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The authors gratefully acknowledge the active and enthusiastic participation in the energy market simulation by the students in their class on ''Energy Markets and Policy'' in the Stanford University Graduate School of Business. This work was supported by a grant from the Precourt Institute for Energy and the TomKat Center for Sustainable Energy at Stanford University and also by a grant from the International Policy Implementation Lab at the Freeman Spogli Institute for International Studies (FSI) at Stanford University.

Simulating the Interaction of a Renewable Portfolio Standard with Electricity and Carbon Markets

The authors ran a game-based simulation of an electricity market with both an RPS and a cap-and-trade market for greenhouse gas emissions allowances. High renewable energy shares reduced and shifted the output of thermal units and pushed down both electricity and carbon prices. The markets for renewable energy, carbon allowances, and spot and forward electricity interacted in complex ways that are relevant to the behavior of actual markets.

Mark C. Thurber, Trevor L. Davis and Frank A. Wolak

I. Introduction

California's electricity market is subject to a renewable portfolio standard (RPS) and a cap-and-trade market for greenhouse gas (GHG) emissions. These policy instruments establish markets for renewable energy certificates (RECs) and greenhouse gas emissions allowances, respectively. Many other jurisdictions also deploy overlapping policy tools in pursuit of different energy, environmental, economic, and political goals.[1] As the markets that result become more complex, they are less amenable to analysis with theoretical models and potentially more vulnerable to strategic behavior that was not

http://dx.doi.org/10.1016/j.tej.2015.04.007

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anticipated by the market designers.

In an earlier classroom simulation, we found a game-based methodology to be very effective in highlighting vulnerabilities of wholesale electricity markets under a stringent cap and trade (Thurber and Wolak, 2013). We have now extended this earlier work to incorporate the retail side of the electricity market, intermittent renewable energy, an RPS, and critical peak pricing (CPP) programs by electricity retailers.

From a practical standpoint, one of the most significant challenges of simulating these complex markets is bringing participants up to a level at which they can participate in the market in a sophisticated manner. This drove us to create an entirely new platform for the game so that we could run it in real time in a classroom and introduce each new market element to participants in turn. A substantial added benefit of this new approach is the ability to incorporate the simulation into short-duration workshops that alternate game play with lectures in order to introduce policymakers and regulators to important market concepts.

In the remainder of this article we describe what we found running the full simulation in a classroom setting. Because all trades in the game are executed by means of our Web-based clearinghouse, we can obtain a complete picture of the carbon allowance and REC markets. We highlight the following observations, which show the potential of the game to deliver policy insights even while functioning as an educational tool:

A substantial added benefit of this new approach is the ability to incorporate the simulation into short-duration workshops.

First, there were significant interactions in the game between the markets for renewable energy, carbon allowances, spot and forward electricity, and retail electricity. A number of these interactions have been noted in real markets. However, one advantage of our simulation game is that features of the market can be stress-tested in ways that would be impossible in the real world. Heavy penetration of renewable energy in the game—prompted in part by the prospect of high REC prices—effectively shifted and reduced the output of thermal units, which produce GHG emissions when they operate. This outcome mimicked the so-called ‘‘duck curve’’ load shape (see California ISO, 2013) and crashed electricity prices during the hours when wind and solar energy generation was high. High renewable energy shares also discouraged retailers from signing forward contracts for electricity by creating the expectation of low spot prices and blunting the ability of generators to exercise market power. The game results highlighted some important additional nuances. For example, while high renewable energy shares tended to push down the price of both carbon allowances and electricity prices, this effect could be totally undone by the presence of sufficient market power in the carbon market.

Second, it was difficult to avoid some exercise of market power in both carbon and REC markets. This was partly due to the limited number of players in the market: seven generators and seven retailers. But there were other causes too. Initial distributions of RECs or carbon allowances could be lopsided, making the exercise of unilateral market power more likely. (Our games hinted that allocating allowances more evenly among participants might provide not only a direct dilution of initial market concentration but also a ‘‘nudge’’ to trading these instruments.) And critically, the number of players either in need of or able to supply RECs or allowances naturally tended to dwindle as the compliance deadline drew near and teams completed trades deemed to be essential to meeting their compliance obligations. Those few remaining usually found

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themselves with substantial market power on either the selling or buying side.

Third, it was difficult in our game to predict how supply and demand for RECs would develop, making REC prices quite volatile. There was uncertainty around how many wind and solar facilities would be built, how much energy they would generate, and how this would compare to realized electricity demand. Moreover, the market power problems mentioned above often kept REC prices uncertain even after overall RPS compliance had become a foregone conclusion. Policies to limit price uncertainty—for example by establishing floor and ceiling prices for RECs—would have made RECs a more predictable source of revenue for renewable energy projects in our game. In the real world, cap-and-trade systems have benefited from recent focus on the risks of price extremes and market power (Borenstein et al., 2014), while REC markets—despite suffering from the same (or worse) problems—have not yet received comparable attention.

II. Description of the Energy and Environmental Market Game

Our original classroom game, as described in Thurber and Wolak (2013), added fixed-price forward contracts and tradable carbon allowances to the Electricity Strategy Game (ESG), a wholesale electricity market simulation developed by Borenstein and Bushnell (2011). The new simulation game is played on a fully integrated Web platform that incorporates many additional market elements.[2] We added retail players that can directly negotiate the price and quantity transacted in fixed-price forward contracts for energy with generating companies as well as decide whether to call ''critical peak pricing rebate'' (CPP-R) periods, which reduce the demand for wholesale electricity from retail customers. Wholesale electricity suppliers can now acquire intermittent wind and solar units, which when they run produce RECs that can be sold to retailers to comply with the RPS.[3]

It was difficult in our game to predict how supply and demand for RECs would develop, making REC prices quite volatile.

In this article we highlight results from two pairs of games (2A/2B and 3A/3B[4]) that incorporated the full set of available markets elements.[5] Each pair of games (for example, 2A/2B) was played simultaneously, with each team playing the role of generating company (''genco'') in one game and retailer in the other. Seven gencos and seven retailers played in each game. Each genco held one of seven portfolios of five to eight dispatchable generating units each.[6] Three gencos were located in the North zone and four gencos in the South zone, and there was a 750 MW transmission line between zones. When the distribution of supply and demand in the North and South caused the transmission line to reach its capacity, the North and South markets separated.

