Probabilistic Simulation Methodology for Evaluation of Renewable Resource Intermittency and Variability Impacts in Power System Operations and Planning (3.4)

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***Abstract*—We report on the development of a comprehensive, stochastic simulation approach for power systems with renewable and storage resources operating in a competitive market environment. The approach explicitly represents the uncertain and time-varying natures of the loads and supply-side resources, as well as the impacts of the transmission constraints on the hourly day-ahead markets. We adopt Monte Carlo simulation techniques to emulate the side-by-side power system and transmission-constrained hourly day-ahead market operations. The approach quantifies the power system economics, emissions and reliability variable effects. We address the implementational aspects of the methodology so as to ensure computational tractability for large-scale systems over longer periods. Applications of the approach include planning and investment studies and the formulation and analysis of policy. We illustrate the capabilities and effectiveness of the simulation approach on representative study cases on a modified *IEEE* 118-bus test system. The results provide valuable insights into the impacts of deepening penetration of wind resources.**

I. INTRODUCTION

Renewable resources, such as wind and solar, are widely viewed as clean sources of energy with virtually zero fuel costs and emissions. However, renewable resource generation outputs are highly variable, intermittent and only controllable by the operator to a limited extent. The variable/intermittent nature of the wind speeds, for example, presents major challenges in the integration of wind resources as the wind may fail to blow when the system actually needs the wind generation output [1], [2], [3]. Indeed, a frequent phenomenon in many regions with wind resources is the pronounced output of wind generation, due to the appropriate wind speeds, in the low-load hours and rather low or near zero outputs, due to the low wind speeds, during the peak-load periods. Such a misalignment of the wind generation and load patterns, coupled with the limited controllability over wind resources, implies that the full potential of grid integrated wind resources may not be realized. Moreover, there are concerns about the "spilling" of wind energy during low load conditions due to the insufficient load demand and the physical impossibility to shut down the base-loaded units for short time periods.

A basic mechanism that system operators use to manage the integrated renewable generation variability and intermittency is to increase the reserve levels [4]. Such operational tactics, typically, lead to increases in both the overall production costs and the emissions, notwithstanding the zero fuel costs and emissions of the renewable resources. It is precisely such situations that can advantageously exploit the flexibility of utility-scale storage resources to improve the utilization of the renewable resources [5]. Storage resources may be used, for instance, to store wind energy whenever produced and release it during peak-load hours so as to displace the costly energy from polluting generating units. While storage resources are highly costly investments, their effective management – charge-discharge schedule and operations – impacts considerably the total production costs since they influence the variable portion of the costs [6]. A particularly acute need is a practical simulation tool that can reproduce, with good fidelity, the expected variable effects in systems with renewable and storage resources. Such a tool has myriad applications to power system planning, operations, investment analysis, as well as policy formulation and assessment.

We report on the development of a stochastic simulation approach with the ability to take explicitly into account the market structure, the various sources of uncertainty – including the renewable resource generation output variability/intermittency –, the coordinated operation of multiple integrated storage units controlled by the independent system operator (*ISO*), and the impacts of the transmission constraints on the deliverability of the electricity to the loads in the evaluation of the expected production costs, expected emissions and reliability indices. The conventional probabilistic simulation approach, based on the load duration curve model, is unable to represent the transmission constraints, nor capture the inter-temporal effects required in the simulation of the renewable and storage resources. The representation of such features requires that the demands and resources be modeled as random-processes. Our methodology incorporates such random-process-based models and so is capable to account for the spatial and temporal correlations among the demands and among the renewable resource generation outputs at the various sites. We have developed a storage scheduler to assist with the decisions to determine the participation of each storage unit in the

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markets over time, in coordination with the demands and available supply-resources, and with the inter-temporal system operational constraints fully considered. The storage scheduler takes full advantage of arbitrage opportunities in the operations of the multiple storage units over the specified scheduling period.

