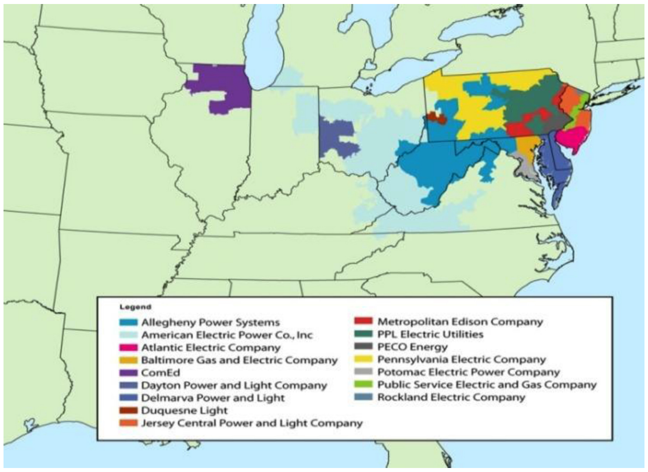

Fig. 1. PJM operating footprint.

transmission system. PJM operates the following markets: energy (both day-ahead and real-time), financial transmission rights, ancillary services (regulation, spinning reserve, etc.), and capacity market known as reliability pricing model.

Among the RTOs under Federal Energy Regulatory Commission's jurisdiction, PJM is the largest RTO with the peak load of over 140 GW on August 2, 2006, with more than 1000 generating units. PJM control area covers all or parts of 13 states and the District of Columbia in the mid-Atlantic region. The operating territory of PJM is shown in Fig. 1.

Since the operating territory of PJM expands many states, the potential state legislation related to electric grid can have potentially significant impact on operation, and planning of its transmission system and electricity market.

Primarily, renewable energy standards are mandated by individual states to reduce carbon emissions from electric power generators, diversify the fuel, and location from which electric supply comes, and to achieve electric cost stability. Thus, state regulatory bodies are interested in analyzing and understanding the potential impact of large penetration of these intermittent resources, in their state territories. Note that the electrical boundaries of zonal (control) areas do not necessarily match with the state boundaries. However, we can analyze their impact within a state boundary by studying the impact on relevant zonal areas that are approximately located inside that state territory.

B. Modeling of Solar Energy Penetration

On a particular solar device level, such as solar panel, the output from one solar panel has particular energy profile [23] which typically has a rounded step-function, due to availability of sun, i.e., *insolation*. Individual solar panels commonly experience power output variations in the one-second to several-minute timeframe. When many solar panels are grouped together in a particular building or site, the short-term variations of individual solar devices are attenuated as a percentage of the aggregate and the dominant power output variations for the entire solar building or site occur in the minute-to-hour time frame. Similarly, the minute-to-minute power output of individual solar buildings or sites are attenuated in systems with multiple solar energy resources, leaving regional solar fluctuations in the hour-to-day time frame as the dominant system-wide effect.

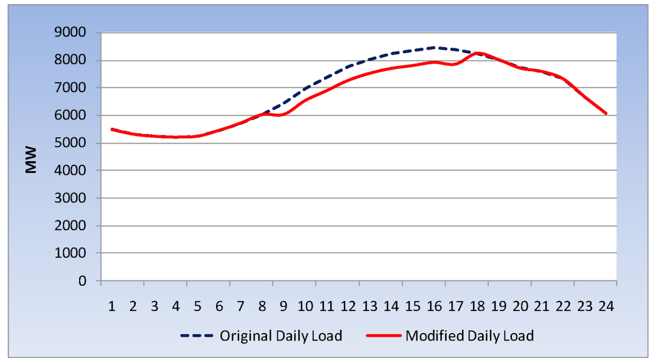

Fig. 2. Daily load shape.

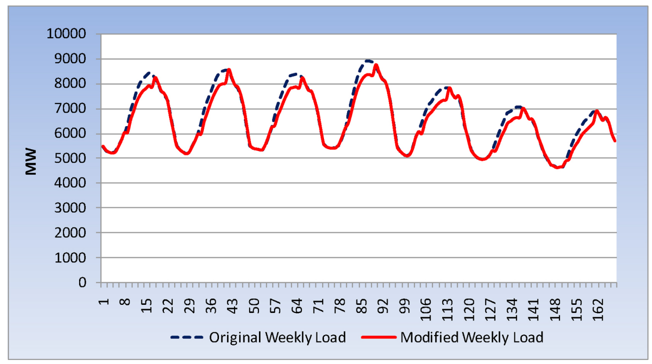

Fig. 3. Weekly load shape.