There were also three retail companies in the North and four in the South. Unless they signed fixed-price forward contracts with gencos, the retail companies had to procure power from the short-term market to meet customer demand in each hour; they in turn sold electricity to their customers at a fixed retail rate of \$100/MWh. A retailer could declare a CPP Rebate in any hour. The effect of doing this was to shift the retailer's demand curve in by an average of 20 percent, with some random variation in the actual effectiveness of the CPP-R. The retailer then had to pay \$100 for each MWh that demand was reduced relative to the retailer's ''business as usual'' demand forecast, representing rebate payments made to consumers to encourage conservation. The retailer was still paid its usual \$100/MWh for the realized demand.

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Table 1: Intermittent Renewable Energy Technologies in the Game[a]

Name	Type	Location	Capacity (MW)	Overall Capacity Factor (Wind/Sun as Forecast)	Hourly Capacity Factor (Wind/Sun as Forecast)				Variable Cost ($/MWh)	Fixed Cost ($/hr)
					4am	10am	4pm	10pm		
Altamont Pass	Wind	North	800	25%	40%	10%	10%	40%	$0	$10,000
Shiloh	Wind	North	800	25%	40%	10%	10%	40%	$0	$10,000
Tehachapi	Wind	South	800	25%	40%	10%	10%	40%	$0	$10,000
San Gorgonio	Wind	South	800	25%	40%	10%	10%	40%	$0	$10,000
Central Valley	Solar PV	North	1,300	15%	0%	30%	30%	0%	$0	$20,000
Imperial Valley	Solar PV	South	1,300	15%	0%	30%	30%	0%	$0	$20,000
Central Coast	Solar PV	South	1,300	15%	0%	30%	30%	0%	$0	$20,000
Mojave Desert	Solar CSP	South	1,000	20%	0%	30%	50%	0%	$0	$30,000

[a] To represent intermittency in a stylized way, the actual capacity factor in each hour was modeled as a random variable with a truncated normal distribution (no capacity factors less than 0 percent or greater than 100 percent) with standard deviation of 20 percentage points. This resulted in an expected average generation per hour (accounting for the truncation of the distribution) of 216 MWh for wind, 199 MWh for solar PV, and 202 MWh for solar CSP. We set there to be 100 percent correlation between realized capacity factors of units of the same type in the same location in the same period (e.g., any wind unit in the North would produce exactly the same amount of energy in a given hour as any other wind unit in the North). All other units were uncorrelated with each other.Any upfront costs of acquiring renewables were, in effect, levelized in the game into an hourly fixed cost. The fixed costs in Table 1 translate into the following levelized costs of electricity if capacity factors are as forecast: $46/MWh for wind ($10,000/hr divided by 216 MWh/hr), $100/MWh for solar PV ($20,000/hr divided by 199 MWh/hr), and $149/MWh for solar CSP ($30,000/hr divided by 202 MWh/hr). These levelized costs were chosen to be on the low end of the ranges assembled by Borenstein (2011) for these technologies, although with fixed costs for CSP were set relatively higher than those for PV due to the limited experience base with CSP projects. The prospect for storage is part of the appeal of real solar CSP developments (Denholm et al., 2013), but we have not yet incorporated the possibility of storage into this game.

Games 2A/2B were played in class and each consisted of two electricity market ''days,'' where each day consisted of four ''hours,'' each with a different forecast for both electricity demand and wind and solar conditions. Games 3A/3B had four electricity market days and were played outside of class over about two weeks. Before each electricity market day, gencos submitted offer prices (indicating their willingness to supply energy) for each of their generating units in each hour of the game. The intersection of the resulting aggregate supply curve with the realized demand curve (which is downward sloping but relatively inelastic) in each hour determines the short-term price of electricity and quantity of generation in that hour.

At any point in the game,[7] gencos were allowed to acquire an unlimited number of wind, solar photovoltaic (PV), and/or concentrating solar power (CSP) units, which have the stylized characteristics shown in **Table 1**. In all hours in the electricity market after a renewable unit was acquired, it generated electricity (and produced RECs) for its owner at zero variable cost in accordance with the realized wind and solar conditions. It also incurred a fixed cost in each hour regardless of whether it was running, consistent with the actual cost structure of these generation units.

The strengths and weaknesses of each type of unit were set to be broadly reflective of how these technologies might perform in California. Wind units have the lowest fixed costs and the highest capacity factor, and their generation is typically highest at night (10 pm and 4 am hours). Solar PV units have higher fixed costs and generate power during the day (10 am and 4 pm). CSP units are most expensive but can deliver significant power in late afternoon, when demand in our simulation is generally highest relative to supply.

Each of the games incorporated an RPS requiring that retailers procure 20 percent of the total electricity they sold from wind and solar units or face a $365/MWh penalty for any portion of this obligation not

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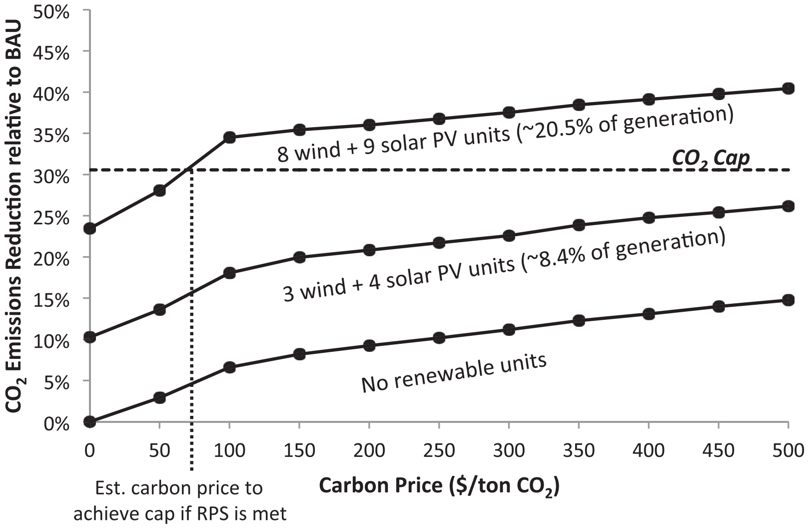

Figure 1: Benchmark Simulation to Estimate the Required Carbon Price to Meet the CO_2 Cap with Different Levels of Wind and Solar Generation. Each curve is generated by: (1) Adding the specified number of renewable units into the system, spread evenly among the gencos, (2) Bidding in all dispatchable units (natural gas, coal, hydro, and nuclear) at their marginal costs, including the variable cost of carbon at the specified carbon price, (3) Running the market with electricity demand and wind and solar generation set to be exactly as forecast, and (4) Comparing the resulting CO_2 emissions to the ''Business as Usual'' (BAU) case where there is no carbon price and no wind and solar capacity. As more renewable units are added to the system, a lower carbon price is required to meet a given emissions reduction target.

