An Insurance Contract to Boost Storage Participation in the Electricity Market in the Presence of Renewable Generation

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Abstract

Energy storage technologies are key to improving grid flexibility in the presence of increasing amounts of intermittent renewable generation. We propose an insurance contract that suitably compensates energy storage systems for providing flexibility. Such a contract provides a wider range of market opportunities for such systems while also incentivizing higher renewable penetration in the grid. Specifically, we consider a two-settlement day-ahead electricity market in which generators, including renewable producers and storage owners, bid to be scheduled for the next operating day. Due to production uncertainty, renewable generators might be unable to meet their day-ahead production schedule, and thus are subject to pay a penalty for shortages. As a hedge against these penalties, we propose an insurance contract between a renewable producer and a storage owner, in which the storage reserves some energy to be used in case of renewable shortfalls. We show that such a contract incentivizes the renewable player to bid higher, thus increasing renewable participation in the electricity mix. At the same time, it provides an extra source of revenue for storage owners that may not be profitable with a purely arbitrage based strategy in the day-ahead market. Further, we prove this contract is economically beneficial for both players. We validate our analysis through two case studies.

Keywords: Energy storage, renewables, day-ahead market

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1. Introduction

The declining costs of storage technologies have motivated numerous studies regarding their usefulness to enhance grid flexibility. In particular, the fast ramp capability of these energy sources make them an ideal candidate to improve system reliability as renewable penetration in the electricity grid increases [1]. As storage technology has improved, electricity markets have started to adapt their regulations to allow these energy sources to participate in the market. More such changes will follow the U.S. Federal Energy Regulatory Commission Rule 841 [2], which requires Regional Transmission Organizations (RTOs) and Independent System Operators (ISOs) to recognize the physical and operational characteristics of electric storage resources to facilitate their participation in the RTO/ISO markets.

In recent years, the most cost-effective entry point for storage operators in the electricity market has been to provide services in the ancillary market, such as frequency regulation [3]. However, this market is relatively small as compared to those that cover other grid services, and initial results where they can generate money (say by meeting the duck curve related supply shortfall) have began to appear. In California alone, a total of 13GW of peaking capacity provided by conventional generators is expected to retire within the next two decades. This capacity is a substantially larger amount than the frequency regulation market in the entire United States, estimated at 5GW [4]. Therefore, peaking capacity represents a large potential market for storage operators. However, at current storage prices, arbitrage to provide energy in the day-ahead markets based on mechanisms such as time of usage prices are rarely cost-effective [5]. It is of great interest to identify a market mechanism in which storage operators can be compensated for their provision of flexibility rather than merely arbitrage to provide energy. Such a mechanism will have two benefits. One, by providing extra revenue to storage owners, it will boost investments into storage technology even further. Two, as storage becomes more economical, it will lead to a higher penetration of intermittent renewable energies into the grid, while ensuring reliability of electricity supply. Note that recent adaptation of market regulations for the participation of energy storage has followed the changes in how intermittent renewable producers can offer their energy.

In this paper, we focus on a stylized model of a two settlement day-ahead market, in which energy suppliers (conventional generators, renewable generators, and storage operators) offer their production for delivery in the next operating day. The production schedule is settled by an ISO, which uses a least-cost strategy to dispatch the generators so that the overall supply meets the demand at the lowest cost possible. Generators that deviate their actual production from their schedule are penalized, and thus there is an incentive to follow this schedule. These policies have traditionally been imposed for non-renewable, firm generators; however, the adoption of the same treatment for intermittent renewable generators has also started recently as grids move away from a take-all-renewables approach in order to cut down on the increasing need for system-level reserves [6]. However, levying of such penalties leads to renewables bidding conservatively in the market [7]. We consider a scenario in which renewables are treated as conventional generators (i.e. they bid in the day-ahead market and are charged penalties for deviation) and propose a mechanism on the lines of an insurance contract with sources of flexibility such as storage that can counteract such undesirable decrease in renewable participation.

This insurance contract can be viewed as lying between the two extremes of the ISO incurring the increasing cost of system reserves in a grid takes all renewable scenario and the renewable incurring the entire cost of its intermittency and hence bidding conservatively. In practice, there is already a move towards asking the renewable power producers to shoulder (some) of the responsibility of hedging against their own production variability. As an example, the Bonneville Power Administration (BPA) has a self-supply program in cooperation with Iberdrola Renewables, in which variable energy resources are allowed to supply their own balancing services in lieu of incurring the cost of the services provided by BPA [8]. The mechanism we propose is a step towards putting such ad hoc arrangements on a firmer analytical footing.

1.1. Main Contribution

Our main contribution is the design and analysis of an insurance contract between a storage owner and a renewable producer. We consider a two settlement day-ahead (DA) electricity market, in which all generators (including renewables and storage units) bid to be scheduled to produce in the next operating day. In real-time, all excess renewable energy is curtailed and any shortfalls are penalized in a ex-post imbalance resolution mechanism. We propose that as a hedge against production uncertainty and intermittence, the renewable producer be allowed to establish an insurance contract with a storage owner. Through this contract, the storage owner commits to reserve some amount of energy to be used in case of renewable shortage, while the renewable producer purchases the right to call upon this energy reserve in case of underproduction. In this framework, the storage unit (seller) sets a lower bound on the per unit price of reserve being offered, and the renewable generator (buyer) establishes an upper bound for that price. The insurance contract is only feasible when there exists at least one reserve price for which both participants voluntarily agree to sign the contract.

The chief technical difficulty in the analysis is from the fact that the decisions made by the participants for the contract and in the day-ahead market are coupled while the decisions of the storage owner are also coupled temporally since before discharging, it needs to be charged. We focus on a scenario in which the storage adopts an arbitrage policy, which is the one that would be used in a peaking capacity service, to show that insurance contracts are feasible and that no participant is worse off by signing them. Provision of additional means of charging the storage (e.g. through a local solar panel) can only benefit both the participants. We show that the presence of an insurance contract incentivizes the renewable producer to bid higher in the day-ahead market, leading to an increase in the amount of renewable energy taken by the grid. We also derive a condition for which a storage unit is profitable as an insurance provider, even if it is not profitable in the day-ahead market. Combined, these results prove that the insurance contract proposed is an opportunity to boost the participation of storage in the market, while increasing the amount of renewable energy in the electricity mix. Our case studies validate the benefits of an insurance contract by exploring both a single-node scenario, in which there is no network congestion, and a modified IEEE 14-bus power system case with constrained transmission capacity.

1.2. Related Work

Recent works have characterized the marginal value of storage both when operated by a wind power plant [9] and by a system operator in a power network [10]. Our approach differs from these studies in the ownership of the energy sources analyzed. To the best of our knowledge, there are no works which consider the possibility of establishing contracts between renewables and storage owners to mitigate renewable intermittence, in which each player makes their decision individually. A related stream of work analyzes how storage can optimally bid in the electricity market as an independent asset, taking advantage of arbitrage opportunities [11, 12, 13]. In this paper, we expand the day-ahead arbitrage opportunities by allowing the storage unit to sign a contract with a renewable generator instead of offering that in the market at times with peaking demand.

Studies regarding the simultaneous participation of storage in multiple services, such as energy, ancillary services, and virtual bidding, are numerous and we refer the reader to [14, 15, 16] and the references therein for a representative survey. Although exploring all these market services brings the benefit of a full overview about the revenue potential for energy storage, it comes at the expense of tractability. The models formulated in these types of work generally have numerous parameters and are solved numerically, which may lead to a lack of insights about the drivers of the results achieved. Because one of our goals is to perform analytic studies about the adoption of our insurance contract, our model considers only the day-ahead energy market. A similar approach has been used in [17], in which the authors also analyze the adoption of cap contracts by energy storage systems as a hedge against price volatility. This model choice is also grounded on the fact that other markets, such as frequency regulation, are relatively small as compared to the day-ahead market and may start to saturate as more energy storage systems enter the market. For instance, there are more storage projects entering the PJM Interconnection's queue, although there is operational evidence that their RegD market has become saturated [18]. Therefore, as the market will need to absorb that new capacity, we envision that more storage units will focus on the day-ahead market in the future.