The approach uses an hour as the smallest indecomposable unit of time and uses the realizations of the random processes at these discrete sub-periods. In addition, a snapshot representation of the grid is used to represent the impacts of the transmission constraints on the hourly day-ahead markets (*DAM*s). The simulation methodology – based on the deployment of Monte Carlo simulation techniques – uses systematic sampling mechanisms to compute the realizations of the various random processes and to construct the so-called *sample paths*. The procedure entails sampling the probability distributions associated with the demands and supply-side resource random processes to generate the *input* sample paths that we use to drive the emulation of the hourly *DAM* clearings. The market clearing results are obtained by determining the solution of an optimal power flow [7], [8]. We collect such market outcomes so as to construct the *output* sample paths from which we estimate the various economic, emission and reliability metrics. These metrics include the hourly expected locational marginal prices (*LMP*s), congestion rents, supply-side revenues, wholesale purchase payments, either energy charged into or discharged by storage, and the emissions, as well as the *LOLP* and *EUE*. From the hourly values, we then determine the values for the simulation periods, which are then used to determine the metric values for the study period. The methodology is able to capture the seasonal effects in loads and renewable resource generation outputs, the impacts of maintenance scheduling and the ramifications of new policy initiatives. For the performance of various policy studies, we also provide weekly unit commitment schedules that allow the user to specify the weekly reserves requirements. These features are essential in the analysis of the substitutability of conventional generation by renewable resources and storage technologies under deepening penetration levels. We have also devoted much attention to ensure the computational tractability of the tool so as to allow the simulation over longer-term periods. As such, there is a broad range of applications of the simulation methodology to planning, investment, transmission utilization and policy formulation and analysis studies for systems with integrated renewable and storage resources. A very useful feature of the tool is the ability to quantitatively assess the impacts of deepening penetration of wind and storage technologies.

The body of the paper contains four more sections. In section II, we describe the overall simulation methodology. In section III, we provide illustrative case studies to demonstrate the capabilities of the approach in the investigation of the impacts of deepening wind penetration in systems with integrated storage resources. We conclude with a summary and directions for future work in sections IV and V respectively.

II. APPROACH/METHODS

We devote this section to describe the simulation framework and approach. The simulation is performed for the specified study period, which we decompose into non-overlapping simulation periods. We define each simulation period in such a way that the system resource mix and unit commitment, the transmission grid, the operating policies, the market structure and the seasonality effects remain unchanged over its duration. For the competitive market environment, the natural choice for a simulation period is a week. This choice captures the weekly load (demand) pattern and easily incorporates the scheduled maintenance outages. We further decompose each simulation period into subperiods of an hour, with a subperiod being the smallest indecomposable unit of time represented in the simulation, as shown in Fig. 1. The simulation, as such, ignores any phenomenon whose time scale is smaller than an hour, and we assume that the value of each variable is constant over the hour. The proposed approach is, however, sufficiently general to allow higher or lower resolution if desired.

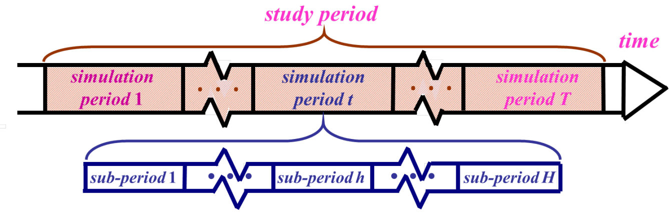

Fig. 1: Conceptual representation of the adopted time framework

To simulate the side-by-side power system and transmission-constrained market operations, we emulate, in each simulation period, the sequence of the 168 hourly *DAM* clearings to determine the hourly market outcome contributions to the performance metrics of interest. We use the hourly discretized time axis in the representation of the variables and evaluate the metrics on an hourly basis. The modeling of the uncertainty in the highly variable demands, renewable resource outputs, conventional generator available capacities and, as a consequence of the market economics, storage resource outputs/demands, is in terms of discrete-time random processes (*r.p.*s), which in this work, are collections of random variables (*r.v.*s) indexed by the 168 hours of the simulation period. These *input r.p.*s are mapped by the *DAM* clearing mechanism into the *output* discrete-time *r.p.*s, as illustrated in Fig. 2. Such output *r.p.*s, whose collections of *r.v.*s are also indexed by the 168 hours of the simulation period, represent the market outcomes. We call a *sample path* (*s.p.*) a collection of time-indexed realizations of the *r.v.*s that define the *r.p* [9]. We note that a *s.p.* intrisically captures the auto-regressive time-series structure of the *r.p.*.