covered by renewable energy certificates (RECs).[8] Generating companies needed to cover their CO_2 emissions over the entire period of the game with sufficient carbon allowances or face a penalty of $500 for each ton of CO_2 emitted in excess of their allowance holdings. The total number of carbon allowances in the game (the ''cap'') was set at a level approximately 30 percent lower than ''business as usual'' emissions in the absence of any carbon regulation.[9]

The relative stringency of the RPS and carbon cap is an important baseline determinant of REC and allowance prices. The benchmark simulation (assuming price-taking behavior by all market participants) shown in Figure 1 illustrates the relationship between the RPS and the carbon cap in our game. As has been observed in Europe, strong renewable energy mandates push down the carbon price needed to meet a particular CO_2 cap—potentially all the way to zero if the RPS itself reduces emissions to the level of the cap or below. To create a more interesting game, we intentionally set the carbon cap in this market such that it would not likely be met by complying with RPS targets alone. Figure 1 suggests that the market in our game could meet the RPS with 8 wind plus 9 solar PV units (representing about 20.5 percent of total generation) and then satisfy the cap with an allowance price of around $70/ton of CO_2.

In games 2A/2B, all available carbon allowances were freely distributed in equal shares to the gencos at the start of the game. In games 3A/3B, all of the allowances were auctioned off, with both gencos and retailers eligible to bid. RECs and carbon allowances were freely tradable among teams at any point during the game,[10] including during a ''true up'' period after the final day of the electricity markets and before any compliance penalties were assessed.

IIII. Observations from the Game

A. Summary of game results

Table 2 illustrates some of the results in games 2A/2B and 3A/3B. Renewable energy generation comfortably exceeded the 20 percent RPS target in all four games; only in game 2B was it even close. As would be expected, lower REC prices were observed in games that exceeded the RPS target by a greater margin. Aggregate emissions came in under the CO_2 cap in all games except 2B. However, the average traded carbon price remained high in games 3A and 3B due to significant market power issues (see Section III.D). Market power also played a role in REC markets, but to a lesser degree, for reasons that we will discuss.

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Table 2: Summary of Games.

Game	2A	2B	3A	3B
Renewable Generation as % of Total	28.3%	22.8%	28.1%	44.1%
Average Traded REC Price	\$116	\$161	\$97	\$22
CO_2 Emissions as % of Cap	92.3%	101.2%	88.8%	74.0%
>50% of CO_2 Allowances Initially Held by One Player			✓	✓
Average Traded CO_2 Allowance Price	\$112	\$298	\$290	\$304
Average Electricity Price (Generation-Weighted)	\$38	\$59	\$108	\$66

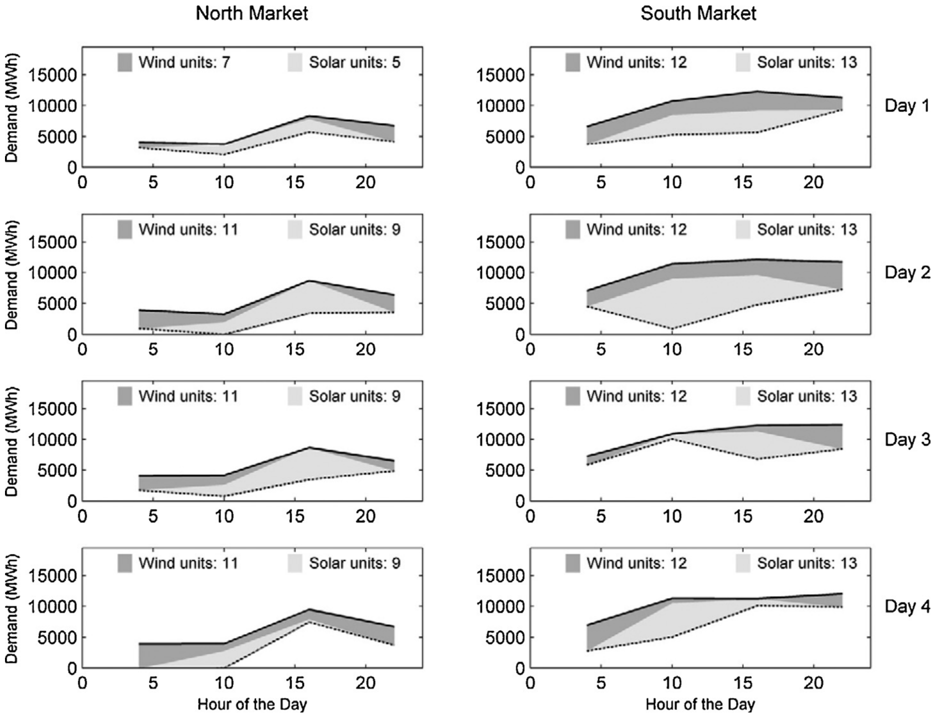

Figure 2: Total Demand Over Each Day in Each Region (Solid Line) and Remaining Demand after Subtracting Renewable Generation in the Region (Dotted Line), for Game 3B. The dark gray shaded areas represent wind generation, and the light gray shaded areas represent solar generation. Results between the simulated hours (4 am, 10 am, 4 pm, and 10 pm) are interpolated. Wind and solar represented 44 percent of total generation in this game.

Spot electricity prices, which strongly influenced genco profitability, were a complicated function of renewable energy share and carbon price expectations. As we will discuss in Section III.B, high wind and solar penetration tended to push down electricity prices by displacing higher-variable-cost units. Expectations of a higher carbon price would push up electricity prices as gencos built carbon costs into their bids. Such expectations could derive either from supply-demand fundamentals in the carbon market, as in game 2B, or from concerns that one or two teams might hold all of the available allowances, as in games 3A and 3B.