Several other works have analyzed the problems of optimal placement of energy storage in the grid and optimal sizing of these systems [19, 20, 21, 22]. While we do not specifically consider the placement problem, we evaluate how this aspect plays a role in the adoption of our insurance contract through a case study in which the location of the storage in the power grid is varied.

1.3. Paper Organization

The remainder of this paper is organized as follows. Section 2 introduces the mathematical model. The problem is formulated in Section 3, in which the utility functions of the participants are presented and the characteristics required of the insurance contract are defined. In Section 4, we derive expressions for the bidding strategies of the participants in the day-ahead market, as well as their conditions to sign the contract, which are then used to prove the feasibility of the insurance contract and to analyze the profitability of the storage owner. Section 5 presents our case studies, which are followed by final conclusions and some directions for future work in Section 6.

2. Supply and Electricity Market Models

2.1. Energy Storage Model

Consider a day divided into N discrete time slots indexed by $k \in \mathcal{K} := \{0, 1, ..., N-1\}$. The state of charge of the storage x_k is the amount of energy stored at the beginning of the time slot k. For the perfectly efficient energy storage considered, the state of charge follows the dynamics

$$x_{k+1} = x_k - u_k \ \forall k \in \mathcal{K}, \tag{1}$$

where u_k is the amount of energy extracted or injected in the storage, which is positive (resp. negative) when the storage is discharging (resp. charging). The input u_k can be denoted as the difference between the charged quantity $u_k^- \geq 0$ and the discharged quantity $u_k^+ \geq 0$ at time k. Therefore, the storage dynamics can be rewritten as

$$x_{k+1} = x_k - u_k^+ + u_k^- \ \forall k \in \mathcal{K}. \tag{2}$$

Given a finite energy capacity $\overline{E}$ for the storage, the state and inputs are constrained by

$$0 \leq x_k \leq \overline{E} \ \forall k \in \mathcal{K} \tag{3}$$

$$u_k^+ u_k^- = 0 \ \forall k \in \mathcal{K} \tag{4}$$

$$u_k^+, u_k^- \geq 0 \ \forall k \in \mathcal{K}. \tag{5}$$

The constraint (3) sets the bounds on the amount of energy that can be stored in the storage unit, (4) is a complementarity constraint which prevents the storage from charging and discharging simultaneously, and (5) is a positivity constraint. For simplicity, we do not initially consider the power constraint of this storage unit, which restricts the ramp rates of this energy source. However, such constraint is incorporated in the battery model of our case study in Section 5.2.

We point out that, although we consider a perfectly efficient storage unit, the problem can be generalized to include parameters relative to energy loss and efficiency. As shown in [23], if the complementarity constraint (4) holds, the storage dynamics can be described by the difference equation

$$x_{k+1} = \alpha x_k - \frac{1}{\eta^+} u_k^+ + \eta^- u_k^- \quad \forall k \in \mathcal{K}, \tag{6}$$

where $\alpha \in (0, 1]$, $\eta^+ \in (0, 1]$ and $\eta^- \in (0, 1]$ are the leakage coefficient, discharging efficiency, and charging efficiency, respectively. In Section 4.2, we will derive conditions for which constraint (4) is satisfied. Further, the efficiency and leakage parameters are also incorporated in the storage model in the case study in Section 5.2.

Using the storage dynamics (2) and writing (3) recursively, we can write the energy constraint in the compact form

$$\mathbf{0} \leq \mathbf{A}^+\mathbf{u}^+ + \mathbf{A}^-\mathbf{u}^- \leq \overline{\mathbf{E}}, \tag{7}$$

where $\mathbf{A}^+ \in \mathbb{R}^{N\times N}$ and $\mathbf{A}^- \in \mathbb{R}^{N\times N}$ are triangular matrices with $A^+_{ij} = -1$ and $A^-_{ij} = 1$ for all $i \geq j$, and the column vectors $\mathbf{u}^+ \in \mathbb{R}^N$ and $\mathbf{u}^- \in \mathbb{R}^N$ are defined as $\mathbf{u}^+ = [u^+_0, ..., u^+_{N-1}]^T$ and $\mathbf{u}^- = [u^-_0, ..., u^-_{N-1}]^T$. Further, $\mathbf{0}$ is the null column vector of size N, and $\overline{\mathbf{E}} = \overline{E}\mathbf{1}^\mathbf{T}$, where $\mathbf{1}^\mathbf{T} \in \mathbb{R}^N$ is the all-ones column vector. Let $\mathcal{U}$ denote the set of all pairs $(\mathbf{u}^+, \mathbf{u}^-)$ that satisfy the storage constraints (2) – (5). A storage policy $(\mathbf{u}^+, \mathbf{u}^-)$ is said to be feasible if $(\mathbf{u}^+, \mathbf{u}^-) \in \mathcal{U}$.

2.2. Renewable Production Model

The renewable production is modeled as a discrete-time random process defined by $R = \{R_0, ..., R_{N-1}\}$. For each time slot k, the random variable R_k has a continuous and twice differentiable probability density function $f_k(r_k)$ and cumulative density function $F_k(r_k)$. For simplicity, the random variables $\{R_k\}$ are assumed to be mutually independent.

2.3. Electricity Market Model

We model a day-ahead (DA) market that is operated by an independent system operator (ISO) who is responsible for meeting the load reliably. In this market, all generators bid the amount of energy they are willing to commit for delivery in the next operating day. Each player also informs the ISO of their asking price, which is the minimum price per unit of energy they are willing to accept in order to deliver the amount committed. The ISO clears the market by scheduling the generators in a least-cost fashion that prioritizes the least expensive generators so that the supply meets the demand and the customer pays the lowest possible energy price. In real-time, an imbalance resolution mechanism penalizes the generators that do not supply the amount of energy that they were cleared for.

In this work, we will focus on the bidding strategies of a renewable power producer and a energy storage system, which are modeled as in Sections 2.1

and 2.2. The network structure considered has unconstrained transmission capacity, and thus all generators are paid a single market price. With this assumption, we ignore transmission line congestion and the emergence of locational marginal prices (LMPs) in the system nodes. The analysis of possible impacts of network congestion in the decisions of the generators is left as a direction for future work, as the incorporation of such constraints would require a more detailed mathematical model. However, although we do not address this problem in our theoretical analysis, we perform a case study in a congested network in Section 5.2.

Because the DA market is typically composed of a large number of players, each individual generator is considered small relative to the whole market. Therefore, we assume that the generators cannot exercise market power and the market is competitive. With that assumption, the generators are price takers. Further, the DA energy price vector over the entire day $\lambda \triangleq [\lambda_0, ..., \lambda_{N-1}]^T$ is assumed to be fixed and known. Finally, we assume the load to be known. All these assumptions simplify the analysis and allow us to focus on the insurance contract being proposed.

Given that the renewable production is stochastic, in real time, this producer may be unable to meet his commitments. We assume that all renewable production exceeding the commitment is curtailed. If the renewable production is below its commitment, it pays a penalty per unit of shortfall at price $\lambda_p > \max(\lambda)$ that is fixed and known. The curtailment assumption is supported by the existing no-compensation trend observed in markets with high wind penetration. The penalty λ_p may refer to the price asked by a peaker plant that is called in to compensate the shortfall.

3. Problem Formulation

We are interested in designing and analyzing an insurance contract between a renewable producer and a storage owner. We first introduce the utility functions of each participant and then define the problem to be solved.

3.1. Utility Functions

The utility function of each participant is his expected profit.