Our simulation uses the so-called *independent Monte Carlo* technique [10], and requires the construction of multiple *independent and identically distributed* (*i.i.d.*) *s.p.*s for each output *r.p.* to estimate the performance metrics [1]. Each simulation

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[1] Note that in this context, the phrase "*i.i.d. s.p.*s" has the sense that the *s.p.*s constitute the realizations of independent identically distributed *r.p.*s

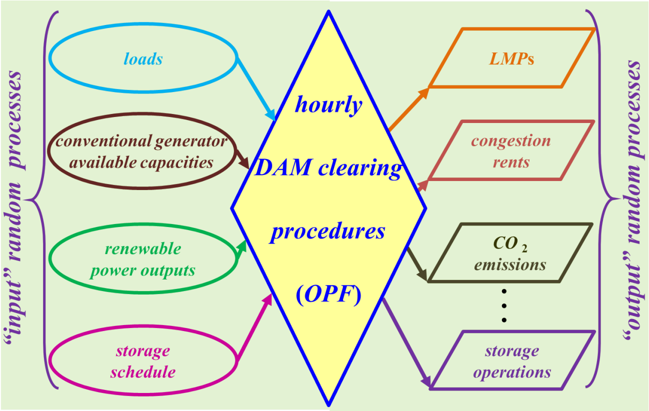

Fig. 2: Conceptual structure of the simulation approach

run constructs a *s.p.* for each output *r.p.*s. The construction proceeds as follows: sample paths of the input *r.p.*s, obtained by sampling the input *r.p.* joint cumulative distribution functions (*j.c.d.f.*s), are mapped into *s.p.*s of the output *r.p.*s by the market clearing mechanism model [7], [8] for each hourly *DAM*. The hourly market outcomes of interest include the locational marginal prices (*LMPs*), the total wholesale purchase payments, the total supply-side revenues, the total congestion rents, CO_2 emissions, the loss-of-load events and associated unserved energy.

We carry out multiple simulation runs in order to create the output *s.p.*s from which we estimate our performance metrics. We select our performance metrics to be the expected values of the time-indexed *r.v.*s whose collection is the output *r.p.* of interest. In practice, we make use of the collected *i.i.d.* *s.p.*s to estimate, for a given output *r.p.*, the sample mean point estimate of each constituent, time-indexed *r.v.*. The number of simulation runs is chosen to ensure that the estimation of a given expected value falls within a pre-specified confidence level interval [11].

We briefly discuss the stochastic models for the input *r.p.*s and their use in the Monte Carlo simulation in the following order: demands, renewable resource generation outputs, conventional generator available capacities and storage outputs/demands. Note that we make the widely-used assumption that the stochastic models for the demands, renewable outputs and conventional generator available capacities are statistically independent of each other. Storage on the other hand, is highly dependent on the loads and other supply-resources.

From the outset, we wish to capture the spatial and temporal correlations among the various buyer demands. Now, given that the cleared demands, as observed from historical load data, are seasonal and have a weekly cycle, we assume that, in each week of the same season, the buyer demands over a week period can be modeled by a discrete-time *r.p.*, whose random vectors of buyer demands are indexed by the 168 hours of the week. Such representation explicitly accounts for the correlations across buyer and time that exist among the constituent *r.v.*s that correspond to the hourly demands of each buyer over a one-week duration. We construct the *j.c.d.f.* of the hourly buyer demand *r.p.* by gathering weeks of hourly buyer demands from a seasonally disaggregated historical database. In terms of the Monte Carlo method, such *j.c.d.f.* may be directly sampled to yield a *s.p.* whose collection of hourly realizations determines the maximum demand bid by each buyer in the associated hourly *DAM*s.

