2018 Annual American Control Conference (ACC)
June 27–29, 2018. Wisconsin Center, Milwaukee, USA

Bilateral Contracts Between NGPPs and Renewable Plants Can Increase Penetration of Renewables

Nayara Aguiar[1], Vijay Gupta[1], Pramod P. Khargonekar[2], and Indraneel Chakraborty[3]

***Abstract*— As the renewable penetration in the grid increases, the grid-takes-all-renewable paradigm will no longer be sustainable. We consider a day-ahead (DA) electricity market composed of a renewable generator, a natural gas power plant (NGPP) and a coal power plant (CPP). Each player provides the Independent System Operator (ISO) with their commitment and their asking price. The ISO schedules the generators using a least-cost strategy. Because of the intrinsic uncertainty of the renewable generation, the renewable player might be unable to meet its DA commitment. In the event of a shortfall, the renewable generator incurs a penalty so that the non-renewable sources are not forced to consume the cost of renewable intermittence. It has been recognized that such a penalty can lead to conservative bidding by the renewable generator, which may lead to lower than desired penetration of renewable energy in the grid. We formulate and analyze a contract between the renewable producer and the NGPP so that the NGPP reserves some amount of natural gas to hedge the renewable producer against shortfalls. Expressions for the optimal commitments of the players and for the optimal reserve contract are derived. When a reserve contract is established, we observe an increase both in the average profit of the players involved and in the renewable participation in the market. Thus, we show that a Pareto-optimal contract between market players can improve renewable penetration.**

I. Introduction

Increasing renewable penetration in the grid is a widely shared policy and social objective now. For low penetration of renewables, these objectives may be best served by providing special treatment to renewables through mechanisms such as tax credits and allowing renewables to self-schedule. However, as renewable penetration increases, these measures may impose increasing cost and economic stress on non-renewables (resulting in unproductive friction in the market) and to high prices paid by the consumers. Thus, it has been proposed that renewable producers will need to be treated in a similar fashion to the non-renewable producers in that they would need to commit in a market that leads to dispatch of the various producers, and any deviations from the commitment would lead to penalties [3], [4].

It should be emphasized that such a scenario, where the renewables compensate the grid (and the other power plants) for the stress on the reliable provision of electricity that their intermittence imposes, will only be widespread as the relative share of the renewables in the energy production mix becomes significant. However, since such a situation is already occurring in relatively small grids such as in island countries such as Britain [7] and Ireland [17], it is an interesting topic of research to identify the effects that this scenario would have. It has been shown [3] that renewable producers would likely bid conservatively in this case, which may hinder the objective of increasing the renewable share. In this paper, we show that the development of new market mechanisms may be useful to counter this effect.

Specifically, we consider a stylized and simplified day-ahead (DA) electricity market model composed of three players – a renewable producer, a NGPP and a CPP – that represent different types of generators. The renewable player represents a wind farm, the NGPP is representative of a thermal plant with fast ramp rates, while the CPP corresponds to a class of thermal plant with slow ramp rates. All the players present a commitment and asking price in the DA market, and are dispatched by the market operator or the independent system operator (ISO). The NGPP and CPP can always meet their commitments; however, if in real time, the renewable producer is unable to meet its commitment, it is penalized (in the case of a shortfall) or curtailed (in the case of overproduction). In this set-up, we first identify the optimal bidding strategies for the participants and their consequent expected profits. Then, we analyze the case in which the renewable generator is allowed to purchase a reserve from the NGPP to cover possible production shortages. We show that the average profit of the players involved in the reserve contract increases when an agreement for reserve is achieved. The adoption of the contract also incentivizes the renewable player to bid higher, and thus promotes the increase of renewable energy in the grid. Thus, we suggest that a Pareto-optimal complete contract for a subset of players in the power market can increase their respective profits, while achieving the social objective of higher usage of renewable power as an additional benefit. The contract does not require grid-takes-all-renewable paradigm, that requires non-renewable players to absorb the cost of intermittence of renewables to improve renewable energy usage. As a comparison point, we also present the results if the NGPP and the renewable plant belong to the same player.