3.1.1. Baseline case

In this scenario, both the renewable and the storage participants only bid in the day-ahead market and insurance contracts are not allowed between them. The expected profit of the renewable producer is

$$J_r^b(\mathbf{C_r}) = \sum_{k=0}^{N-1} \lambda_k C_{rk} - E_{Rk}\left[I(C_{rk}-R_k)\lambda_p(C_{rk}-R_k)\right], \tag{8}$$

where $\mathbf{C_r} = [C_{r0}, ..., C_{r(N-1)}]^T \in \mathbb{R}^N$ is the vector containing the commitments for each time slot k. For each k, the first term of the expected profit corresponds to the revenue acquired for committing to the day-ahead market and the second term is the expected penalty due to shortage.

For the storage owner, the baseline utility function is

$$J_s^b(\mathbf{u}^+, \mathbf{u}^-) = \sum_{k=0}^{N-1} \lambda_k(u_k^+ - u_k^-) - g(u_k^+, u_k^-), \tag{9}$$

where, for each k, the first term is the revenue for supplying to and cost for demanding from the market, while the second term is a cost function related to the operation of the storage. This operational cost function $g(u_k^+, u_k^-)$ is assumed to be convex and strictly increasing in the decision variables (u_k^+, u_k^-).

3.1.2. Insurance contract case

In this case, the storage and the renewable players are allowed to establish an insurance contract for reserve. In the contract, the storage supplies some amount of energy to the renewable producer in case of shortage, instead of offering this energy in the day-ahead market. The expected profit of the renewable producer in this scenario becomes

$$\begin{aligned} J_r^c(\mathbf{C_r}, \mathbf{G_r}, \pi_\mathbf{r}) = &\sum_{k=0}^{N-1} \lambda_k C_{rk} - \pi_{rk} G_{rk} \\ &- E_{Rk}\left[I(C_{rk}-R_k-G_{rk})\lambda_p(C_{rk}-R_k-G_{rk})\right], \end{aligned} \tag{10}$$

where the vectors $\mathbf{G_r} = [G_{r0}, ..., G_{r(N-1)}]^T \in \mathbb{R}^N$ and $\pi_\mathbf{r} = [\pi_{r0}, ..., \pi_{r(N-1)}]^T \in \mathbb{R}^N$ contain the reserve amounts and the (per unit) prices for each time k. As compared to the baseline case, the renewable producer has the additional cost of the contract, and the reserve amount helps decrease the expected penalty. For the storage unit, the expected profit is

$$J_s^c(\mathbf{u}^+, \mathbf{u}^-, \pi_\mathbf{s}) = \sum_{k=0}^{N-1} \pi_{sk} u_k^+ - \lambda_k u_k^- - E_{Rk}\left[g(\min(C_{rk}-R_k, u_k^+), u_k^-)\right], \tag{11}$$

where $\pi_{\mathbf{s}} = [\pi_{s0}, ..., \pi_{s(N-1)}]^T \in \mathbb{R}^N$ is the per unit of reserve price vector. The last term is the expected operational cost, which shows that the amount supplied by the storage is the lesser of the renewable shortage and the reserve in the contract. In this problem set-up, we consider that the storage is supplying energy exclusively to the renewable player and charging from the grid.

Note that the participants decide individually which reserve price they are willing to pay or accept, as well as the amount of energy in the reserve procured or offered. For that reason, each source has his own price and reserve vectors. However, if an agreement is reached, these vectors will be the same and equal to the values established in the insurance contract.

3.2. Contract Design Problem

Through an insurance contract, the storage unit commits to maintaining some energy reserve available to be used in case of renewable shortage. The contract is signed ex-ante, while in real-time, the storage is called upon to supply this reserve in case of renewable shortage. If the shortage is less than the reserve established in the contract, the storage unit will supply only the amount needed to cover the shortfall; if the reserve is not enough to cover the shortage completely, the storage supplies the entire reserve and the renewable producer is responsible for paying the penalty corresponding to the shortage remaining. An insurance contract $\mathcal{C}$ is defined as the pair $\{\pi, \mathbf{G}\}$ that establishes the price per unit $\pi = [\pi_0, ..., \pi_{N-1}]^T \in \mathbb{R}^N$ and amount of energy $\mathbf{G} = [G_0, ..., G_{N-1}]^T \in \mathbb{R}^N$ to be set aside as a reserve by the storage at each time k. We say that a contract $\mathcal{C}$

- is individual rational if no participant is worse off by signing the contract, i.e. their expected profit does not decrease in the presence of the contract;
- is feasible if it induces a storage policy $(\mathbf{u}^+, \mathbf{u}^-) \in \mathcal{U}$ and is individual rational.

The renewable producer tries to maximize his own expected profit when deciding how much to bid in the day-ahead market and how much reserve to purchase through an insurance contract with the storage unit. These two decisions are made sequentially, as the contract is signed ex-ante. Then, in the day-ahead market, the renewable producer solves

$$\mathcal{P}_1 : \max_{\mathbf{C_r} \geq \mathbf{0}} \; J_r^c(\mathbf{C_r}, \mathbf{G_r}, \pi_{\mathbf{r}}), \tag{12}$$

where $\mathbf{G_r}$ and $\pi_\mathbf{r}$ are treated as given. For the insurance contract, the problem to be solved is

$$\mathcal{P}_2 : \max_{\mathbf{G_r}, \pi_\mathbf{r} \geq \mathbf{0}} \; J_r^c(\mathbf{C_r^*}, \mathbf{G_r}, \pi_\mathbf{r}), \tag{13}$$

where $\mathbf{C_r^*}$ solves $\mathcal{P}_1$. Similarly, for the storage unit, the maximization problem

$$\mathcal{P}_3 : \max_{\mathbf{u}^- \geq \mathbf{0}} \; J_s^c(\mathbf{u}^+, \mathbf{u}^-, \pi_\mathbf{s}) \tag{14a}$$

$$\text{s.t.} \;\; (\mathbf{u}^+, \mathbf{u}^-) \in \mathcal{U} \tag{14b}$$

corresponds to the day-ahead market decision on how much to charge, given the amount decided to supply to the renewable producer, and

$$\mathcal{P}_4 : \max_{\mathbf{u}^+, \pi_\mathbf{s} \geq \mathbf{0}} \; J_s^c(\mathbf{u}^+, \mathbf{u}^{-*}, \pi_\mathbf{s}) \tag{15a}$$

$$\text{s.t.} \;\; (\mathbf{u}^+, \mathbf{u}^{-*}) \in \mathcal{U}, \tag{15b}$$

refers to the insurance contract ex-ante decision. Note that these problem definitions can be easily written for the baseline case by maintaining only the day-ahead problem, letting the reserve amounts and price be zero, and letting the storage supply energy to the day-ahead market instead of to the renewable producer.

4. Main Results

4.1. Renewable Participation

The renewable generator will solve the profit-maximizing problems (12) and (13) to decide how to participate in the market. The following results can be proven using along the lines of [24].

Theorem 1. *For every time slot k, the optimal renewable bid in the day-ahead market is given by*

$$C_{rk}^* = G_{rk}^* + F_k^{-1}\left(\frac{\lambda_k}{\lambda_p}\right), \tag{16}$$

where the optimal reserve amount to be purchased in the insurance contract is the maximum available, i.e. $G_{rk}^* = G_{max,k}$, if the per unit price satisfies the price constraint

$$\pi_{rk} \leq \lambda_k, \tag{17}$$

and $G_{rk}^* = 0$ otherwise.

Proof. See Appendix A. □

The optimal strategy of this participant is reduced to that for the baseline case if we set the reserve to be zero. As a buyer, the renewable producer sets an upper bound on the reserve price. If the storage unit asks for a reserve price above that threshold, the renewable producer is better off without a reserve, and then an insurance contract is not signed. In such a situation, we say there are no feasible insurance contracts, since it is not individual rational for the renewable producer to purchase a reserve.

We observe that the renewable producer's bid increases as the amount of reserve purchased through the contract increases. This can be interpreted as a *moral hazard*, which occurs when an agent behaves in a riskier way because someone else bears the cost of this increased risk. Here, in case the renewable producer is unable to meet this extra commitment, the cost of delivering this amount is borne by the storage unit. Nevertheless, we will show Section 4.3 that it is still beneficial for the storage unit to engage in the insurance contract.