When such solar panels are installed in large scale in a particular area, such as residential and commercial buildings or even in a particularly large state territory, their impact on the system operation can be modeled as statistical averaged and aggregated output. This aggregated output can be further modeled as *load reduction* or *load modifier* for the hours when there is abundant insolation. Using that load modification concept, we can model and simulate the electric grid system in organized multilateral markets, *with* and *without* that large solar penetration to observe their impact.

The changes in the load shapes, due to load modification, are shown in Figs. 2 and 3. Fig. 2 shows the original load versus modified load for a typical day, while Fig. 3 shows the similar data for a typical week for a particular zone with assumed solar penetration.

Since the state within PJM that we studied is Pennsylvania, load modification due to solar energy penetration is applied to the following transmission areas whose territories fall within that state: Allegheny Power (APS),[3] Duquesne Light and Power, Metropolitan Edison, Philadelphia Electric Company, Pennsylvania Electric Company, and PPL Electric Utilities. We also assume that the potential solar energy penetration in the state of Pennsylvania can have the impact of 2.5% load reduction (for the entire year) in these zonal areas in the year 2015, if legislation is issued in the present time. Since the load reduction due to solar penetration should apply only to load hours when there is abundant insolation, this translates into

[3]APS operating territory covers other states as well.

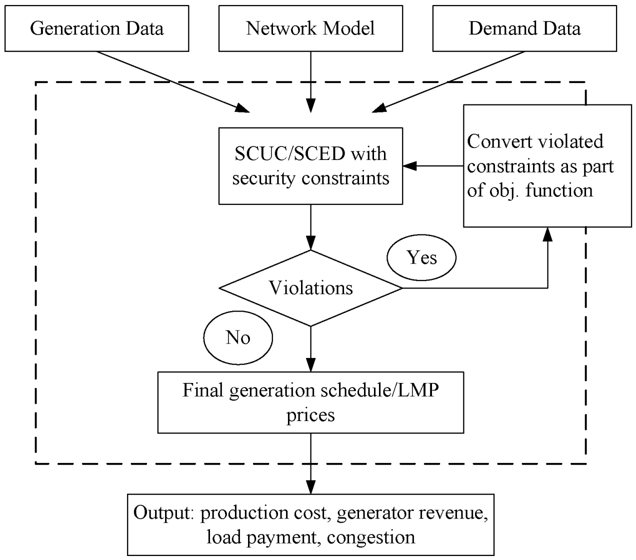

Fig. 4. Market simulation process diagram.

6.3% load reduction in hours from 9 A.M. to 17 P.M. (insolation hours).

III. Methodology and Assumptions

This type of economic assessment requires the simulation of the power system operation which occurs in a competitive market environment. In other words, it requires a multiarea production costing algorithm model [24] that incorporates detailed representations of the entire transmission system. It mimics the market operation, using similar unit-commitment and economic dispatch algorithm. The mathematical formation of these algorithms is given in the appendixes. It is a chronological simulation of the system operation while recognizing transmission constraints and other unit operating constraints such as minimum up/down time. It assumes marginal cost bidding, performs a least-cost (bid) dispatch, and calculates hourly LMP for each node in the system.

For this analysis, we adopt the market simulation approach [25] which is shown in Fig. 4. It is also used in conducting economic analysis of major transmission upgrade projects. Since this method is previously described in detail, we only describe its major steps here.

In summary, generation, transmission network, and demand data are fed into the commitment/dispatch algorithm. This optimization algorithm, which can use either linear programming (LP) or mixed integer programming (MIP), optimizes the production cost, while accounting any violated constraints. Optimal solution is reached after some iteration (for each hour of simulation). Generation schedule and LMP prices are produced as final results.

The optimization method used in this simulation is MIP. MIP is used to solve unit commitment problem in PJM market since 2004 [26]. Global optimality, better measure of optimality, and improved modeling of security constraints are some of the benefits associated with MIP optimization method, compared with Lagrangian relaxation (LR) algorithm. Additions of new constraints and variables do not require the addition of new LR multipliers, as in LR algorithm, so that problem definition can be improved significantly. The disadvantages of MIP method are that it requires increased memory, large variations in runtimes, and complex constraint formulations.