B. Interactions between renewable energy, carbon, and electricity markets

As shown in **Figure 2** for a game (3B) in which 44 percent of total generation came from wind

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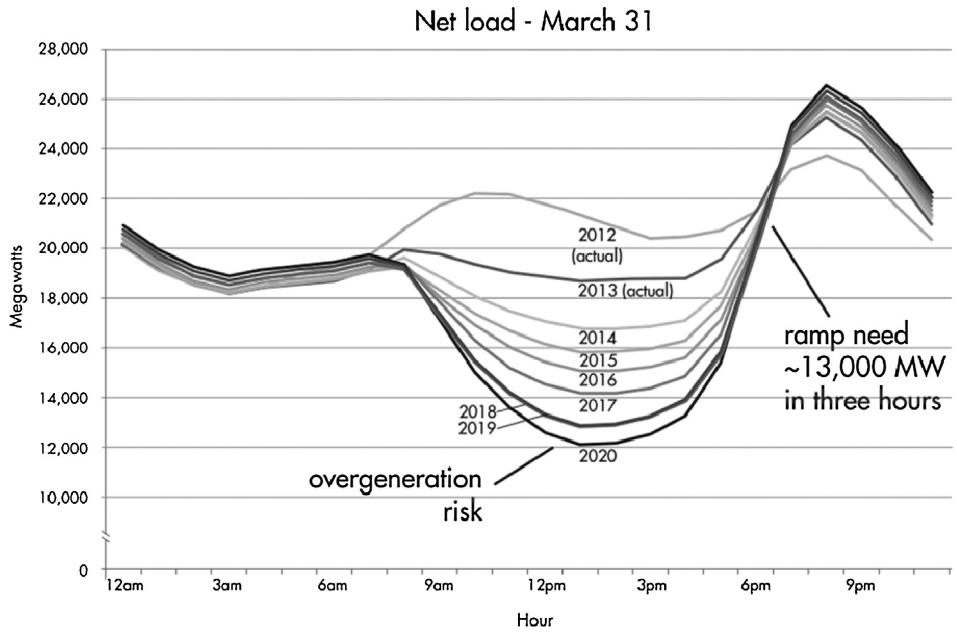

Figure 3: Example of the ''Duck Curve,'' Taken from California ISO (2013), ''Fast Facts: What the Duck Curve Tells us About Managing a Green Grid'' (http://www.caiso.com/Documents/Flexibleresourceshelprenewables_FastFacts.pdf). The idea is that a steady increase in solar generation over time takes a big chunk out of effective daytime load, creating a profile that looks like a duck, with a rapid swing in dispatchable power needs as the sun sets.

and solar, renewable generation could significantly depress the effective load to dispatchable units while shifting the time of the peak. The intermittent nature of wind and solar also led to significant hour-to-hour variability in the load profile. In real electricity markets like California's, the load profile that results from significant penetration of solar energy is known as the ''duck curve'' (**Figure 3**). Our results in Figure 2 do not exactly replicate the duck curve due to the limited number of hours we considered, the stylized characteristics of our wind and solar units, and the fact that players in our game wisely diversified between wind and solar rather than skewing too heavily toward solar alone. Wind was cheaper—and as a result turned out to be more profitable in most cases—while acquiring solar was a bet in part that the 4 pm hour would continue to yield higher electricity prices than other periods. The results show the value of the simulation for exploring the kinds of load curves (whether shaped like ducks or other animals) that may be generated by different policy incentives.

As in some real markets, zero-variable-cost generation from renewables exerted significant downward pressure on wholesale electricity prices (and genco profitability). **Figure 4** illustrates this effect, comparing the 10 am hour in the North region in a game with no renewable energy to the 10 am hour in a game with significant renewable energy and broadly similar bidding from dispatchable units (Game 3B, Day 4). In the latter case, wind and solar generation alone was sufficient to meet demand, resulting in an electricity price of zero.

In regions and periods with heavy renewable penetration, generators stopped trying to exercise unilateral market power by submitting offer prices in excess of the marginal cost of their thermal units, realizing that it was often futile because of all of the zero-variable-cost renewable generation. **Figure 5** shows how renewable energy discouraged such attempts. In Day 2 of game 3B (top of Figure 5), the ''Big Gas'' and ''Old Timers'' teams in the South region both bid in all of

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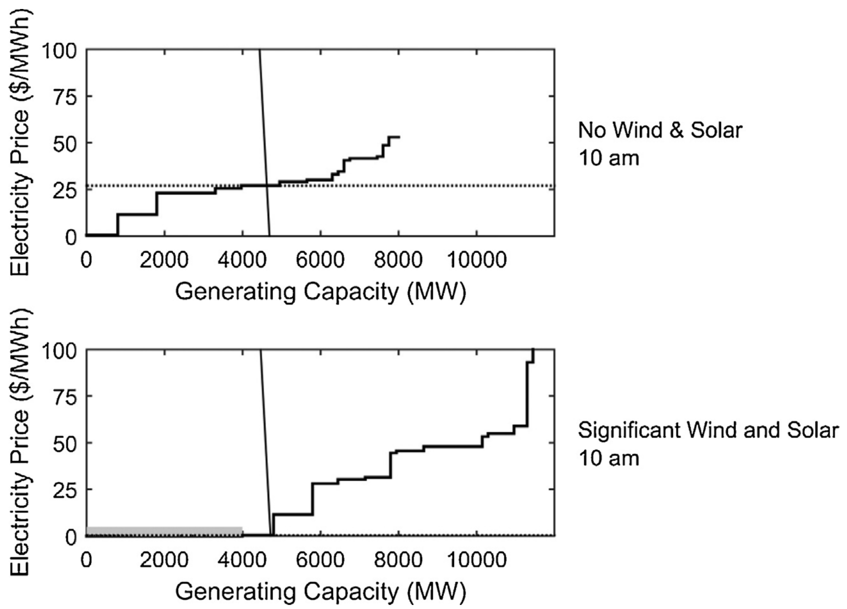

Figure 4: Comparison of the 10 am hour in the North Region for a Game with No Wind and Solar Units (Top) and One with a Significant Number of Wind and Solar Units. Wind and solar generation are indicated with a gray bar (bottom). In each case, the series of steps is the bid curve, the near-vertical line is the demand curve, and the dotted horizontal line is the market-clearing price of electricity.

their units at $500/MWh in an effort to push the price to its cap while still keeping enough capacity on-line to reap handsome profits. Without renewables, or even with lesser renewable capacity, this strategy would have been guaranteed to work due to the high South demand in the 4 pm and 10 pm hours. However, in this game it proved a complete failure at 4 pm due to heavy renewable generation and an almost complete failure at 10 pm, when these two teams did manage to spike the price but in so doing took almost all of their own capacity off-line (bottom of Figure 5). There were no comparable attempts to push the electricity price to its cap over the remaining three days of game 3B. (Even so, we have to be careful about extrapolating a benefit to consumers; in the real world, unlike in the game, generators may have advance warning through weather forecasts that renewable generation will be low in certain periods, allowing them to bid very high in these periods.)