4.2. Storage Participation

Even in the baseline case, which is deterministic, deciding how much energy to offer is a complex task for the storage unit. One of the reasons for this complexity is the non-linearity in the complementarity constraint (4). The following results show that this constraint can be relaxed.

Lemma 2. *Given a convex and strictly increasing operational cost function for the storage and considering this participant is a profit-maximizer, the complementarity constraint $u_k^+ u_k^- = 0$ for all $k \in \mathcal{K}$ always holds, both in the baseline case and in the presence of an insurance contract.*

Proof. See Appendix B. □

The results of Lemma 2 allows us to simplify the storage problem by removing the non-linear constraint (4). With this simplification, the maximization problem of the storage in the baseline case becomes a convex optimization problem.

Let $k = \max$ (resp. $k = \min$) refer to the time with the maximum (resp. minimum) day-ahead price. Further, let $\mathbf{e_k}$ denote the standard $k-$th basis vector whose $k-$th entry is equal to 1 and all other entries are zero. We define an *arbitrage policy* as one where the storage unit charges completely when the day-ahead price is the minimum and discharges when the price is the maximum. The participation of the storage in the market is summarized in the following result.

Theorem 3. *In the baseline case, it is optimal for the storage unit to adopt an arbitrage policy, in which the charging policy is given by* $\mathbf{u}^- = \mathbf{e}_{\min}\overline{E}$ *and the day-ahead offer is* $\mathbf{u}^+ = \mathbf{e}_{\max}\overline{E}$*. Further, it is individual rational for the storage to sign an insurance contract following this policy if the per unit price of reserve for* $k = \max$ *satisfies*

$$\begin{aligned} \pi_{s,\max} \geq \lambda_{\max} - \frac{g(\overline{E},0)}{\overline{E}}\big(1 - F_{r,\max}(C_{r,\max} - \overline{E})\big) \\ + \frac{1}{\overline{E}}\int_{C_{r,\max}-\overline{E}}^{C_{r,\max}} g(C_{r,\max} - R_{\max}, 0) f_{\max}(r)dr. \end{aligned} \tag{18}$$

Proof. See Appendix C. □

The lower bound on the price set by the storage unit can be interpreted as the minimum price for which the per unit expected profit earned by signing the contract is at least equal to the per unit expected profit that can be achieved by offering that energy in the day-ahead market.

4.3. Insurance Contract Feasibility

In the presence of an insurance contract, the expected cost of supplying energy faced by the storage unit depends on the probability of shortage of the renewable plant. The following result uses the upper and lower bounds derived in Theorem 1 and Theorem 3 for the reserve price to show that insurance contracts that are mutually beneficial for both the renewable generators and storage owners are feasible.

Theorem 4. *Let the storage charge following* $\mathbf{u}^- = \mathbf{e}_{\min}\overline{E}$*, when the day-ahead price is minimum, and offer the stored energy to the renewable generator when this price is maximum, according to the discharge policy* $\mathbf{u}^+ = \mathbf{e}_{\max}\overline{E}$*. The interval of per unit reserve prices for which both the renewable producer and the storage owner agree to sign an insurance contract, given by* $[\pi_{s,\max}, \lambda_{\max}]$*, with* $\pi_{s,\max}$ *as in* (18)*, is always non-empty.*

Proof. See Appendix D. □

Theorem 4 proves that insurance contracts are always feasible for the framework analyzed, which considers an unconstrained network. In Section 5.2, we show that the feasibility of the contract will depend on the location of these players in the grid, due to the differences in locational marginal prices across the network.

The worst-case scenario for the storage unit occurs when the renewable shortage is at least as large as the reserve amount established in the contract. In this case, the storage unit will incur the operational cost of supplying the full reserve. For a given insurance contract, we can use this fact to establish a lower bound on the expected profit of the storage.

Corollary 5. *Let the storage unit follow the arbitrage policy to charge when the day-ahead price is minimum and offer the reserve* $\mathbf{u}^{+} = \mathbf{e}_{\max}\overline{E}$ *in the insurance contract. Then, the contract with a reserve price* $\pi = \lambda$

- *is feasible;*
- *leads to a storage expected profit that is lower bounded by the day-ahead expected profit for the same policy.*

Proof. The arbitrage policy is feasible, and, from Theorem 4, the contract price proposed is the upper bound of the interval that guarantees individual rationality for both players. Then, this insurance contract is feasible. To find the lower bound on the profit, we analyze the worst-case scenario. In this case, $\min(C_{r,\max} - R_{\max}, \overline{E}) = \overline{E}$, which leads to $J_s^b = J_s^c$. □

4.4. Storage Profitability Analysis

The analysis performed in Section 4.3 is interesting since it identifies a revenue source for the storage owner. This raises an interesting question whether is is possible for the storage owner to be profitable as an insurance provider, even though it is not competitive in the day-ahead market. We highlight that we are not making any inferences about how profitable this energy storage system may be in the frequency regulation, reserve, or any other market other than the day-ahead energy market. Instead, we compare the participation in the day-ahead market versus the provision of reserve to a renewable generator through an insurance contract. Therefore, by stating that a storage unit may not be profitable in the the day-ahead market, we do not claim that this is true if this unit participates in other services.

The day-ahead profit of a storage unit which utilizes an arbitrage policy in the day-ahead market depends on the difference between the highest and lowest energy prices. In the following result, we set bounds on the ratio of these prices to establish a profitability condition for the storage to have an insurance contract, even though it cannot achieve a positive profit in the day-ahead market.

Theorem 6. *Let $g(u^+, u^-)$ be the operational cost function of the storage for discharging u^+ and charging u^-, $\overline{E}$ be its energy capacity, and π denote the per unit price of reserve in the insurance contract. Further, define the following prices*

$$\underline{\Lambda} = 1 - \frac{g(0, \overline{E})}{\lambda_{\max}\overline{E}} - \frac{g(\overline{E}, 0)}{\lambda_{\max}\overline{E}} \tag{19}$$

$$\begin{aligned}\overline{\Lambda} = & \frac{\pi}{\lambda_{\max}} - \frac{g(0, \overline{E})}{\lambda_{\max}\overline{E}} - \frac{g(\overline{E}, 0)F_{r,\max}(C_{r,\max} - \overline{E})}{\lambda_{\max}\overline{E}} \\ & - \frac{1}{\lambda_{\max}\overline{E}} \int_{C_{r,\max}-\overline{E}}^{C_{r,\max}} g(C_{r,\max} - R_{\max}, 0) f_{\max}(r) dr\end{aligned} \tag{20}$$

When following the arbitrage policy to charge $\mathbf{u}^- = \mathbf{e}_{\min}\overline{E}$ and discharge $\mathbf{u}^+ = \mathbf{e}_{\max}\overline{E}$, the storage unit is profitable as an insurance provider, but not in the day-ahead market, if

$$\underline{\Lambda} \leq \frac{\lambda_{\min}}{\lambda_{\max}} < \overline{\Lambda}. \tag{21}$$

Proof. Proof follows from direct inspection of the expected profits for the storage unit in the baseline scenario and in the insurance contract case. For that, we simultaneously check conditions for this player to not be competitive in the day-ahead market ($J_s^b \leq 0$) and be profitable as an insurance provider ($J_s^c > 0$). □

The condition (21) derived in Theorem 6 establishes a lower and an upper bound on the ratio between the minimum and the maximum day-ahead prices in the time interval considered. This price ratio is a determinant factor to how much profit the storage unit can expect to achieve using arbitrage. If the lower bound holds, the difference between the maximum and minimum day-ahead prices is not high enough to cover the storage operational costs and yield a positive profit for this storage unit when it operates in the day-ahead market only. On the other hand, the upper bound is satisfied when the payments from the insurance contract are high enough to cover both the storage operational cost and the payments made to charge from the grid.