The classical MIP implementation utilizes a branch and bound scheme. This method attempts to perform an implicit enumeration of all combinations of integer variables to locate the optimal solution. It can solve nonconvex problems with multiple local minima. Since the MIP methods utilize multiple LP executions, recent advances in both computer hardware and software have helped MIP methods to improve significantly [27]. Several significant advances in MIP algorithms, including heuristics, node presolve, and cutting planes, were introduced and incorporated into CPLEX 6.5 [28], [29]. These methods introduce numerous redundant constraints into the problem with the objective of finding solutions that are integer feasible at the LP corner points. This idea attempts to transform the combinatorial problem into a series of constrained LPs.

Since it will be a few years in the future, before the relevant state legislation is passed and significant penetration of solar energy resources will occur in the respective transmission areas, we assume the study year to be 2015. This is a reasonable assumption given that the cost of solar resources must decrease to have large penetration into the electric grid.

A number of key assumptions are made in this paper as follows.

1) Existing available transmission capacity is accessible to solar generation.
2) The balance of generation is not optimized for solar energy. Also, operation and maintenance (O&M) cost of solar energy resources are not considered. Hence, solar resources act like price-taker in the simulated electricity market.
3) Increased O&M of conventional generators due to increased ramping and cycling, due to load fluctuation caused by solar energy impact, was not considered.
4) All study results are in 2015 nominal dollars.

IV. Results

Since the main objective of this paper is to estimate the short-term economic impact of solar penetration in PJM electricity market, the key economic and system variables that were considered in this paper include system production cost, average zonal market prices, congestion (both hours and dollars), and transmission losses. These key variables are further explained below.

The system production costs are the costs to generate energy at the desired level of output for each simulation period to meet demand. It is the summation of the hourly fuel cost (generally, the largest component of total production cost), O&M cost, start-up cost, and emission cost for each generating unit in the system as follows:

$$\mathrm{PC}_i = \mathrm{FC}_i + \mathrm{OM}_i + \mathrm{ST}_i + \mathrm{EC}_i. \tag{1}$$

TABLE I

CHANGES IN SYSTEM PRODUCTION COST

Zone	Base Case	Solar Case	Changes in Production Cost
ACEC	243	235	(8)
AEP	9 406	9,302	(104)
APS	3 486	3 466	(20)
BG&E	1 062	1 057	(5)
COED	4 116	4 077	(39)
DP&L	1 172	1 168	(4)
DPLC	504	487	(16)
DQE	632	631	(1)
JCPL	532	510	(22)
METED	1 124	1 085	(39)
PECO	1 873	1 810	(64)
PENNELEC	2 552	2 542	(10)
PEPCO	1 185	1 175	(11)
PPL	2 016	1 991	(24)
PSEG	1 908	1 853	(54)
VIEP	3 872	3 830	(43)
Total	35 682	35 218	(463)

TABLE II

CHANGES IN CONGESTION

Constraints	Base Case		Solar Case		Changes	
	Constrained Hours	Shadow Price ($ million)	Constrained Hours	Shadow Price ($ million)	Constrained Hours	Shadow Price ($ million)
AP-South (basecase)	1137	58	1213	68	76	10
Altoona-Bearrock	799	29	631	16	(168)	(13)
Central Interface	1566	24	1512	25	(54)	1
Clover Transformer	767	17	755	16	(12)	(1)
AP-South (contingency)	148	16	159	18	11	2
East Interface	48	6	50	2	2	(4)
Sandy Springs-High Ridge	34	4	13	0	(21)	(4)
Linwood-Chichester	127	4	80	1	(47)	(3)
Calvert Cliff-Indian River DC tie	5515	4	6004	3	489	(0)
Calvert Cliff-Vienna DC tie	4855	4	4838	3	(17)	(0)

The change, typically the saving, in production cost, due to some key factor, is the primary measure of immediate economic benefit. The key factor in this paper is the solar penetration which has the impact on load (reduction).

The byproduct of this market simulation is the nodal prices for each node, as well as zonal prices for each zone in the system. These nodal market prices are known as LMP. The detailed formulation of LMP is given in Appendix B.