Joint operation of renewable sources with a different power generation source to mitigate renewable intermittence is not a new idea (see, particularly, the long literature on using hydro generators, e.g. [2], [6]). In economics as well, the literature on the boundaries of firms is extensive. Seminal works include [11], [12], [20], among others. However, existing work largely considers the hydro energy source to

[1]Department of Electrical Engineering, University of Notre Dame {ngomesde,vgupta2}@nd.edu
[2]Department of Electrical Engineering and Computer Science, University of California, Irvine pramod.khargonekar@uci.edu
[3]Department of Finance, University of Miami i.chakraborty@miami.edu

978-1-5386-5428-6/$31.00 ©2018 AACC

be used as a storage mechanism and often assumes it to be operated entirely by the renewable producer. Given the declining prices of natural gas and its desirable characteristics such as fast ramp rates [9], NGPPs are a natural candidate to compensate the intermittence of renewable sources. There is some recent work on the interdepenency of the natural gas and the electricity infrastructures, as discussed in [13]. Joint operation of natural gas power plants and renewable producers has been considered in [19]. However, that work assumes that the renewable and the NGPP *jointly* optimize their decisions. We are interested in the case when the cooperation between the two players is through a bilateral contract. How the generation volatility in a grid with increasing renewable participation impacts the natural gas generation and prices is discussed in [16]. In [14], a model that relates the uncertainties of natural gas-fired generation due to fuel constraints and the cost of electricity is developed. Unlike this stream of work, our focus is on the interactions of NGPPs and renewable players in the electricity market, and assume, for now, that the NGPP player has unconstrained access to the fuel needed for generation. Finally, we would like to mention the direction that considers provision of storage to mitigate the intermittence of renewables (see, e.g., [5], [10]). While these works have so far largely assumed that these storage options are owned and operated by a centralized source, one can envisage designing similar bilateral contracts as considered in the paper between renewables and providers of such storage options.

The main contribution of this work is the design and analysis of a bilateral contract between a renewable producer and a NGPP. We show that such a contract can increase social welfare by increasing the profits of both these players (and not harming any of the other participants) and also lead to higher share of the total energy being supplied by the renewable source. While the market is necessarily stylized and many important aspects of both the physical and market structures of the grid are ignored, our results show that introduction of new market mechanisms such as these bilateral contracts have the potential to increase the renewable penetration while minimizing the friction with other market participants.

The remainder of this work is organized as follows. Section II presents the electricity market model considered, and the utility functions of the players, along with the optimization problems faced by them. Section III formulates the optimal strategies for their commitment and for the reserve contract. Simulation results are shown in Section IV, and Section V states the final conclusions and future work.

II. Electricity Market Structure

A. Market Structure

We consider a stylized two-settlement electricity market consisting of a DA market followed by an imbalance resolution mechanism. The market is operated by an independent system operator (ISO) who is responsible for meeting the load reliably. In the DA market, generators bid the amount of energy they are willing to commit for delivery in the next operating day. Each player also informs the ISO with 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. The imbalance mechanism occurs in real-time, and penalizes the generators that deviate their production from their DA commitment. For simplicity, we make the following assumptions:

Assumption 1. *We focus on meeting the load at a particular time, so that issues such as ramp constraints can be ignored.*

Assumption 2. *The load L is accurately known to the ISO.*

Three players – a renewable generator, a natural gas power plant (NGPP) and a coal power plant (CPP) – compete in the DA market, with asking prices λ_r, λ_n, and λ_c per unit of supply, respectively.

Assumption 3. $\lambda_r < \lambda_n < \lambda_c$.

Given Assumption 3, as the load increases, the renewable generator is the first to be scheduled in the DA market, followed by the NGPP and the CPP, in that order. Following the usual practice in DA markets, all the scheduled players are paid the same energy price. In a market with a sufficiently large number of players, the aggregated offers will yield a smooth upward-sloping curve [15]. Because our model has only three players, the curve of the aggregated offers is not smooth, which leads to a non-decreasing piecewise supply function. Therefore, to determine the DA energy price, we define the following interval sets:

- $\mathcal{I}_1 = [0, C_r^*(\lambda_r)]$;
- $\mathcal{I}_2 = [C_r^*(\lambda_r), C_r^*(\lambda_n)]$;
- $\mathcal{I}_3 = [C_r^*(\lambda_n), C_r^*(\lambda_n) + C_n^*(\lambda_n)]$;
- $\mathcal{I}_4 = [C_r^*(\lambda_n) + C_n^*(\lambda_n), C_r^*(\lambda_c) + C_n^*(\lambda_c)]$;
- $\mathcal{I}_5 = [C_r^*(\lambda_c) + C_n^*(\lambda_c), C_r^*(\lambda_c) + C_n^*(\lambda_c) + C_c^*(\lambda_c)]$;

where $C_r^*(.)$, $C_n^*(.)$ and $C_c^*(.)$ are the commitments that the renewable, NGPP, and CPP players, respectively, make by optimizing their utility functions. The expressions for the optimal commitments will be presented in Section III-A, where it will be shown that the commitment functions adopted by the players are increasing with the DA energy price. Figure 1 illustrates the non-decreasing piecewise continuous function that we will use for the DA energy price, and the intervals depicted are as defined earlier. Let λ_2 obey $C_r^*(\lambda_2) = L$, and λ_4 obey $C_r^*(\lambda_4) + C_n^*(\lambda_4) = L$. Then, the DA energy price is given by

$$\begin{aligned}\lambda_{DA} = \; & \lambda_r I(L \in \mathcal{I}_1) + \lambda_2 I(L \in \mathcal{I}_2) + \lambda_n I(L \in \mathcal{I}_3) \\ & + \lambda_4 I(L \in \mathcal{I}_4) + \lambda_c I(L \in \mathcal{I}_5).\end{aligned} \tag{1}$$

Assumption 4. *The renewable production is a random variable with continuous and twice differentiable probability density function $f_R(r)$ and cumulative density function $F_R(r)$. Further, $f_R(r) > 0$ for all interval of interest.*

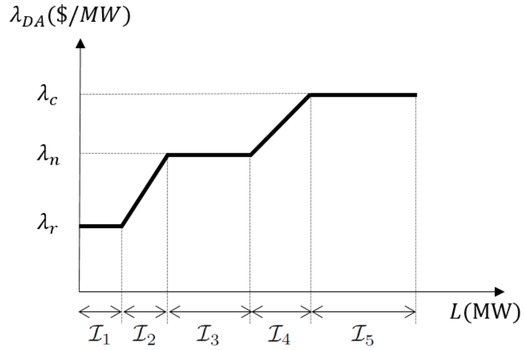

Fig. 1. DA energy price.

Assumption 5. *Both the natural gas and the coal power plant are always able to meet their commitment.*

Given that the renewable production is stochastic, in real time, it may not be able to meet its dispatch commitment.

Assumption 6. *All renewable production that exceeds the commitment is curtailed. If the renewable production is less than the commitment, that generator pays a penalty per unit of the shortfall at price $\lambda_p > \lambda_c$ that is fixed and known.*

The curtailment assumption is supported by the existing no-compensation trend observed in markets with high wind penetration (e.g., in Ireland, the payments for overproduction will cease in 2018). λ_p may correspond to the price asked by a peaker plant that is called in to compensate the shortfall.

Having to pay a penalty for shortfall leads to conservative bidding from the renewable producer [3]. While this protects the customer from paying high prices due to expensive peaker plants being called in to compensate for renewable intermittence, it may lead to reduction in the share of energy supplied by the renewable source. We show that allowing a reserve contract between the renewable producer and the NGPP, under which the NGPP reserves a block of fuel to act as a back-up generator in case of shortage in renewable production, can resolve both these effects simultaneously.

B. Utility Functions

The decision-making strategy of each player aims to maximize its own utility function, which is simply its expected profit. Note that the DA energy price λ_{DA} is deterministic and the only source of stochasticity in the problem is the renewable production. We now present the utility functions for the players in our model for three scenarios in which the market structure allows various interactions between the NGPP and the renewable producer.

1) Case 1 - No bilateral contract allowed between renewable player and NGPP: This is the baseline case in practice now, in which the renewable producer and the NGPP do not interact outside the market setup above. The expected profit of the renewable generator is given by

$$u_r(C_r, \lambda_{DA}) = \lambda_{DA} C_r - E_R\Big[I(C_r - R)\lambda_p(C_r - R)\Big], \tag{2}$$

where C_r is the player's commitment in the DA market, R is the amount of renewable energy production in real-time, the expectation is taken over the renewable production R, and $I(.)$ denotes the indicator function. The first term in (2) is the revenue obtained from committing to the market (if its bid is selected), and the second one is the penalty charged in case of shortage.