This result shows that storage technologies that are still too expensive to bid in the day-ahead market may, instead, offer their energy through an insurance contract with a renewable power plant. Therefore, insurance contracts may be an alternative source of revenue for such storage units, keeping them from being idle when they lack competitiveness, and serving as an additional economic incentive for the improvement of their technology. We note that at places such as California, it has already been identified that there is a limitation in the amount of storage that can provide peaking capacity according to their 4-hour rule, which credits storage units that can sustain 4 hours of operation at maximum output [4]. Further, the ratio between the minimum and the maximum day-ahead prices becomes higher as more peak-shaving services are provided, making it more likely that the lower bound shown in (21) holds, and thus more difficult for new storage operators to enter the market. Therefore, we can envision that insurance contracts would allow for a higher penetration of storage in the grid by serving as an entry point in the market for peaking capacity. In Section 5, we perform a case study in which we show that the condition expressed in Theorem 6 is not too stringent.

4.5. Model Extension - Two-Way Contract Structure

The insurance contract designed allows a renewable generator to request use of an energy reserve from a storage unit in times of underproduction. In this section, we extend the model to a full contract between these two players which also permits production exchange from the renewable generator to the storage if there is excess renewable production.

Trading excess renewable production is profitable both for the storage unit and for the renewable generator. This happens because the renewable generator is subject to curtailment in case of overproduction. Therefore, for this generator, selling excess energy at any price $\epsilon > 0$ is preferable to spilling it. For the storage, purchasing energy at a price lower that the market price leads to a decreased cost of charging. Thus, this contract has the potential to increase the profits to each participant over the contract studied earlier. However, there may be regulations preventing such a level of coordination among bidders in a day-ahead market.

The possibility of extra revenue may affect the renewable participation in the market, as any increase in the day-ahead commitment is now linked both to an increase in expected penalty for shortage and to a decrease in the expected revenue from selling exceeding generation (higher $\mathbf{C_r}$ implies higher expected shortage and lower expected overproduction). To evaluate this trade-off, we modify the renewable utility function (10) to include the opportunity to sell excess production. Let π_{ek} denote the per unit price charged for the excess energy at time k. The modified utility becomes

$$J_r(\mathbf{C_r}, \mathbf{G_r}, \pi_\mathbf{r}, \pi_\mathbf{e}) = \sum_{k=0}^{N-1} \lambda_k C_{rk} - \pi_{rk} G_{rk} + E_{Rk} \left[I(R_k - C_{rk}) \pi_{ek} (R_k - C_{rk}) \right] - E_{Rk} \left[I(C_{rk} - R_k - G_{rk}) \lambda_p (C_{rk} - R_k - G_{rk}) \right]. \quad (22)$$

The following results hold for every time instant $k \in \mathcal{K}$, but the time subscript is suppressed for notational simplicity.

Proposition 7. *Consider the renewable generator participates in the day-ahead market and in the insurance contract with the two-way structure described in Section 4.5. Then, the renewable utility* (22) *is concave in the day-ahead commitment for small enough* π_e*. In this case, the optimal commitment* C_r^* *satisfies the equilibrium condition*

$$\lambda = \lambda_p F_R \left(C_r^* - G_r \right) + \pi_e \left(1 - F_R(C_r^*) \right) \quad (23)$$

As $\pi_e \to \infty$*, that function becomes convex in* C_r*. In such scenario, the player chooses to bid its maximum capacity if*

$$\pi_e \mu_R \leq \lambda C_r - \pi_r G_r - E_R \left[I(C_r - R - G_r) \lambda_p (C_r - R - G_r) \right], \quad (24)$$

where μ_R *is the expected renewable production. Otherwise, the renewable generator bids zero in the day-ahead market and sells all production to the storage unit.*

Proof. See Appendix E □

The analysis above assumes the energy storage will voluntarily agree to purchase the excess renewable energy. Thus, π_e can be at most the energy price λ, otherwise the storage unit is better off by being scheduled as a load in the day-ahead market and charging at the lower cost λ.

If the time instant considered is such that the renewable player has no energy reserve from the insurance contract, but is still able to sell excess energy to the storage unit, we can set $G_r = 0$ and rewrite (23) to find the optimal renewable day-ahead commitment

$$\lambda = \pi_e + (\lambda_p - \pi_e) F_R (C_r^*) \implies C_r^* = F_R^{-1} \left(\frac{\lambda - \pi_e}{\lambda_p - \pi_e} \right). \tag{25}$$

From equation (25), we observe the opportunity cost involved between selling energy to the market or through a bilateral contract with the storage unit. The higher the reselling price π_e, the lower is the day-ahead commitment. This leads to an increased likelihood of having excess energy to resell. Conversely, C_r increases with the day-ahead energy price λ.

5. Case Studies

We analyze the insurance contract proposed for two network scenarios. First, we consider an unconstrained setup in which the renewable and the storage participants are connected to the same node. We later analyze the insurance contract in a modified IEEE 14-bus test system, where the participants may be located in different nodes of the network and thus they may be subject to different locational marginal prices (LMPs). For both cases, the renewable production distribution was estimated from the Wind Integration National Dataset (WIND) Toolkit [25, 26]. For each month, we fitted a Gaussian distribution for the hourly wind production in each hour of the day, and we assumed the productions to be independent across time.

5.1. Single-Node Case

For this analysis, we consider four hubs within the Midcontinent Independent System Operator footprint – Illinois, Michigan, Minnesota, and Indiana hubs. We use the day-ahead price of these hubs that refer to 2018 [27]. Four different wind productions were modeled based on each hub location. The storage unit investigated is a lithium-ion battery with energy capacity $\overline{E} = 12$MWh and a linear variable operation and maintenance cost of $7/MWh [28].

We initially seek to confirm the existence of feasible insurance contracts in all four locations. For that, we considered the contract discussed in Proposition 5 and generated 1000 scenarios for renewable production to evaluate the profit achieved by the storage unit when that contract is signed. We also calculated the profit for the unit in the baseline case. The results of this analysis are shown in Fig. 1, where the shaded area corresponds to the profit variation observed across the 1000 scenarios generated in the presence of an insurance contract.

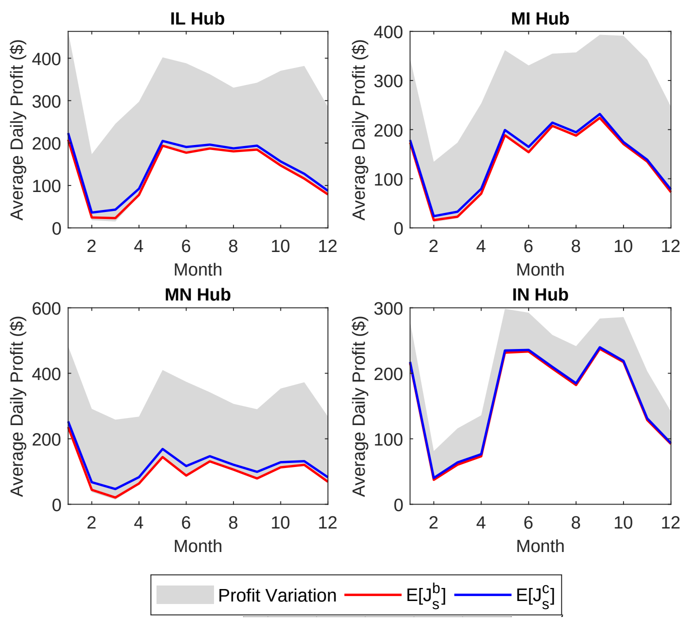

Figure 1: Storage average daily profit for baseline (red) and insurance contract (blue) cases.