Generally, the LMP is comprised of three cost components: system marginal price, marginal congestion cost (MCC), and marginal loss component (MLC). Congestion cost (MCC) between two nodes is the difference between LMP prices of these two nodes, ignoring MLC. Congestion cost is typically incurred by load customers on congested zones, while generators on uncongested zones receive congestion credits

$$\mathrm{CC}_{ik} = \mathrm{LMP}_i - \mathrm{LMP}_k. \tag{2}$$

Electrical losses in a power system are caused by power flowing on transmission lines as dissipated heat. The power flowing on transmission lines, and hence resultant losses in the system, depend on the dispatch pattern of generation

TABLE III

CHANGES IN MARKET PRICES FOR SOLAR HOURS

Zone	Base Case	Solar Case	Changes in LMP
ACEC	80.79	78.45	(2.34)
AEP	71.56	70.04	(1.52)
APS	73.24	71.28	(1.96)
BG&E	77.76	75.68	(2.07)
COED	71.25	69.79	(1.45)
DP&L	71.92	70.43	(1.49)
DPLC	76.26	74.37	(1.89)
DQE	71.11	69.19	(1.92)
JCPL	82.69	80.21	(2.48)
METED	78.19	75.58	(2.60)
PECO	78.80	76.17	(2.62)
PENNELEC	75.10	72.66	(2.44)
PEPCO	76.37	74.73	(1.64)
PPL	78.64	75.98	(2.66)
PSEG	80.38	78.03	(2.36)
RECO	79.19	76.89	(2.30)
VIEP	75.20	73.73	(1.46)
Total	76.38	74.31	(2.07)

to meet the instantaneous load. For example, transmission losses are lower when a generator close to the load center is dispatched compared to a case when a remote generator, farther from the load, is dispatched to meet the same load, all else being equal. This is due to the fact that the power from a remote generator has to flow through long transmission lines to reach to the load, thus incurring losses (both real and reactive power losses) along the way on these lines. In other words, generators in a system have different impacts on losses depending on their locations.

The results of key economic and system variables are further described below along with their discussion.

Changes in production cost (in million dollars) for the study year, due to solar penetration, are given in Table I. The assumed impact on load reduction by solar penetration is modeled explicitly only for those zones whose operating territories fall within Pennsylvania. We can observe that all modeled zones (highlighted with gray) result in production cost savings. In addition, the remaining zones also experience reductions in production cost. The entire system results in total system saving of about $463 million. This is a significant saving to the system. From this result, one can infer that the production cost savings in zones with solar penetration can have secondary (positive) effect of the production cost savings in other zones without solar penetration.

Congestion, represented by shadow price of constrained facilities, such as transmission lines, is also an important variable in the electricity market. It represents an additional (economic) cost to the system due to the physical limitation of electrical equipments which prevents the most economic transfer of power from cheaper generating resources to load. Generally speaking, the higher the congestion (cost) in a system for the time period of interest, the more facilities within that system are limiting or *binding* mathematically.

Reduction of congestion cost is a desirable objective since it reduces the unnecessary economic cost and increases the economic efficiency. Potential impact of solar energy penetration

TABLE IV
CHANGES IN MARKET PRICES FOR ALL HOURS

Zone	Base Case	Solar Case	Changes in LMP
ACEC	74.09	73.27	(0.82)
AEP	66.10	65.59	(0.51)
APS	67.73	67.06	(0.68)
BG&E	71.59	70.82	(0.77)
COED	65.31	64.83	(0.47)
DP&L	66.35	65.86	(0.49)
DPLC	70.22	69.55	(0.68)
DQE	65.79	65.13	(0.66)
JCPL	75.69	74.81	(0.87)
METED	71.93	71.00	(0.92)
PECO	72.37	71.45	(0.92)
PENNELEC	69.26	68.38	(0.88)
PEPCO	70.48	69.92	(0.56)
PPL	72.28	71.34	(0.94)
PSEG	73.80	72.97	(0.83)
RECO	72.76	71.95	(0.81)
VIEP	69.50	68.99	(0.51)
Total	70.31	69.58	(0.72)