For the NGPP, the utility function is

$$u_n(C_n, \lambda_{DA}) = \lambda_{DA} C_n - \mu_n C_n - F_n(C_n), \tag{3}$$

where C_n is the DA market commitment of the NGPP and μ_n is the operation and maintenance (O&M) cost per unit of production for actual operation of the plant. The function $F_n(.)$ gives the fuel cost for the NGPP, which varies with the desired production output. The NGPP incurs the cost of purchasing fuel to meet the commitment C_n. For a production amount P_n, the NGPP fuel cost function is assumed to be given by a quadratic function

$$F_n(P_n) = a + bP_n + cP_n^2. \tag{4}$$

Quadratic functions are commonly used in the literature to model fuel costs for a variety of generators. They are derived from approximations of fuel input-production output measurements in thermal plants [15]. Both the function parameters and the O&M cost are positive quantities.

For the CPP, letting C_c be the player's DA commitment,

$$u_c(C_c, \lambda_{DA}) = \lambda_{DA} C_c - \mu_c C_c - F_c(C_c). \tag{5}$$

Similarly to the previous players, the CPP earns a revenue from committing to the market, which is the first term of the function. The second term is the O&M production cost, while the third term is the fuel cost for the CPP, assumed to be given by

$$F_c(P_c) = \alpha + \beta P_c + \gamma P_c^2 \tag{6}$$

for a desired output P_c.

2) Case 2 - Renewable-NGPP bilateral contract for reserve: In this scenario, the renewable player and the NGPP have the permission to sign a bilateral contract in which both parties agree on a transaction price and a reserve amount of gas that the NGPP agrees to store to cover any shortfalls in production by the renewable producer. The contract is signed before the players decide on their DA commitments. In this case, the utility function of the renewable player is given by

$$\begin{aligned} u_r(C_r, G_r, \pi_r, \lambda_{DA}) &= \lambda_{DA} C_r - \pi_r G_r \\ &\quad - E_R\left[I(C_r - R - G_r)\lambda_p(C_r - R - G_r)\right], \end{aligned} \tag{7}$$

where G_r and π_r respectively are the reserve purchased and the price offered per unit of power in the reserve.

For the NGPP, the utility function is given by

$$\begin{aligned} &u_n(C_n, G_n, \pi_n, \lambda_{DA}) = \lambda_{DA} C_n - \mu_n C_n - F_n(C_n + G_n) \\ &+ \pi_n G_n - E_R\left[I(C_r - R) I\left(G_n - (C_r - R)\right) \mu_n (C_r - R)\right] \\ &- E_R\left[I(C_r - R) I(C_r - R - G_n) \mu_n G_n\right], \end{aligned} \tag{8}$$

where π_n is the price asked per unit of the reserve G_n. In this scenario, the NGPP incurs the cost of purchasing fuel to meet the commitment C_n and to maintain a fuel reserve enough to produce up to G_n units of energy in case of renewable shortage. The last two terms in (8) are the expected O&M costs in case of shortage. In the second line, the expectation represents the case in which the reserve is larger than the shortage, while the last line indicates the cost incurred if the reserve is not enough to cover the gap completely.

The expected profit of the CPP remains unchanged and is given by equation (5).

3) Case 3 - Renewable-NGPP joint operation: In the final case, we assume that both the renewable plant and the NGPP are owned by the same player, who decides on the renewable commitment C_r, the NGPP commitment C_n, and a reserve G to be used in case of renewable shortage. Therefore, our model reduces to only two players. For the renewable-NGPP player, the expected profit will be the sum of (7) and (8):

$$\begin{aligned} u_{rn}(C_r, C_n, G, \lambda_{DA}) &= \lambda_{DA}\left(C_r + C_n\right) - \mu_n C_n \\ &- F_n(C_n + G) - E_R\left[I(C_r - R - G)\lambda_p(C_r - R - G)\right] \\ &- E_R\left[I(C_r - R)I\left(G - (C_r - R)\right)\mu_n(C_r - R)\right] \\ &- E_R\left[I(C_r - R)I(C_r - R - G)\mu_n G\right]. \end{aligned} \tag{9}$$

Note that the terms corresponding to the reserve contract transaction disappear since they represent only an internal transfer in this case. Further, note that there is not a single price asked by this joint player, and in this sense, our model is different from that of [1]. The second player is the CPP, and its expected profit is again given by equation (5).