As proved in Corollary 5, the storage unit's expected profit in the presence of an insurance contract, shown in blue, is lower bounded by the profit achieved in the baseline case. The profits in these scenarios are closer in cases with higher probabilities of renewable shortage, since this leads to the storage having to supply higher energy amounts more frequently. The annual expected profits for the storage unit both for the baseline and for the insurance contract case are presented in Table 5.1. These results confirm that it is individual rational for the storage unit to sign an insurance contract with a renewable generator, as the contract proposed leads to an increase in the expected profit of the storage unit.

We also evaluated how much renewable energy was taken by the grid in real-time, which corresponds to the minimum between the renewable production and the renewable commitment. Through the insurance contract proposed, the storage commits to deliver some energy reserve at the hour of

	IL Hub	MI Hub	MN Hub	IN Hub
Baseline	4.8909	4.9643	3.7147	5.8605
Insurance contract	5.3212	5.2350	4.4157	5.9527

Table 1: Annual expected profit for storage player ($\times 10^4$\$)

the day with the highest day-ahead energy price, if needed. Thus, we focused our analysis on that hour, as the behavior of the renewable generator during other times will reduce to that observed in the baseline case. Fig. 2 shows that the insurance contract leads to an increase in renewable integration in the grid at the time of peak demand, for all hubs and all months. This is due to the change in the optimal bidding strategy of the renewable generator, which gives more room for extra production to be taken by the grid. This trend may also be observed in other hours of the day if the renewable plant finds other flexible sources that are willing to have an insurance contract at these times.

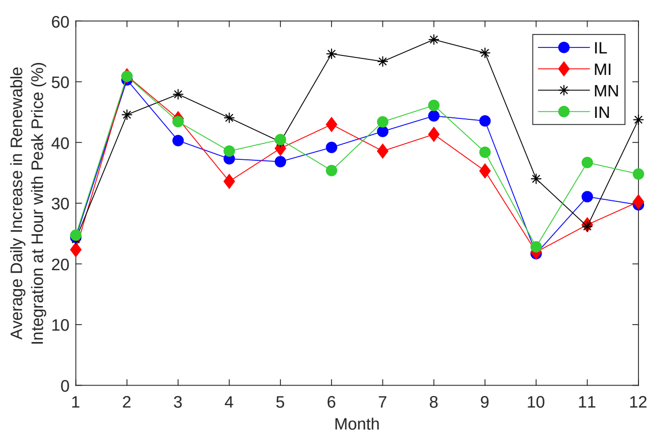

Figure 2: Increase in renewable energy taken by the grid at the hour with maximum day-ahead energy price.

Finally, we check the condition presented in Theorem 6 to verify whether there are any days of the year for which the storage unit investigated is profitable as an insurance provider, even though it is not competitive in the day-ahead market. The results presented in Fig. 3 show that this situation happens more often in the Minnesota hub, while it is less frequent in the Indiana hub.

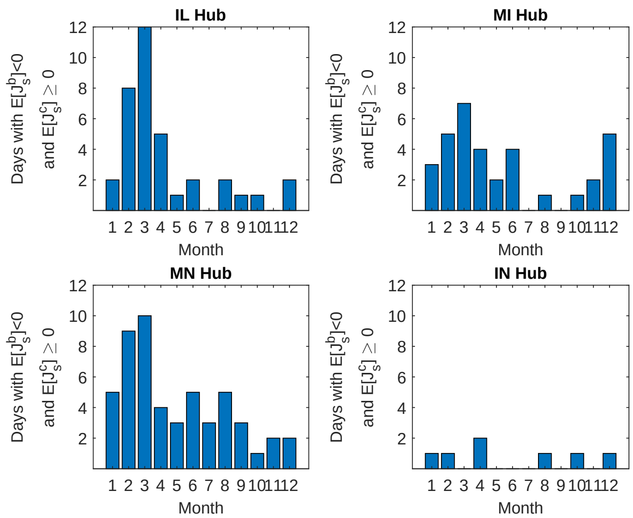

Figure 3: Number of days per month in which storage unit is profitable as an insurance provider, but not in the day-ahead market.

In fact, we can observe from Table 5.1 that operating in the Indiana hub yields a higher expected profit for the storage unit, as compared to the other hubs. Thus, the energy prices in this location are such that they enable the storage player to participate more often in the day-ahead market. Similarly, the Minnesota hub is the location for which the storage is less competitive, leading to the lowest expected profit and a higher occurrence of days in which this source can be profitable as an insurance provider, but not as a bidder in the day-ahead market.

5.2. Modified IEEE 14-Bus Test System Case

We now evaluate the insurance contract in a case with constrained transmission capacity. We use the IEEE 14-bus test system show in Fig. 4, and we adopt the data from MATPOWER [29] with the following modifications:

- All transmission lines have a 80MW capacity.
- Generators at buses 1 and 2 have a 15MW ramp rate for 30min reserves.
- A wind power plant with 32MW capacity is added.

- A storage unit with energy capacity $\overline{E} = 50$MWh, power capacity $\overline{P} = 20$MW, linear cost \$7/MWh, loss factor $\alpha = 0.95$, charge and discharge efficiencies $\eta^{-} = \eta^{+} = 0.85$ is added.

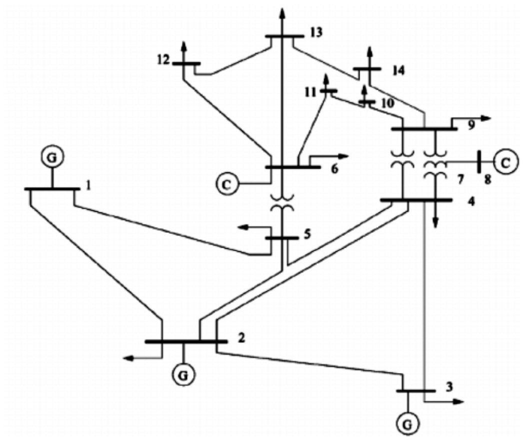

Figure 4: IEEE 14-bus test system used in this case study.

We analyze a multi-period set-up with $N = 24$ time slots corresponding to each hour of the day. The distribution for the wind production was estimated from the WIND Toolkit [25, 26] considering the month on July and the location in the Illinois hub. Further, we added a demand profile that follows a typical demand curve for July in the Illinois hub, which was inferred from the day-ahead price curve for this location and month. In the baseline case, we considered the penalty for a shortage is such that the ratio $\lambda_k/\lambda_p = 0.4\ \forall k$. The total demand and the baseline wind profiles are presented in Fig. 5.

We solve for a multi-period optimal economic dispatch for this network. The second modification permits that there is enough ramp capability in the system to allow for a feasible solution for this problem, even with variable demand and renewable production profile. We consider 14×14 scenarios, with all possible combinations of bus location for the renewable and the storage players. For each scenario, we let the wind power plant be scheduled based on its baseline commitment and we observe the optimal schedule profile for the storage unit. Then, we determine whether a insurance contract is feasible or not in each situation, considering the storage can supply the amount of energy that it was scheduled for in the baseline case, since we know that is a feasible trade. Note that, in this constrained network case, the participants will take into account their own LMPs when deciding on the price bounds

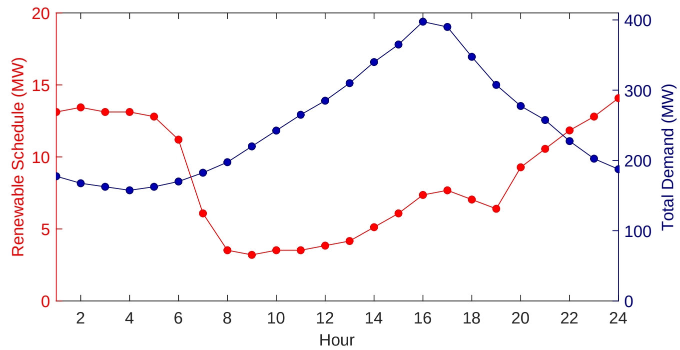

Figure 5: Renewable baseline schedule profile (left, red) and total demand profile (right, blue).

that will make it profitable for them to have an insurance contract. The results can be seen in Fig. 6, where each square is green if the insurance contract is feasible when the wind power plant is located in bus x and the storage is in bus y, and it is red otherwise.