TABLE V
CHANGES IN TRANSMISSION LOSS

Zone	Base Case	Solar Case	Changes in Loss
ACEC	317 953	318886	933
AEP	4 449 328	4 426 536	(22 793)
APS	1 563 655	1 545 123	(18 532)
BG&E	640196	645 010	4 814
COED	2 680 309	2 683 611	3 303
DP&L	753 429	752 244	(1185)
DPLC	709 743	713 217	3 474
DQE	196 974	195 301	(1673)
JCPL	673 852	680,622	6 770
METED	268 997	262 084	(6913)
PECO	749 538	728 809	(20729)
PENNELEC	1 362 291	1 372 590	10 299
PEPCO	383 086	382 019	(1067)
PPL	1 840 026	1 827 857	(12169)
PSEG	1 256 857	1 265 146	8289
RECO	5 585	5 633	48
VIEP	1 896 176	1 878 669	(17 507)
Total	19 747 995	19 683 357	(64638)

on congestion (both hours and dollars) is shown in Table II. For illustrative purpose, only the top ten constraints, of the study year, which have highest shadow prices, are shown. In other words, these top constraints contributed highest congestion cost to the entire system. In the case with solar penetration (solar case in the figures), the congestion costs of seven constraints, out of ten, have decreased. The total reduction of congestion cost for the entire system is about \$18 million.

Based on fundamental economic theory, market prices are excellent indicators of efficient allocation of scarce resources. It represents the (efficient) equilibrium price for the moment of interest, determined by available supply and demand to be met. The scarce resource, in this case, is electricity. Electricity markets have been using *market prices*, represented by LMP, to achieve that short-term economic efficiency. Higher market prices represent a situation where there are less or insufficient supply to meet the demand. Lower market prices represent an opposite situation.

Impact of solar energy penetration on market prices (LMPs in \$/MW) are shown in Tables III and IV. Table III shows the changes in market prices for hours when solar energy is available, while Table IV shows the similar data for all hours. It can be observed that market prices are reduced for all zones, while the reduction is more pronounced for zones modeled with solar penetration. The reduction in markets prices are more pronounced for hours when there is abundant insolation.

Impact of solar energy penetration on transmission loss (in MW) for the study year, is given in Table V. While some zones experienced slightly higher transmission losses, most of the zones with solar penetration have significant reduction of transmission loss (shown in parenthesis). On system level, there is also a significant reduction of transmission loss.

V. CONCLUSION

This paper attempted to quantify the impact of solar energy penetration on PJM electricity market on zonal and system-wide basis. In this paper, we assumed that the power output of many solar energy resources in a large area, comprising many solar buildings or sites, can be modeled as aggregated output, making regional solar fluctuations in the hour-to-day time frame. Hence, the significant penetration of solar energy resources, via roof-top applications, can be modeled as load reduction for hours when there is abundant solar energy, in respective transmission zones. This assumption is valid because the focus of this paper was on analyzing the zonal/system-wide impact due to significant solar energy penetration.

Further Discussion: Overall, significant penetration of solar energy resources can bring about positive economic benefits for the power grid, especially in organized multilateral market areas. Future research should include impact of solar energy penetration on carbon replacement, and combined impact of both solar energy and demand responses.

APPENDIX A
SECURITY-CONSTRAINED UNIT COMMITMENT AND ECONOMIC DISPATCH

A. *Security-Constrained Unit Commitment*

The objective of the security-constrained unit commitment (SCUC) program is to optimize the scheduled generation and price sensitive load while satisfying generation, reserve requirements, transmission constraints, and generator operating constraints, such as minimum down time, minimum runtime, and ramp rates.

Consider generator i, where $i = 1, \ldots, N$ units in the system for a given time $t = 1, \ldots, T$, the objective function of SCUC problem can be mathematically formulated as

$$\min \sum_{i=1}^{N} \mathrm{BC}_i(P_i) + \mathrm{ST}_i + \mathrm{NL}_i + \mathrm{SD}_i \qquad \text{(A.1)}$$

where BC_i is bid curve ($/h) with bid price and generation (normally quadratic) for unit i, which is described as

$$\mathrm{BC}_i(P_i) = a_i P_i^2 + b_i P_i + c_i. \tag{A.2}$$

This objective function is subject to both equality and inequality constraints which are described later.

B. Security-Constrained Economic Dispatch

The objective of the security-constrained economic dispatch (SCED) is to find the minimum cost or bid (depending on the decision variable) for real power generation subject to various equality and inequality constraints in relation to power balance, voltage limits, and other security constraints.