In order to ensure concavity of the expected profit for the renewable-NGPP player with respect to the commitments and reserve decisions, we assume the following:

Assumption 7. *The penalty for shortage satisfies* $\lambda_p > \mu_n$.

In reality, if the penalty is set so that the player is forced to cover the extra cost of calling a peaker plant, then Assumption 7 holds, since that type of plant is typically more expensive than all the other players in the DA market.

In each case, the players decide on the commitment that will maximize their own profit. Then, we define the optimization problem for the renewable generator as

$$\max_{C_r \geq 0}\ u_r(C_r, G_r, \pi_r, \lambda_{DA}). \tag{10}$$

For the NGPP, the commitment decision is

$$\max_{C_n \geq 0}\ u_n(C_n, G_n, \pi_n, \lambda_{DA}). \tag{11}$$

For the CPP player, the optimal commitment is given by

$$\max_{C_c \geq 0}\ u_c(C_c, \lambda_{DA}). \tag{12}$$

Finally, for the joint operation case, we have the following problem for the renewable-NGPP player

$$\max_{C_r \geq 0,\ C_n \geq 0,\ 0 \leq G \leq G_{max}}\ u_{rn}(C_r, C_n, G, \lambda_{DA}). \tag{13}$$

III. Main Results

We will first derive the optimal commitments, which are a function of the optimal reserve contract, if such a contract is permitted. Then, we present the optimal contract.

A. Optimal Commitments

We begin by deriving the optimal commitments for the three players. Denote the set of optimal contracts as $S_C^* = (C_r^*(\lambda_{DA}), C_n^*(\lambda_{DA}), C_c^*(\lambda_{DA}))$. Also, let C_r^j be such that

$$\lambda_{DA} - (\lambda_p - \mu_n)F_R(C_r^j - G_{max}) - \mu_n F_R(C_r^j) = 0. \tag{14}$$

Theorem 1. *Define the DA energy price as in (1). The optimal commitment strategies for the players in the market are given as*

- *Case 1 - No bilateral contracts are allowed:*
$$S_C^* = \left(F_R^{-1}\left(\frac{\lambda_{DA}}{\lambda_p}\right), \frac{\lambda_{DA} - b - \mu_n}{2c}, \frac{\lambda_{DA} - \beta - \mu_c}{2\gamma}\right). \tag{15}$$
- *Case 2 - Renewable-NGPP bilateral contract:*
$$S_C^* = \left(G_r^* + F_R^{-1}\left(\frac{\lambda_{DA}}{\lambda_p}\right), \frac{\lambda_{DA} - b - \mu_n}{2c} - G_n^*, \frac{\lambda_{DA} - \beta - \mu_c}{2\gamma}\right). \tag{16}$$
- *Case 3 - Renewable-NGPP joint operation:*
$$S_C^* = \left(C_r^j, 0, \frac{\lambda_{DA} - \beta - \mu_c}{2\gamma}\right). \tag{17}$$

Proof. Proof will be provided in the journal version. □

Remark 1. *Each player is willing to bid only if the DA energy price is at least equal to their own asking price. Otherwise, their optimal choice is to bid a zero amount.*

Remark 2. *For a bilateral contract to exist in case 2, both the renewable producer and the NGPP must agree on the reserve amount. Hence, at the commitment moment, we will have* $G_r^* = G_n^* = G^*$. *The optimal reserve contract decision will be presented in Section III-B.*

Remark 3. *The optimal commitment strategy in case 2 reduces to that derived for case 1 if no agreement is reached for the bilateral contract. However, even if there is a reserve, the optimal commitment strategy in case 2 is not the same as that for case 3.*

B. Optimal Reserve Contract

The reserve contract decision is modeled as a bargaining game in which the renewable player (buyer) and the NGPP (seller) seek an agreement that can benefit both of them. The renewable generator is interested in purchasing a reserve as a hedge against its intermittence, with the goal of avoiding paying the penalty in case of shortage. For the NGPP, the contract is an opportunity to earn a revenue by serving as a back-up generator for the renewable player, but without necessarily incurring the O&M production cost, since the production is only needed in case of shortage. In short, an agreement will only be reached if the expected profit of both players is greater with the existence of the contract than without it. Specifically, two conditions must hold for a contract to exist at price π_c and amount G_c. First, it must hold that $u_r(C_r^*, G_c, \pi_c, \lambda_{DA}) - u_r(C_r^*, 0, 0, \lambda_{DA}) = u_n(C_n^*, G_c, \pi_c, \lambda_{DA}) - u_n(C_n^*, 0, 0, \lambda_{DA})$. Second, no player should benefit from deviating from this equilibrium.