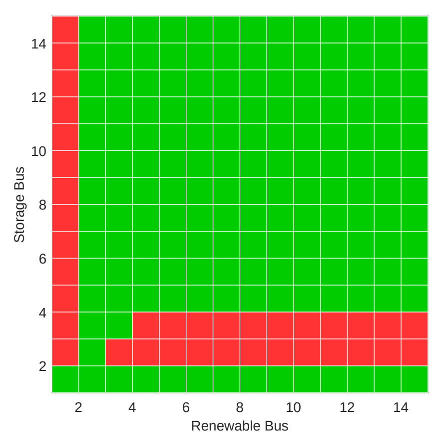

Figure 6: Insurance contract feasibility for the modified IEEE 14-bus test system. For each renewable bus x and storage bus y, the green squares indicate that the insurance contract is feasible, while the red ones are cases in which it is not.

We observe that all squares in the diagonal, corresponding to when the renewable and the storage players are at the same bus, are cases with feasible insurance contracts. This result conforms with our analytical studies and the single node case study. There are cases, however, in which it is not individual rational for both players to have a contract. This is explained by the price disparity between certain nodes in this network. The storage is discharging at times with high demand, during which the grid becomes congested. The distribution of generation and load in this test case is such that node 1 has consistently the lowest LMP during congestion times, while node 2 has the highest one. Fig. 7 shows the LMPs for all nodes for the representative case with the storage at node 1 and the wind power plant at node 3 (the same pattern was also observed for all other cases).

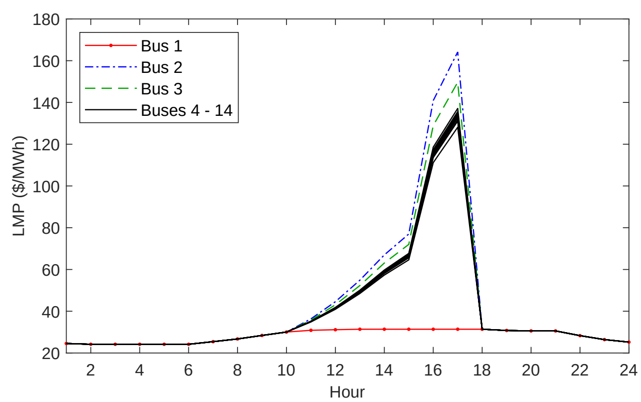

Figure 7: Locational marginal prices for all nodes in a representative case with the wind power plant at node 3 and the storage at node 1.

If the renewable generator is at node 1, he will set an upper bound on the contract price that is significantly lower than any other LMP; thus, if the storage is at any other node, he will not accept such a low offer, since supplying to the market at any other LMP is more profitable. This scenario represents the vertical line of red squares in Fig. 6. Similarly, if the storage unit is at node 2, he will set a lower bound on the contract price that is too high for the renewable generator to accept if he is at any other node. The significant price gap between the LMP at bus 3 and at all the other buses explains the remaining cases with no feasible insurance contract. The LMPs at all the remaning buses are close together, allowing for an insurance contract to be signed in these remaining cases. For this case study, it can be argued that the storage owner should simply disregard the possibility of an insurance contract and decide to install the storage system at the bus that is more likely to have a high LMP. However, as the number of storage units located at a certain bus increases, the LMP at that location will decrease due to the peak shaving aspect of the storage operation in the grid. Thus, buses at which insurance contracts are currently infeasible may experience a change in this feasibility condition once the distribution of storage, as well as of other generators and loads, in the grid changes.

In the cases with a feasible contract, the expected profit of both participants increase at the hours in which a contract is signed, and we also allow for more renewable energy to be taken by the grid. Therefore, we showed that the insurance contract proposed can incentivize storage and renewable participation in the market even in a congested network.

6. Conclusions and Future Work

We proposed a bilateral insurance contract between a renewable power plant and a storage unit. We proved the feasibility of this contract and showed that it leads to a mutually individual rational solution, in that no participant is worse off by signing the contract. The proposed insurance contract also promotes the increase of renewable participation in the market, and provides an additional source of revenue for some storage units when they are not profitable in the day-ahead market. In our case studies, we validated our design both in an unconstrained and in a constrained power grid.

Directions for future work include extending our analysis to a multi-player scenario, in which multiple storage units and renewable players can choose to have an insurance contract. We can also explore the case with a storage aggregator as an insurance provider. We can consider that, through an aggregator, owners of different storage technologies are able to offer their energy to be used in case of renewable shortage. Some interesting questions arise in this problem set-up, such as which storage to call upon to produce in real-time in case of renewable shortage, and how to design a payment scheme that makes this framework profitable for the participants. Further, if the aggregator charges for this service, we can also analyze how he should set the price charged.

7. Acknowledgements

This research was supported by NSF grants 1739295, 1550016, and 1544724.

Appendix A. Proof of Theorem 1

We use backwards induction to solve for the decisions of the renewable generator. We first solve for the DA commitment C_{rk} for each time k, taking the prior insurance contract decisions as fixed. The utility function (10) is concave in the commitment decisions. Thus, taking its the derivative with respect to C_{rk}, we find the optimal renewable commitment.

$$\begin{aligned}\frac{\partial J_r^c}{\partial C_{rk}} &= \lambda_k - \lambda_p F_{Rk}\left(C_{rk} - G_{rk}\right) = 0 \\ \Rightarrow C_{rk}^* &= G_{rk}^* + F_{Rk}^{-1}\left(\frac{\lambda_k}{\lambda_p}\right). \qquad \text{(A.1)}\end{aligned}$$

Substituting (A.1) back in the expression for the expected profit, we find

$$\begin{aligned}J_r^c = &\ \left(\lambda_k - \pi_{rk}\right) G_{rk} + \lambda_k F_{Rk}^{-1}\left(\frac{\lambda_k}{\lambda_p}\right) \\ &- E_{Rk}\left[I\left(F_{Rk}^{-1}\left(\frac{\lambda_k}{\lambda_p}\right) - R\right)\lambda_p\left(F_{Rk}^{-1}\left(\frac{\lambda_k}{\lambda_p}\right) - R\right)\right] \\ \Rightarrow J_r^c = &\ \left(\lambda_k - \pi_{rk}\right) G_{rk} + J_r^{b*}, \qquad \text{(A.2)}\end{aligned}$$

where the last term in (A.2) is the expected renewable baseline profit for the optimal baseline commitment. From this, we observe that it is individual rational for this player to purchase any available reserve through an insurance contract as long as the price is $\pi_{rk} \leq \lambda_k$. Otherwise, the renewable player is better off without the contract.

Appendix B. Proof of Lemma 2

Let $(\mathbf{u}^+, \mathbf{u}^-)$ and $(\tilde{\mathbf{u}}^+, \tilde{\mathbf{u}}^-)$ be two distinct feasible storage policies such that, for every k,

$$-u_k^+ + u_k^- = u_k,\ u_k^+ u_k^- = 0 \qquad \text{(B.1)}$$

$$-\tilde{u}_k^+ + \tilde{u}_k^- = u_k,\ \tilde{u}_k^+ \tilde{u}_k^- > 0 \qquad \text{(B.2)}$$

Following [23, Theorem 1], we can show that $u_k^+ < \tilde{u}_k^+$ and $u_k^- < \tilde{u}_k^-$. Therefore, for a strictly increasing cost function,

$$g(\min(C_{rk} - R_k, u_k^+), u_k^-) \leq g(u_k^+, u_k^-) < g(\tilde{u}_k^+, \tilde{u}_k^-). \qquad \text{(B.3)}$$

Let J_s and $\tilde{J}_s$ denote the profit attained by the storage under these policies. The storage will be better off with the policy that satisfies the complementarity constraint if and only if $J_s > \tilde{J}_s$. We show that this always holds if the cost function is convex and strictly increasing. From the definitions (B.1) and (B.2), it follows that

$$\tilde{u}_k^+ - u_k^+ = \tilde{u}_k^- - u_k^-. \tag{B.4}$$

Let U_k denote the difference above and note that $U_k > 0$.