We apply a similar approach to the stochastic modeling of the multi-site renewable resource generation outputs. The following method is well adapted to the modeling of multi-site wind or solar power outputs for example. To make the explication of the model concrete, we limit our discussion to the treatment of the *r.p.*s used to model the wind speeds/power outputs. We assume that each wind speed at each farm location is uniform for the entire farm. Furthermore, we assume that the wind speeds are seasonal and have a daily cycle. In a similar manner as with the hourly buyer demands, we seek to capture the spatial and temporal correlations of the wind speed *r.v.*s across locations and hours of the day. Thus, we represent the multi-site hourly wind speeds by a discrete-time *r.p.*, whose random vectors of wind farm wind speeds are indexed by the 24 hours of the day. The construction of such a discrete-time *r.p.* closely follows that of the hourly buyer demand *r.p.*. In the specific case of the multi-site hourly wind speed *r.p.* however, we need to generate 7 daily *s.p.*s in order to construct the *s.p.* for the 7×24 hours in a week. This may done by sampling and juxtaposing 7 independent *s.p.*s from the *j.c.d.f.* of the multi-site wind speed *r.p.*. The result is a week-long wind speed *s.p.* that is then converted into the corresponding wind power output *s.p.* via the use of wind farm characteristic power curves [12]. The collection of hourly wind power output realizations contained in the week-long sample path is used to determine the wind power output quantities offered in the associated hourly *DAM*s.

We model each conventional resource as a multi-state unit with two or more states – outaged, various partially derated capacities and full capacity. We assume that each conventional resource is statistically independent of any other generation resource. We use a Markov chain model with the appropriate set of states and transition intensities to represent the underlying *r.p.* governing the available capacity of each conventional resource [13]. We assume statistically independent exponentially-distributed *r.v.*s. to represent the transition times between the states. Such model allows us to explicitly represent the periods during which a conventional unit might be up, down, or running at derated capacities in the simulation. The methodology for simulating the available capacity of a conventional resource over time is well documented in the literature, and can be found under the names of *next-event method* [14], *state duration sampling* [15], or simply *sequential simulation* [16], [17]. In terms of our approach, the state of a seller resource, i.e., its available capacity, is thus determined for each hour of the week. The collection of hourly realizations constitutes a week-long *s.p.* of a seller resource available capacity. We use the hourly realizations of such a *s.p.* to determine the resource maximum output quantity offered in the associated hourly *DAM*s.

The characterization of the storage unit participations in the hourly *DAM*s is a function of the demands and supply-side resources. As such, the analytical description of the associated *r.p.* is quite involved. The construction of associated *s.p.*s is, however, quite manageable. To this end, we have developped a storage scheduler to determine how each storage unit should behave in the hourly *DAM*s of a given scheduling period. Since the storage units are assumed to be controlled by the *ISO*, the objective of the storage scheduler is to maximize the sum of the hourly social surpluses as determined by the outcomes of the hourly *DAM*s. The storage scheduler solves a "look-ahead" multi-period *OPF* that uses plausible realizations of the buyer demands and supply-side resource available capacities in each hour of the scheduling period to "optimally" coordinate the storage unit operations. The inter-hour constraints imposed by storage dynamics are explicitly represented so as to produce schedules that are chronologically consistent. The generated schedules consist of the hourly status of each storage unit (discharge, charge, idle) as well as the associated charged/discharged energy. They provide the appropriate information for the emulation of the hourly *DAM*s. We view a storage schedule as the basis for creating a *s.p.* associated with the storage unit participations in the hourly *DAM*s. As such, a storage schedule forms the input *s.p.* that is used to determine the storage unit maximum outputs offered/maximum demands bid in the hourly *DAM*s.