Because the commitments of the players are constrained to be greater than or equal to zero, from the NGPP optimal commitment expression (16), we find that the maximum value that the reserve can take is

$$G_{max} = \frac{\lambda_{DA} - b - \mu_n}{2c}. \qquad (18)$$

Theorem 2. *Define the day-ahead energy price as in (1), the renewable optimal commitment as in (16), and the maximum reserve as in (18). The renewable generator and the NGPP are always able to reach an agreement for a reserve contract. Moreover, the optimal reserve contract, represented by $S_G^* = (G^*, \pi^*)$, is such that the optimal reserve amount and the equilibrium price are, respectively,*

$$G^* = G_{max} \qquad (19)$$

$$\pi^* = \lambda_{DA} - \frac{\mu_n}{2} + E_R\left[I\left(C_r^* - R\right) I\left(G^* - \left(C_r^* - R\right)\right)\mu_n \frac{C_r^* - R}{2G^*}\right] + E_R\left[I\left(C_r^* - R\right) I\left(C_r^* - R - G^*\right)\frac{\mu_n}{2}\right] \qquad (20)$$

Proof. Proof will be provided in the journal version. □

Remark 4. *The bilateral contract will only be signed if the DA energy price is at least equal to the NGPP asking price, in which case both the renewable player and the NGPP would be willing to bid in the DA market.*

Remark 5. *The expressions for the optimal contract show that the NGPP decision faces two opposite trends since by choosing to make a G_{max} reserve available, the NGPP also chooses not to bid in the DA market. Therefore, the higher the expectation of incurring the O&M production cost, the higher will be the contract price that would make this player accept the agreement.*

IV. Simulations

We analyze scenarios with different renewable energy (RE) penetration levels, which we define as the ratio between the renewable expected production and the load. We fix the load at $L = 7000MW$ and model the renewable production as a Gaussian random variable with a distribution truncated from below at zero with the parameters shown in Table I. As the renewable penetration increases, both the mean and the standard deviation of the production increase. The fuel cost function parameters are taken from [18]. For the NGPP, they are $a = \$240$, $b = \$10.833/MW$, and $c = \$0.00741/(MW)^2$ and for the CPP, they are: $\alpha = \$319.65$, $\beta = \$17.5035/MW$, and $\gamma = \$0.007995/(MW)^2$. The O&M production cost for those players are given by $\mu_n = \$12.50/MW$ and $\mu_c = \$3.50/MW$. Finally, we let $\lambda_r = \$15/MW$, $\lambda_n = \$60/MW$, and $\lambda_c = \$80/MW$.

Figure 2 shows how the commitment of the renewable producer to the DA market changes with increasing penalty, in case there is no possibility of reserve contract. We notice that, for every RE penetration level, the commitment decreases as the penalty increases. Thus, even though imposing a penalty is a strategy for the market designer to avoid renewable overbidding and decrease the intermittence effects in the grid, excessive penalties may lead to conservative renewable participation in the market. In the subsequent analysis, we fix the penalty at $\lambda_p = \$300/MW$.

TABLE I
Renewable Production Distributions

RE Pen. (%)	10	15	20	25	30	35
$\mu_r(GW)$	0.7	1.05	1.4	1.75	2.1	2.45
$\sigma_r(GW)$	0.07	0.1575	0.28	0.4375	0.63	0.98
RE Pen. (%)	40	45	50	55	60	65
$\mu_r(GW)$	2.8	3.15	3.5	3.85	4.2	4.55
$\sigma_r(GW)$	1.4	1.89	2.275	2.6	2.94	3.3
RE Pen. (%)	70	75	80	85	90	95
$\mu_r(GW)$	4.9	5.25	5.6	5.95	6.3	6.65
$\sigma_r(GW)$	3.675	4.07	4.48	4.9	5.355	5.82

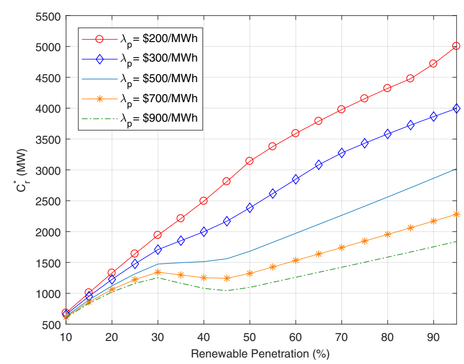

Fig. 2. Renewable commitment with no reserve contract.