In the presence of an insurance contract, and for the case $\min(C_{rk} - R_k, u_k^+) = u_k^+$, the inequality $J_s > \tilde{J}_s$ gives us

$$\begin{aligned} g(\tilde{u}_k^+, \tilde{u}_k^-) - g(u_k^+, u_k^-) &> \pi_{sk}(\tilde{u}_k^+ - u_k^+) - \lambda_k(\tilde{u}_k^- - u_k^-) \\ g(\tilde{u}_k^+, \tilde{u}_k^-) - g(u_k^+, u_k^-) &> (\pi_{sk} - \lambda_k)U_k. \end{aligned} \tag{B.5}$$

From (B.3), we note that the left hand side of (B.5) is always positive. Thus, this condition always holds if $\pi_{sk} \leq \lambda_k$. As this inequality coincides with the upper bound set by the renewable producer on the reserve price (17), it must be satisfied when a contract is signed. Therefore, in the presence of an insurance contract, the storage policy satisfying $u_k^+ u_k^- = 0$ will be chosen and the constraint (4) can be relaxed. It is straightforward to notice that this result is also true if $\min(C_{rk} - R_k, u_k^+) = C_{rk} - R_k$, as well as for the baseline case, for which the right side of (B.5) will be zero.

Appendix C. Proof of Theorem 3

Since the storage baseline problem is convex, an optimal solution will satisfy the KarushKuhnTucker (KKT) conditions. Let the column vectors $\underline{\mu} = [\underline{\mu}_0, ..., \underline{\mu}_{(N-1)}]^T$ and $\overline{\mu} = [\overline{\mu}_0, ..., \overline{\mu}_{(N-1)}]^T$ be the Lagrange multipliers corresponding to the lower and upper storage energy constraints (7), respectively, and the multipliers $\overline{\rho_k}$ and $\underline{\rho_k}$ refer to the positivity constraint (5). Further, let $\mathbf{A_k^{+T}}$ and $\mathbf{A_k^{-T}}$ denote the transpose of the $k-$th column of the matrices $\mathbf{A}^+$ and $\mathbf{A}^-$. For every k, the stationarity conditions are given by

$$\lambda_k - \frac{\partial}{\partial u_k^+} g(u_k^+, u_k^-) - \mathbf{A_k^{+T}} \underline{\mu} + \mathbf{A_k^{-T}} \overline{\mu} + \overline{\rho_k} = 0, \tag{C.1}$$

$$-\lambda_k - \frac{\partial}{\partial u_k^-} g(u_k^+, u_k^-) + \mathbf{A_k^{+T}} \underline{\mu} - \mathbf{A_k^{-T}} \overline{\mu} + \underline{\rho_k} = 0. \tag{C.2}$$

The complementarity slackness conditions are

$$\underline{\mu} \circ (\mathbf{A}^{+}\mathbf{u}^{+} + \mathbf{A}^{-}\mathbf{u}^{-}) = \mathbf{0}, \tag{C.3}$$

$$\overline{\mu} \circ (\overline{\mathbf{E}} - \mathbf{A}^{+}\mathbf{u}^{+} - \mathbf{A}^{-}\mathbf{u}^{-}) = \mathbf{0}, \tag{C.4}$$

where, for two matrices A and B of the same size, $A \circ B$ denotes their Hadamard (element-wise) product. The last condition is that all multipliers must be non-negative. Proof that an arbitrage policy is optimal in the baseline case follows from direct inspection of the KKT conditions (C.1) – (C.4) for the policy $(\mathbf{u}^{+}, \mathbf{u}^{-})$, with $\mathbf{u}^{+} = \mathbf{e}_{\max}\overline{E}$ and $\mathbf{u}^{-} = \mathbf{e}_{\min}\overline{E}$, where $\mathbf{e_k}$ is the standard $k-$th basis vector, and $k = \max$ ($k = \min$) refers to the time with the maximum (minimum) day-ahead price.

If the storage signs the insurance contract and offers $\overline{E}$ at the time $k = \max$, his expected profit is

$$J_s^c = (\pi_{s,\max} - \lambda_{\min})\overline{E} - g(0, \overline{E}) - E_{R,\max}[g(\min(C_{r,\max} - R_{\max}, \overline{E}), 0)]. \tag{C.5}$$

The last term in (C.5) can be rewritten as

$$\int_0^{C_{r,\max}-\overline{E}} g(\overline{E}, 0) f_{\max}(r)dr + \int_{C_{r,\max}-\overline{E}}^{C_{r,\max}} g(C_{r,\max} - R_{\max}, 0) f_{\max}(r)dr. \tag{C.6}$$

In case he opts out, and instead offers his supply in the day-ahead market,

$$J_s^b = (\lambda_{\max} - \lambda_{\min})\overline{E} - g(0, \overline{E}) - g(\overline{E}, 0). \tag{C.7}$$

The condition for individual rationality is that $J_s^c \geq J_s^b$. Using the expressions above and recognizing that

$$\int_0^{C_{r,\max}-\overline{E}} g(\overline{E}, 0) f_{\max}(r)dr = g(\overline{E}, 0) F_{r,\max}(C_{r,\max} - \overline{E}) \tag{C.8}$$

yields the price condition presented in Theorem 3.

Appendix D. Proof of Theorem 4

We need to show that the upper bound (17) on the price is always above or equal to the lower bound (18), considering the arbitrage policy.

$$\begin{aligned} \lambda_{\max} \geq & \lambda_{\max} - \frac{g(\overline{E}, 0)}{\overline{E}} \left(1 - F_{r,\max}(C_{r,\max} - \overline{E})\right) \\ & + \frac{1}{\overline{E}} \int_{C_{r,\max}-\overline{E}}^{C_{r,\max}} g(C_{r,\max} - R_{\max}, 0) f_{\max}(r)dr \end{aligned} \tag{D.1}$$

This condition reduces to

$$g(\overline{E},0)\left(1-F_{r,\max}(C_{r,\max}-\overline{E})\right) \geq \int_{C_{r,\max}-\overline{E}}^{C_{r,\max}} g(C_{r,\max}-R_{\max},0)f_{\max}(r)dr \tag{D.2}$$

The integral on the right hand side can be bounded from above as

$$\begin{aligned}
\int_{C_{r,\max}-\overline{E}}^{C_{r,\max}} & g(C_{r,\max}-R_{\max},0)f_{\max}(r)dr \\
&< \int_{C_{r,\max}-\overline{E}}^{C_{r,\max}} g(\overline{E},0)f_{\max}(r)dr \qquad\qquad \text{(D.3)} \\
&= g(\overline{E},0)\left(F_{r,\max}(C_{r,\max})-F_{r,\max}(C_{r,\max}-\overline{E})\right) \\
&\leq g(\overline{E},0)\left(1-F_{r,\max}(C_{r,\max}-\overline{E})\right),
\end{aligned}$$

which is the same as (D.2). Thus, the condition for the reserve price interval to be non-empty holds.

Appendix E. Proof of Proposition 7

The first and second order derivatives of J_r with respect to C_r are

$$\frac{\partial J_r}{\partial C_r} = \lambda - \lambda_p F_R\left(C_r - G_r\right) - \pi_e\left(1 - F_R(C_r)\right) \tag{E.1}$$

$$\frac{\partial^2 J_r}{\partial C_r^2} = -\lambda_p f_R\left(C_r - G_r\right) + \pi_e f_R(C_r) \tag{E.2}$$

It is straightforward to note that (E.2) will be negative (positive) for small (large) enough π_e, which means the function is concave (convex). Further, the condition (23) is found by setting (E.1) to zero. In the convex case, the optimal bid is found by checking when the expected utility is maximized at the boundary $C_r = 0$ and when this happens at the maximum C_r.

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