To be of practical value, we focused on the implementational aspects of the simulation approach so as to improve its computational tractability. A first step is the judicious selection of the number of simulation periods to be simulated. We take advantage of the fact that several weeks in a season have similar load (demand) shapes and renewable generation output patterns. We select a representative week among them for simulation and weigh the results by the number of weeks it represents. This way, we reduce the number of simulation periods and cut down the computational efforts. Our extensive testing indicates that, for regions with four distinct seasons, 14-18 representative weeks suffice to cover a year.

Another measure to reduce the computational burden is to systematically "warm-start" the storage scheduler runs and the market clearing optimizations.

We also have studied in depth a wide range of *variance reduction techniques*. Our findings indicate that only the control variate technique [18] is effective in bringing about significant variance reduction. The use of the hourly aggregated available generation capacity, i.e., the sum of conventional resource and renewable available capacities, as a control variate in each hour h of the simulation period can reduce computations by 50% for some of the metrics, particularly for the economic ones. However, the control variate scheme performs poorly in the evaluation of the reliability indices due to the weak correlation observed in practice between the control variate and the hourly total unserved energy.

A further step to improve the computational tractability is the parallelization of the simulation of each representative week on dedicated cores/computers. Parallelization of the simulation runs themselves – within the Monte Carlo simulation of each representative week – is in theory achievable achievable, since all simulation runs are independent from one another (in the sense of *independent Monte Carlo* as defined in II).

III. SIMULATION RESULTS

We performed extensive testing of the simulation approach and illustrate its application with two representative studies carried out on a modified *IEEE* 118-bus test system [19] using scaled *ISO* load data for the year 2007 [20] and historical wind data from the *ISO* geographic footprint [1]. In these case studies, we scale the load data so that the annual peak load is 8,300 *MW*. The 99 conventional generation units of the test system have a total nameplate capacity of 9,914 *MW*. The system incorporates 4 wind farms, whose wind turbine characteristics, including power curves, are collected from *NREL* wind integration studies [1]. The aggregated nameplate capacity of wind power amounts to 2,720MW (unless otherwise specified), about 30% of the annual peak load, and is equally distributed among the 4 wind farms. We assume that each buyer bids his/her load as a *fixed* demand in each hourly *DAM*s. We use the estimated marginal costs of the generating units as offering prices throughout the simulations. Owing to the fact that wind power has no fuel cost, we assume that wind power is offered at 0 *$/MWh*. We limit our analysis to a single year in order to gain insights into the nature of the results obtained. Taking into account the seasonality effects, as well as the maintenance schedules of the conventional generation units, we select 16 representative weeks out of the 52 weeks of the year. We perform a unit commitment for every one of the 16 representative weeks so as to maintain the desired reserve margins (15% of weekly peak load unless otherwise specified). For the test system, our extensive numerical studies indicate that beyond 100 simulation runs, there is too little improvement in the statistical accuracy of the economic and emission metrics to warrant the extra computing-time needed for the execution of additional simulation runs. The computation of the reliability metrics, however, required about 500 simulation runs, owing to the fact that our test system is relatively reliable and the loss of load events constitute rare occurences.

In the first case study, we examine the power system behavior under deepening wind penetration: from 0 *MW* total nameplate capacity in the base case to 2,720 *MW*, using increments of 680 *MW*. Each case is evaluated with and without storage resources. In the no storage cases, the supply-side resources consist only of the 99 conventional generation units and the 4 wind farms with the 15% reserves margin provided solely by the conventional units. In the storage cases, the system has a single storage unit with 400 *MW* capacity, 5,000 *MWh* storage capability and a round-trip efficiency of 0.89. The 15% reserves margin is met by both the conventional units *and* the storage unit. As the wind penetration deepens, the overall wholesale purchase payments and CO_2 emissions are reduced, while there are rather marked improvements in the system reliability indices, as shown in Fig. 3 and Fig. 4 respectively.