Lacking the same exposure to the exercise of market power by generators, retailers also stopped hedging their spot price risk through the purchase of fixed-price forward contracts from gencos. (As discussed in Thurber and Wolak (2013), high forward contract obligations for gencos have the beneficial effect of discouraging gencos from attempting to exercise market power because they are unlikely to benefit and may even be forced to buy high-priced spot power.) In a benchmark game we played without renewable energy (or a cap-and-trade for carbon), retailers bought almost 40 percent of their electricity via forward contracts with gencos in order to limit their exposure to genco market power and potentially high spot prices. In game 3B, with its proliferation of wind and solar units, retailers bought 100 percent of their power on the spot market.

Renewable generation would be expected to lower wholesale electricity prices both directly, by pushing higher-cost units out of the generation mix, and indirectly, by increasing the likelihood that the carbon cap will be met and thereby decreasing the expected carbon cost that generators factor into their bids. These basic effects were observed in our game, but so were more surprising interactions between the renewable energy, carbon, and electricity markets. For example, the very high renewable energy share in game 3B largely held down electricity prices in the first two days of the game. As shown in Figure 5, it became clear to generators that they could not as easily push up short-term prices by submitting high offer prices for their thermal units. Moreover, renewable generation in game 3B was sufficiently high that the carbon cap would easily be met in the aggregate, suggesting that the cost of buying allowances to cover emissions would be low. These calculations

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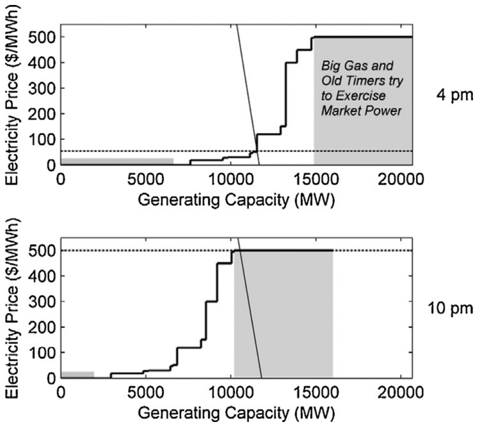

Figure 5: High and Unpredictable Wind and Solar Generation (Gray Bars at Left) Makes it More Difficult for Generators to Successfully Exercise Market Power by Bidding at the Price Cap. ''Big Gas'' and ''Old Timers'' succeeded in spiking the price in the 10 pm hour, but with little benefit to themselves, as the vast majority of their thermal units did not run (bid curves shown for game 3B, day 1, south region).

initially led gencos to bid in the zero-carbon-price marginal costs of all of their thermal units in Day 2 (see the top bid curve in **Figure 6**), resulting in low electricity prices. However, between Day 2 and Day 4, all of the gencos realized that a single team (Big Coal) was holding nearly all of the available carbon allowances. This meant that Big Coal would be able to extract significant profits in the carbon market even with CO_2 emissions coming in significantly below the cap. By Day 4, therefore, gencos began factoring carbon prices of $200–300/ton into their electricity market bids, knowing that they might have to pay this much or more for allowances to cover emissions from their thermal units (see the bottom bid curve in Figure 6). Because thermal units still set the market-clearing price in most hours, the result was high electricity prices in the final market day despite the significant renewable capacity.

C. Why did gencos acquire so many renewable units?

The game results raise an important puzzle: Why did generators collectively sabotage themselves by buying so many renewables?[11] Large amounts of renewable energy significantly harmed their profitability by pushing down spot electricity prices and also by limiting their ability to exercise market power. Gencos did benefit from selling RECs to retailers, but the oversupply of renewables pushed down REC values—as well as the market-clearing electricity prices that each renewable unit would be paid. Gencos did not face any RPS compliance obligations themselves, and there should in theory have been little incentive for gencos to buy renewables to push down the price of carbon, as higher carbon prices actually benefited most gencos as long as they incorporated this cost into their bids. (Thurber and Wolak (2013) showed that a higher carbon price actually enhances profitability of all but one of the gencos in the game by pushing up electricity prices faster than it increases costs and pushes units out of the merit order, although it is possible that not all players appreciated this fact.)

Several factors were likely involved in the extraordinary renewable energy build-outs that we saw in almost every run of the game. First, unlike in the real California, there is no transmission interconnection queue or other regulatory or investment constraint on how rapidly new renewable units can be brought online.[12] California generators may be grateful that they do not live in a state with more efficient processes for interconnecting new wind and solar facilities!

Second, the RPS in our game—unlike the real RPS in California and most other jurisdictions—had teeth, in the form of high penalties for retailers that failed to cover their 20 percent RPS requirement. Gencos therefore had confidence that they could sell RECs to retailers at good prices, at least if the RPS target was not exceeded by too much in the aggregate. In fact, some teams intentionally bought up significant renewables early in

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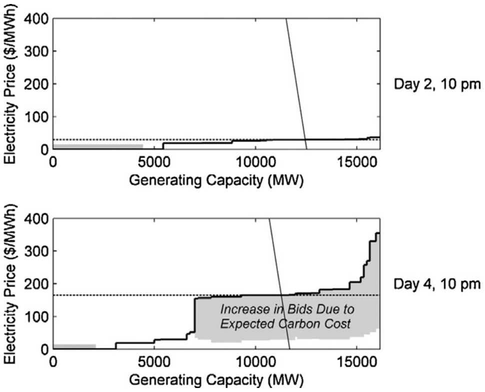

Figure 6: High renewable generation in game 3B makes it clear that aggregate emissions will be far under the CO_2 cap, explaining the low carbon costs factored in to day 2 bids (top), but gencos realize by day 4 that one genco holds almost all of the allowances, so they need to start building in a high carbon cost anyway (bottom) (bid curves shown for south region).

the game in an effort to accumulate market power in the REC market, with the hope that other gencos would refrain from buying additional renewables as self-defeating.

Third, it proved difficult for teams to collectively restrain purchases of renewables by all of the other six gencos, though they certainly tried. All it took was one team that insisted on ''irrationally'' buying additional wind and solar units even after significant renewable capacity was in place. The fundamental incentives problem was that new renewable additions could be quite profitable to an individual generator, as long as nobody bought too many so that electricity and REC prices stayed high. But without some effective (and perhaps illegal) way of restraining new additions, renewables overcapacity tended to develop, hurting all generators.

D. REC and carbon allowance trading

If trading is competitive, REC and carbon allowance prices should be a function of whether the electricity market is on target to meet its respective compliance targets for renewables and CO_2 emissions. If renewable generation is falling short of the 20 percent RPS target, this should increase REC prices and stimulate further wind and solar additions. If carbon emissions are looking like they will come in above the 30-percent-below-business-as-usual cap, this should boost the price of allowances and stimulate mitigation actions, which could include the incorporation of a higher price of carbon into electricity market bids as well as the acquisition of more renewable units.