Again, consider generator i, where $i = 1, \ldots, N$ units in the system for a given time $t = 1, \ldots, T$, the objective function of SCED problem can be mathematically formulated as

$$\min \sum_{i=1}^{N} \mathrm{BC}_i(P_i) \tag{A.3}$$

subject to

$$\sum_{i=1}^{N} P_i = P_D + P_L \tag{A.4}$$

$$P_i^{\min} \le P_i \le P_i^{\max} \forall i \tag{A.5}$$

$$F_l \le F_l^{\max} \forall i. \tag{A.6}$$

Equations (A.4)–(A.6) represent power balance constraint in the study system, real power limits (min, max) of each generator, and real power flow limits of each transmission line.

APPENDIX B
FORMULATION OF LMP

We assume "average loss" in the paper. Following the formulation used for SCED, we can further modify (A.4)–(A.6) by adding appropriate Lagrangian multipliers to the equality and inequality constraints as follows:

$$\min \sum_{i=1}^{N} \mathrm{BC}_i\,(P_i) \tag{A.7}$$

subject to

$$\sum_{i=1}^{N} P_i = P_D + P_L \ : \ \lambda \tag{A.8}$$

$$P_i^{\min} \le P_i \le P_i^{\max} \, \forall i \ : \ \mu \tag{A.9}$$

$$F_l \le F_l^{\max} \, \forall i \ : \ \theta. \tag{A.10}$$

Equations (A.8)–(A.10) are similar to (A.4)–(A.6), except that they are written with extra variables. These extra variables, λ, μ, and θ [30] are known as Lagrangian multipliers and represent penalty for imbalance of supply and demand, penalty for binding generator limits, and shadow prices for respective binding transmission lines. These shadow prices form the basis for congestion components of LMP, when there are congestions—binding transmission flow—in the system.

Then, LMP at each bus i in the system can be written as

$$\mathrm{LMP}_i = (1 + \mathrm{ML}_i)\,\mathrm{LM}_{ref} + \sum_{x=1}^{X} \sum_{y=1}^{Y} \mathrm{SP}_{xy}\mathrm{SF}_{xyi}. \tag{A.11}$$

This equation decomposes the locational price into the price of energy at a reference bus (LMP_{ref}), the cost of losses relative to the reference bus (ML_i * LMP_{ref}), and the cost of congestion ($\Sigma_x \Sigma_y \mathrm{SP}_{xy}\mathrm{SF}_{xyi}$).

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THE STATE OF NEW HAMPSHIRE

PUBLIC UTILITIES COMMISISON

DE 16-576

ELECTRIC DISTRIBUTION UTILITIES

Development of New Alternative Net Metering Tariffs and/or Other Regulatory Mechanisms and Tariffs for Customer-Generators

AFFIDAVIT of Jameson Brouwer, CTO of EKM Metering, Inc. In Support of City of Lebanon, NH Rebuttal Testimony

I, Jameson Brouwer of EKM Metering Inc. with a business address of 122 Benito Avenue, Santa Cruz, California 95062, do state that the following responses to the questions set forth herein are true and accurate to the best of my knowledge and belief:

1. Are you the same Jameson Brouwer who provided an affidavit in support of City of Lebanon, NH testimony in this proceeding, dated 10/24/16, and are you still employed as CTO of EKM Metering Inc.?

Yes.

2. Are the revenue grade electrical meters that EKM manufactures and sells as certified to comply with ANSI C12.1-2008 and ANSI C12.20-2010 capable of metering more than one AC circuit with a single meter with revenue grade accuracy and if so how?

Yes. EKM Metering's Omnimeter Pulse v.4 and Omnimeter Pulse v.4 UL have both been tested and certified to ANSI C12.1 and ANSI C12.20. This is a highly accurate standard and is much more accurate than is required by most utility owned meters in the United States. The combination of EKM Omnimeters with CTs are Class 0.5 (at least 99.5% accurate). Each Omnimeter can measure one or multiple circuits. When measuring multiple circuits, you can either use 1 CT around all lines on the same phase in the same direction of current flow, or multiple CTs with one CT around each line on the same phase. In these cases the meter will accurately measure the combined kWh on all circuits.

Signature: ______________________________ Date: December 19, 2016