However, it is also clear from these plots that the reductions and improvements are characterized by diminishing returns as the wind penetration deepens. Results show that such phenomenon may be partially offset with the integration of the storage unit. Overall, storage works in synergy with wind to

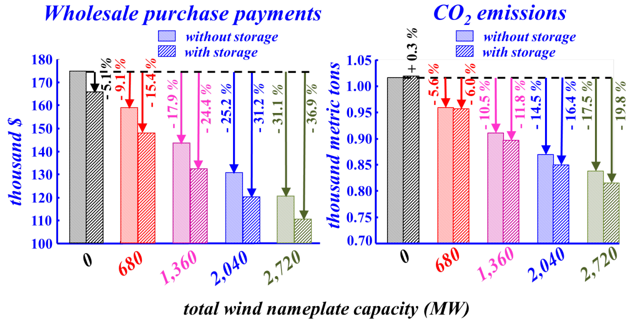

Fig. 3: Expected hourly total wholesale purchase payments (left) and CO_2 emissions (right)

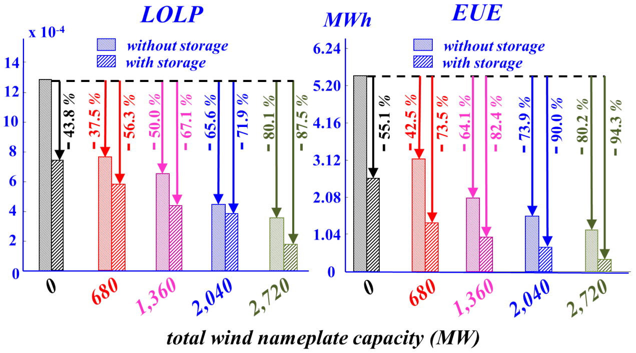

Fig. 4: Annual reliability metrics

drive further down wholesale purchase payments and improve system reliability. On the other hand, CO_2 emissions are not significantly affected by the integration of a storage unit. We attribute this result to the fact that CO_2 emissions largely depend on the relative utilization of the various fossil-fuel fired units. In a system where the nameplate wind capacity does not exceed the system base load, the storage unit draws its energy from base-loaded fossil-fuel fired units. Its impact on CO_2 emissions are due to the differences in the emission rates of the base-loaded fossil-fuel fired units from which it charges, versus those of the peaking units that it displaces upon discharge. In our system, the base-loaded units tend to be slightly more polluting than their peaking counter-parts, hence the slight increase in CO_2 emissions seen in the absence of the wind resources. As wind penetration levels increase, however, the relative utilization of the fossil-fuel fired units differs due to the higher prevalence of wind variable outputs.

In the second case study, we investigate to what extent a combination of wind and storage resources may substitute for conventional resources from purely a system reliability perspective. The base case with no wind and storage resources evaluates the system *LOLP* and *EUE* for a 15% system reserves margin. In all the other cases, the conventional resource mix is supplemented by the 4 wind farms with a total nameplate capacity of 2,720 *MW* and 4 identical storage units, each with 100 *MW* capacity, 1,000 *MWh* storage capability and 0.89 round-trip efficiency. In these cases, the reserves are provided by the conventional *and* storage resources and we examine the impacts of progressively retiring some conventional resources, thus decreasing reserves margin levels.

Figure 5 shows the $LOLP$ and EUE as a function of the system reserves margin levels (the studies here have been carried out for one particular representative week).