Considering REC markets first, we see that price levels indeed broadly tracked the level of wind and solar penetration (Table 2). The highest average REC price was observed in the game with the lowest renewable energy penetration (2B), while the lowest average REC price was observed in the game with highest renewable energy penetration (3B).

And yet the detailed trading patterns shown in **Figure 7** also highlight important departures from what one would expect in the competitive market case. The RPS target was met in the aggregate in all four games, but the REC price did not go all the way to zero in any of them. In the waning moments of most games, there ended up being a limited number of teams with RECs remaining to sell. Even if they could not sell all of their remaining RECs, they were able to sell the ones they had at a substantial mark-up due to the absence of competing suppliers. In game 3A, for example, Big Coal made a healthy trading profit by holding on to its RECs until just before the close of trading and then selling large quantities at high prices even though the RPS target had been comfortably met in the aggregate. (In game 3B, there was such an oversupply of RECs and abundance of REC suppliers that this strategy was not feasible even near the end of trading.)

The degree of market power observed in the carbon market proved a strong function of the initial allowance distribution. Because allowances

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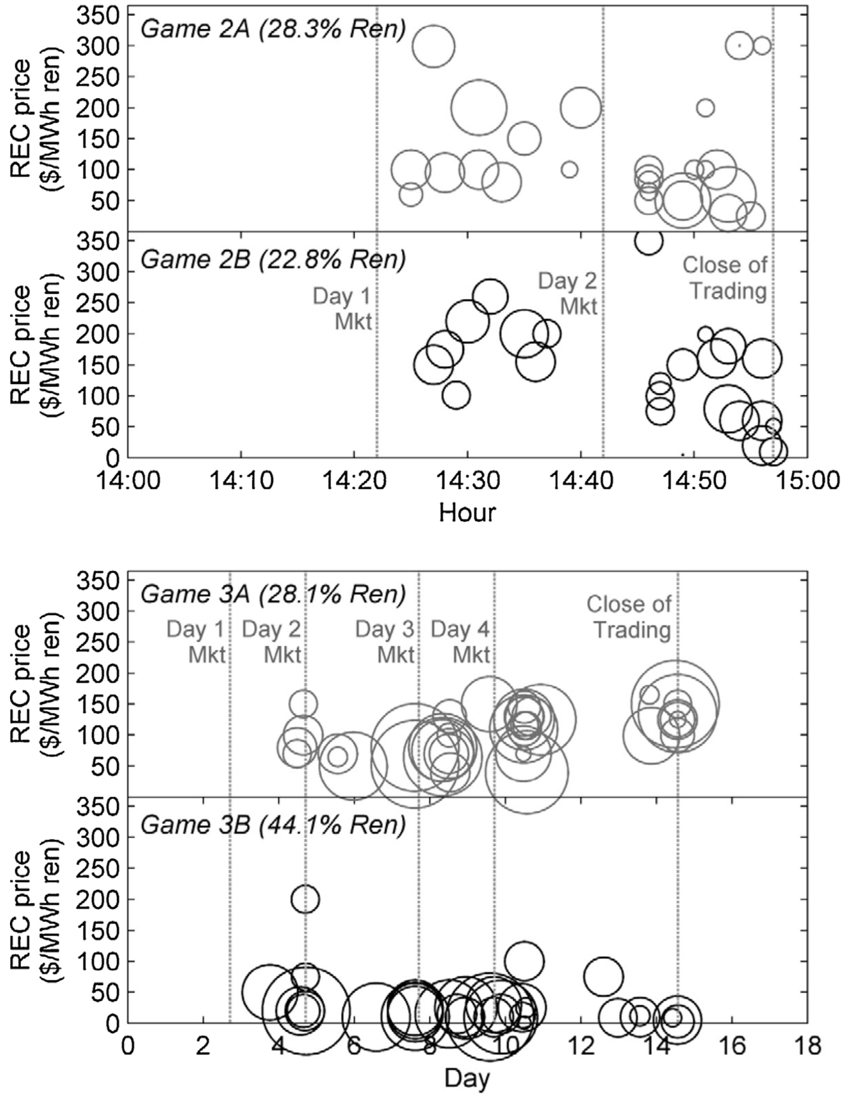

Figure 7: REC Trading in Games 2A/2B and 3A/3B. Each circle is a trade, with the *x*-coordinate of the center indicating time of the trade, *y*-coordinate indicating price, and area of the circle proportional to trade volume. Circles are gray for ''A'' game trades and black for ''B'' game trades. The trading in games 2A/2B took place in one class period; the trading in games 3A/3B took place over a period of about two weeks. Renewable generation share as a percentage of total generation is shown in parentheses for each game.

in games 2A/2B were evenly distributed among all seven gencos at the outset, there were enough allowance sellers and buyers to produce competitive outcomes (Figure 8). In game 2A, once it became clear after day 2 of the electricity market that emissions were well within the cap, allowance prices went to very low levels. In game 2B, emissions narrowly exceeded the cap after the day 2 market was run, and the resulting scarcity of allowances drove prices toward the price cap of \$500/ton of CO_2.

Carbon market behavior was very different in games 3A/3B, in which 100 percent of allowances were distributed via a sealed bid, uniform price auction. Initial allowance supply after the auction ended up being quite concentrated in comparison with allowance supply in games 2A/2B or REC supply in any game. In both 3A and 3B, a single team ended up holding more than 50 percent of the allowances after the auction, and that team (Big Gas in game 3A and Big Coal in game 3B) also ended up being the provider of all allowances sold on the final day of trading. As a result, the final day carbon price was set not by competitive supply and demand—after all, there were plenty of allowances in aggregate to meet demand in both games—but rather by a game of eleventh-hour ''chicken'' between monopoly sellers and a limited number of prospective buyers. As the final minutes of trading approached in game 3A, the number of buyers dwindled and Big Gas was forced to accept lower prices. In game 3B, monopoly supplier Big Coal held to a firmer line in refusing to lower allowance prices below \$300. This resulted in heavy losses for both Big Coal and prospective buyers that were unable to cover their emissions, but in a repeated game this might still have been a good strategy for Big Coal to show that it was willing to stick to its negotiating position even at significant cost to itself.