The average realized profit of the renewable player and the NGPP for the case with a bilateral contract for reserve are shown in Figure 3. The values are normalized by those achieved when bilateral contracts are not allowed. The averages were taken over the results of 1000 simulation runs. Numerical results confirm that a reserve contract for G_{max} is settled for all levels of renewable penetration, making both players achieve an average profit larger than they would if they had not signed a contract.

Although we do not present the simulation results in detail due to lack of space, it can also be confirmed that the profit of the CPP in the DA energy price (that is a proxy for the price paid by consumers) remains unchanged by allowing a contract between the renewable producer and the NGPP. The main intuition behind this fact is that the sum of the commitments of the renewable and the NGPP players remains unaffected whether there is a contract permitted between them or not. Thus, the sum of the profits of all players does not decrease with the introduction of a contract. Notice that if the renewable producer and the NGPP form a joint player, the sum of the utilities may change.

The existence of a contract also allows for an increase in the presence of renewables in the grid, as can be observed

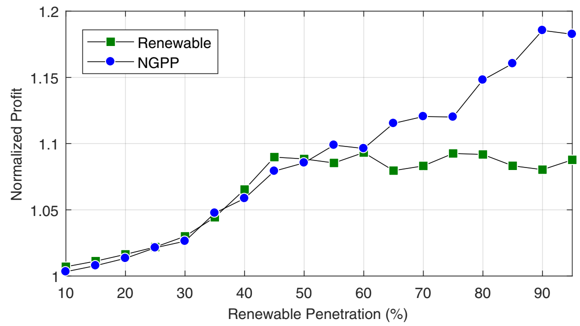

Fig. 3. Renewable and NGPP normalized realized profit

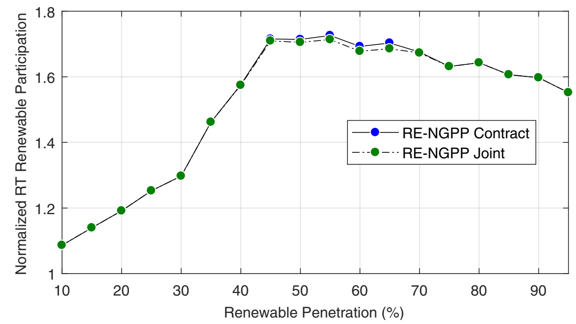

Fig. 4. Normalized renewable participation

in Figure 4, where the values are also normalized by those from the case without bilateral contracts. We observe that the joint operation also incentivizes the renewable penetration, although market anti-trust rules may prevent such consolidation among the power producers from occurring.

V. Conclusions and Future Work

We model a DA electricity market composed of three producers and an ISO. The market uses a single market-clearing price to schedule the generators in a least-cost dispatch manner. The expressions for optimal commitment for the players are derived for three cases, where the renewable producer and the NGPP bid independently in the first, they are able to sign a bilateral contract for reserve in the second, and, in the last case, they operate jointly. The optimal reserve contract is modeled as a bargaining game, and the expressions for the decisions are derived. It is shown that the adoption of a contract functions as an incentive for the renewable player to bid more, which leads to an increase in the renewable participation in the grid.

Private stakeholders and policymakers can help achieve the Pareto-improvement suggested in the paper by ameliorating frictions that make it difficult to share renewable intermittance risk contracts across a wider set of participants. Solutions may include facilitating trade of such arm's length hedging contracts in energy exchanges, joint ventures between NGPPs and renewable energy producers, or other mechanisms.

In future work, the model can be modified to include details such as a lower and an upper bound for the production of each player, and the possibility of selling the natural gas that was not used back in the natural gas spot market. Other directions may include a different approach regarding the penalty for shortage, which currently is not fixed in most of the electricity markets. Further analysis can adopt a stochastic model for this penalty and also evaluate what types of policies that penalize renewables for underproduction could yield the best results for the overall system performance.

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