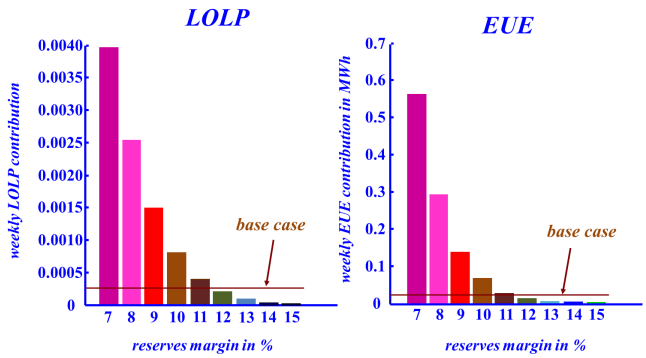

Fig. 5: Weekly *LOLP* and *EUE* versus system reserves margins

The simulation results indicate that the 2,720 *MW* of installed wind capacity – about 30% of the peak load (8,090 *MW*) – can substitute for about 300 *MW* of retired conventional generation capacity – about 3.7% of peak load. Absent storage units, with all other conditions unchanged, the 2,720 *MW* wind can replace only about 220 *MW* of retired conventional generation capacity – about 2.7% of peak load. While the wind resources by themselves prove to be poor substitutes for retired conventional resources from a reliability perspective, the integration of the 400 *MW* of total storage capacity – about 4.8% of peak load – increases the wind resource capability to substitute for conventional resources by an additional 1% of the peak load. This result indicates that wind and storage resources can work synergystically.

IV. CONCLUSION

In this paper, we present the comprehensive, stochastic simulation framework we developed to emulate the side-by-side behavior of power system and market operations over longer-term periods. Our approach makes detailed use of discrete-time *r.p.*s in the adaptation of Monte Carlo simulation techniques. As such, the framework can explicitly represent various sources of uncertainty in the loads, the available capacity of conventional generation resources and the time-varying, intermittent renewable resources, with their temporal and spatial correlations. In addition, the simulation methodology represents the impacts of the network constraints on the market outcomes. In this way, the simulation approach is able to quantify the impacts of integrated intermittent and storage resources on power system economics, reliability and emissions. The stochastic simulation approach has a broad range of applications in planning, operational analysis, investment evaluation, policy formulation and analysis and to provide quantitative assessments of various what if case studies.

The representative results we present from the extensive studies performed effectively demonstrate the strong capabilities of the simulation approach. The results of these studies on a modified *IEEE* 118-bus system, making use of scaled *ISO* load data and historical wind data in the *ISO* geographic footprint clearly indicate that energy storage and wind resources tend to complement each other and the symbiotic effects reduce wholesale costs and improve system reliability. In addition, we observe that emission impacts with energy storage depend on the resource mix characteristics. An important finding is that storage seems to attenuate the ”diminishing returns” associated with increased penetration of wind generation. The integration of storage capacity can also enhance, to some limited extent, the wind resource poor capability to substitute for conventional resources from purely a system reliability perspective.

The development of the approach provides a practical implement for the simulation of large-scale power systems with integrated renewable and storage resources. As the deepening penetration of renewable resources becomes reality, the interest in exploiting the flexibility afforded by utility-scale storage resources increases. Such developments create myriad opportunities for the effective deployment of the stochastic simulation methodology to provide the quantitative answers to a broad array of questions that need to be answered in the planning, operations and analysis of the integration of these resource additions. The ability to provide the needed answers will be further testimony of the valuable contribution brought about by the developed simulation methodology.

V. FUTURE WORK

The generality of the framework serves as a useful basis for the simulation of the integration of other time-varying and intermittent renewable resources as they become more economic. Examples include concentrated solar plants, tidal power projects and offshore wind farms. In addition, the deeper study of symbiotic interactions between demand response and renewable resources needs to be investigated. The deeper penetration of renewable resources gives rise to critical operational problems that need to be addressed. One such problem is the additional impacts of the variable energy resources on the utilization of the conventional units. In particular, ramping capability requirements in the grid becomes a major issue. The simulation methodology may be extended to provide useful insights into the systematic specification of such requirements. Efforts on this topic will be of considerable interest to industry and will be reported in future papers.

VI. ACCESS TO PRODUCTS

The developed methodology and the implementation software will be available on the website of George Gross (http://energy.ece.illinois.edu/GROSS). Also, on that website relevant publications and theses are available for downloading.

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