The more equal distribution of allowances in games 2A/2B seemed to lead not only to more competitive trading but also to earlier trading. One explanation is that potential monopolists believe that they will

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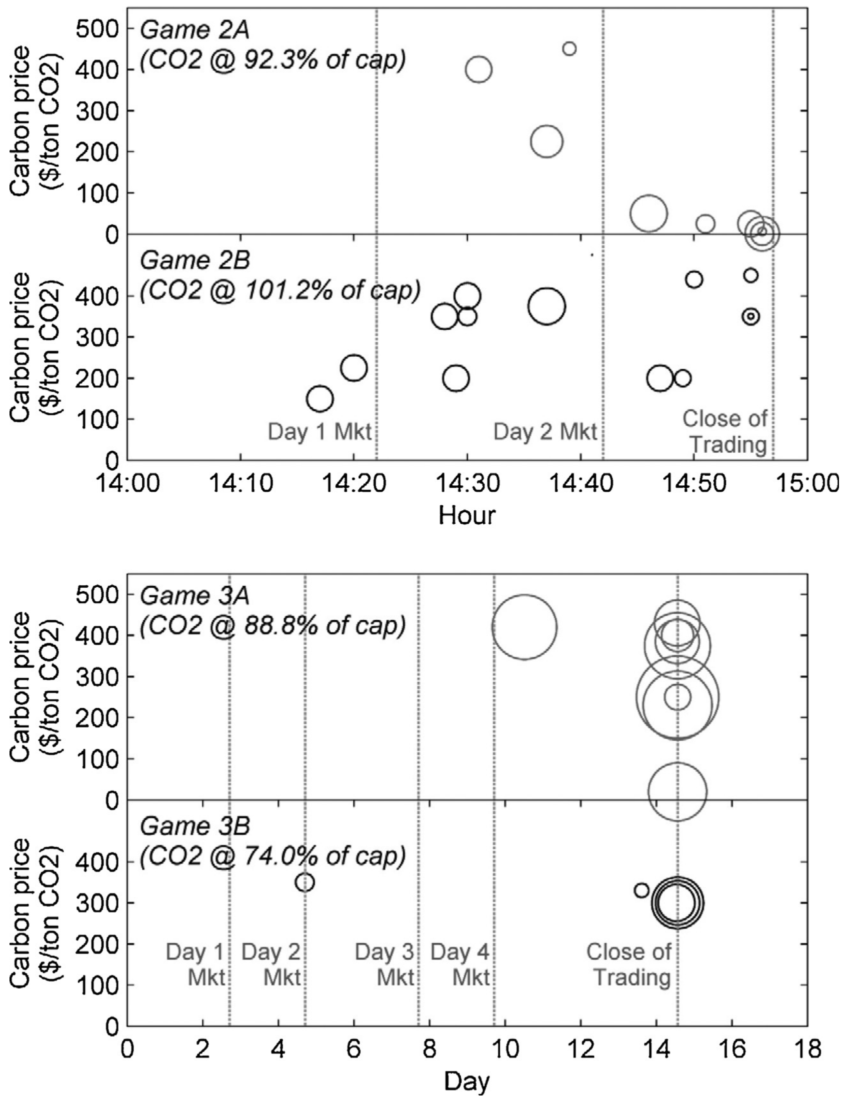

Figure 8: Carbon Allowance Trading in Games 2A/2B and 3A/3B. Each circle is a trade, with the *x*-coordinate of the center indicating time of the trade, *y*-coordinate indicating price, and area of the circle proportional to trade volume. Circles are gray for ''A'' game trades and black for ''B'' game trades. The trading in games 2A/2B took place in one class period; the trading in games 3A/3B took place over a period of about two weeks. Total carbon emissions as a percentage of the cap are shown in parentheses for each game.

have most leverage to extract higher prices as the trading deadline nears. (On the other hand, buyers can also band together to try to squeeze the monopolist with collective buying power as the deadline approaches, as occurred in game 3B.) An alternative explanation that is worthy of further investigation is that a more even distribution of allowances, with multiple likely buyers on both buying and selling sides, somehow constitutes a ''nudge'' to trading that could increase liquidity in these kinds of markets.

IV. Conclusions

Due to the ease of renewables acquisition in our game, the market penetration of utility-scale renewables was more similar to that observed in jurisdictions like Germany with limited interconnection bottlenecks and very favorable financial incentives than to actual experience thus far in California.[13] The game underscored the way high renewable energy penetration can depress wholesale electricity prices, which is a common phenomenon in Germany and other European countries. This situation presents several practical problems. First, it makes dispatchable units less profitable even as they remain needed for when renewable energy is not available. (While the *average* dispatchable unit in our game still broke even after the introduction of renewables, many higher-variable-cost peaker units no longer ran at all and thus could not cover their fixed costs.) Second, it makes the renewable units themselves less able to cover their high fixed costs.

The game illustrated a few of the particular challenges of using an RPS as a tool for stimulating renewable energy investment. First, REC prices are inherently unpredictable due to their sensitivity to the share of renewable generation relative to the RPS target.[14] We saw this phenomenon in the game (at least before teams purchased massive amounts of wind and solar in some games); it is also amply evident in real markets (DOE, 2013). This price uncertainty can make it difficult to leverage RECs as a source of long-term value to

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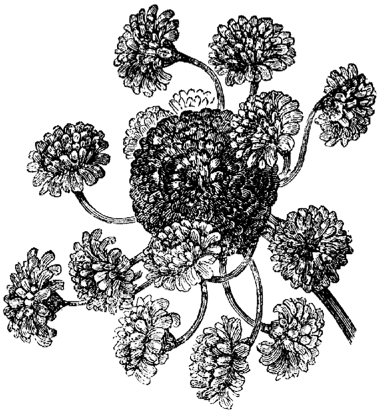
finance renewables, for example as part of PPAs (Cory et al., 2009).[15]

Second, RECs are a more potent prod to investment to the extent that they exist in an environment of relative policy stability and are backed by a credible government commitment to allow their prices to appreciate significantly if renewables targets are not met. This is the situation in our game. But in California, RPS targets and rules have periodically changed, there has been significant uncertainty about the treatment of RECs from out-of-state generation, and transmission constraints and other barriers to renewables that provide utilities with a (reasonable) excuse for arguing that they were incapable of meeting a given target. The various obstacles to bringing on new renewable generation in California are a boon to generators that might face lower average wholesale prices in a more renewables-heavy environment.

The REC and carbon markets in our game illustrated the value of transparency, banking and borrowing, holding limits, and other measures to improve market competitiveness. Because our game had a significant number of renewable energy providers and retailers who needed RECs, the market was usually competitive until near the end of trading when there were few buyers and sellers remaining. One lesson for retailers in our game was that it was safer to purchase RECs well in advance of the compliance deadline rather than risk a high-stakes negotiation at the end. This ''endgame problem'' could be mitigated by allowing banking and borrowing of RECs across periods.

Attempts by players in the game to accumulate a monopoly position in RECs might be mitigated to a degree by more public disclosure of trades or the imposition of position limits. Rules to ensure that renewables ownership, and therefore REC production, is not overly concentrated could help as well.



The game illustrated how the dynamic nature of RPS compliance makes REC prices too volatile to reliably spur renewable energy investment. This may suggest that caps and floors for REC prices would be useful. A REC price floor would keep the RPS relevant even if exogenous factors (for example, a relaxation of RPS targets or a downturn in the economy) make it easier than expected to meet the aggregate target. A REC price ceiling would preserve some politically feasible incentive for renewable energy development even when the RPS target appears unattainable. In effect, an RPS with a price cap and floor would turn into a sliding-scale feed-in tariff for renewable energy where the tariff depends on progress toward the RPS target.

Carbon markets in our game showed a serious tendency toward concentration when 100 percent of allowances were auctioned. In neither of the two games with full auctioning did teams intend to accumulate massive carbon allowance positions, but quite divergent expectations among teams about carbon prices nonetheless led to this outcome. The exercise of unilateral market power in carbon markets that resulted had the effect of pushing carbon prices—and thus electricity prices—far higher than they would have been based only on aggregate supply and demand for allowances. Echoing our observations above for REC markets as well as previous discussion in Thurber and Wolak (2013), these market power problems might have been reduced if our game had incorporated disclosure rules for allowance trades, position limits, banking and borrowing, and floor and ceiling prices.[16]

The game revealed the potential for complex interactions between the various policies in play. For example, electricity

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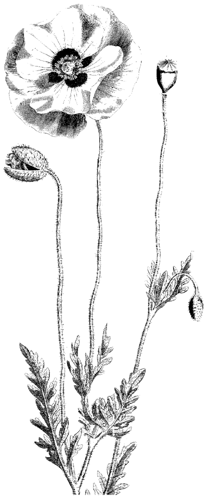
prices spiked when there was market power in the carbon market, but only when the renewable energy fraction was low enough that thermal units still set the electricity price most of the time. High renewable energy generation discouraged retailers from focusing as much on hedging against high prices, but this could cause them to be highly exposed if wind and solar resources are unavailable.

The simulation raises a broader question about the basic wisdom of simultaneously implementing an RPS and a cap-and-trade, as in California. If the cap-and-trade is less stringent than the RPS, there seems to be little justification for having both policies in place unless there is a carbon price floor. In our game, we deliberately set the carbon cap so that it would require additional mitigation actions beyond simply meeting the RPS. This could be rational if the goal is to subsidize the renewable energy industry up to a certain point and then seek the most cost-effective greenhouse gas emissions reductions beyond that. It is important, however, for policymakers to consciously consider (and perhaps simulate) the possible interactions between the RPS and the cap-and-trade.

Early applications of this simulation game as a tool to help policymakers think through possible implications of different policies have been encouraging. In the spring of 2014 we used these market simulation tools with a group of regulators from West Africa who were exploring possible designs for a wholesale market in their country. The game-based approach proved extremely effective in helping these energy officials, who came in with a wide variety of professional and academic backgrounds, collectively grapple with the advantages and disadvantages of different market design choices. We will continue to build out this important education and policy outreach component of the work in parallel with our efforts to run controlled experiments with students that rigorously test the impact of different market rules.■



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Endnotes:

1. In fact, having a patchwork of rules is more often the norm than the exception in energy and environmental policy. California's combined use of an RPS and a cap-and-trade market is one example, but there are many others. Various countries already covered by the EU Emissions Trading Scheme (EU ETS)

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for greenhouse gas emissions have also deployed specific incentives for renewable energy, including feed-in tariffs (notably in Germany and Spain) and RPS-type policies (as in the case of the Renewables Obligation in the U.K.).

2. Trevor Davis coded the new integrated game.

3. Each renewable technology has a different stochastic pattern of output and average capacity factor modeled on the actual pattern of output during the day and capacity factor of actual renewable generation units employing this technology.

4. Games 1A/1B did not have full trading of allowances and RECs and therefore are not discussed here.

5. The games described here were played by students in our Winter 2014 course on ''Energy Markets and Policy'' in the Stanford University Graduate School of Business.

6. These portfolios were originally created by Borenstein and Bushnell (2011) to roughly represent the holdings of California power companies after restructuring. See Thurber and Wolak (2013) for a summary of generation portfolio characteristics.

7. The exception was that renewables acquisition was prohibited during designated periods before each electricity market day was run so that teams would know exactly how many renewable units would be on the system when they decided how to bid in the capacity of their dispatchable generation units, trade forward contracts, and make CPP-R decisions for the coming day's electricity market.

8. We set the RPS non-compliance penalty to be equal to the carbon emissions penalty of \$500/ton of CO_2 multiplied by the emissions rate of the highest emitting thermal unit in the game, which is 0.73 tons CO_2 per MWh. (Note that emissions rates in our game tend to be lower than those of the actual California generating units they are modeled after.) This approach treats wind and solar additions as a carbon mitigation strategy and assumes for the purposes of setting the RPS penalty that the generation they replace would come from the highest-emitting thermal unit.

9. Taking advantage of our secure hold on power as course instructors, we deliberately made both the RPS and the carbon cap far more stringent than would be politically tolerable in the real world, with the goal of making any effects of these policies more visible than they might otherwise have been.

10. RECs are not actually created until the first wind and solar units run, so the earliest any RECs could be traded was after the first day of the electricity market. In the period since the games described here were run, we have added ''shorting'' functionality into the game that lets players trade RECs and carbon allowances they do not have.

11. Note that gencos were able to see all of the renewables that had already been brought online before they acquired new ones.

12. In future versions of the game we could explore the use of PPA contracts between gencos and retailers as an alternative mechanism for bringing new renewable capacity online.

13. It is possible, of course, that gencos in our class would have lost their enthusiasm for renewables acquisition if they had repeated the game a number of additional times. The prospect for substantial renewables earnings through RECs in our game was not as certain as profitability under a generous feed-in tariff.

14. It is often difficult to forecast exactly how much renewable generation will be brought on line in a certain time frame. Renewable generation can also be highly sensitive to the economy (because of its effect on congestion) and, to some extent, weather. Total electricity consumption is also a strong function of the economy.

15. In theory, derivative instruments like fixed-price forward contracts for RECs could help hedge price risk, but the underlying government commitment to stable RPS policy is probably too weak to allow a market for such derivatives to develop.

16. In future investigations we hope to run a large number of games with and without various of these rules in order to test their effectiveness.

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