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Expecting the Unexpected: Emissions Uncertainty and Environmental Market Design

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We study potential equilibria in California's cap-and-trade market for greenhouse gases (GHGs) based on information available before the market started. We find large ex ante uncertainty in business-as-usual emissions and in the abatement that might result from non-market policies, much larger than the reduction that could plausibly occur in response to an allowance price within a politically acceptable range. This implies that the market price is very likely to be determined by an administrative price floor or ceiling. Similar factors seem likely to be present in other cap-and-trade markets for GHGs.

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There is broad consensus among economists that pricing greenhouse gases (GHGs), through either a tax or a cap-and-trade market, should be a central component of a cost-effective climate policy. A substantial and predictable price on GHGs into the distant future provides incentives to limit activities that produce GHGs, make long-lived investments in existing lower-carbon technologies, and fund research and development of new approaches to reducing carbon emissions.[1]

Prices in existing cap-and-trade policies for GHGs, however, have at times been very volatile and have often been so low as to create little incentive to reduce GHG emissions. The European Union Emissions Trading System (EU-ETS), the world's largest GHG market, experienced a sharp drop in prices – from above 20 euros per tonne in early 2011 to below 4 euros in 2013.[2] The European Commission responded in 2014 by reducing the emissions cap.[3] The Regional Greenhouse Gas Initiative (RGGI), which covers electricity generators in the Northeastern U.S., made a similar administrative reduction to the emissions cap in 2014 in response to persistently low allowance prices.[4]

In this paper, we study California's cap-and-trade market for GHGs. The market, which covers emissions beginning in 2013, has the broadest scope of any GHG market in the world. It includes emissions from electricity generation, industrial production, and transportation fuels, which together comprise nearly all anthropogenic emissions except those from agriculture.[5] Throughout the first six years, the program has seen prices at or very close to the administrative price floor. Our analysis finds that in the absence of such administrative intervention, extremely low or extremely high prices are the most likely outcomes.

Two factors drive this conclusion. First, there is a high level of *ex-ante* uncertainty in future "business-as-usual" (BAU) emissions. BAU GHG emissions are closely tied to future economic activity and weather conditions (temperature and rainfall), which are very difficult to forecast. GHG emissions are also subject to the uncertain effects of non-market environmental policies – often referred to in policy debates as "complementary policies" – such as fuel-economy standards, mandated renewable generation shares of electricity production, and energy-efficiency standards.[6] These uncertainties have long been recognized as an

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[1] The largest share of GHGs is CO_2, which we discuss broadly as "carbon emissions" following the popular vernacular.

[2] The standard measure of GHG's is metric tonnes of CO_2 equivalent, CO_2e, in order to convert other greenhouse gases into a standardized climate change metric. One tonne of CO_2e is the quantity released from burning approximately 114 gallons of pure gasoline.

[3] The EU-ETS emissions cap reduction seemed to have relatively little effect until May 2017 when the price began to climb from about 4 euros per tonne, reaching over 24 euros in December 2018.

[4] The RGGI cap reduction has had less effect. The December 2018 allowance auction cleared at \$5.35 per tonne.

[5] Neither the EU-ETS, nor RGGI include transportation fuels. RGGI includes only emissions from electricity generation.

[6] The term "complementary policies" presents some irony, because in economic terms most of these programs are probably more aptly described as substitutes for a cap-and-trade program. However, these policies may increase the political acceptance of cap-and-trade markets by assuring cap-and-trade skeptics that certain pathways to GHG reduction will be required regardless of the allowance price.

issue when forecasting both damages and mitigation costs,[7] but they also create uncertainty in the amount of emissions abatement that will be necessary in order to attain a given cap level.

Second, over the range of GHG prices generally deemed politically acceptable, the predictable price response of GHG abatement is likely to be small compared to the uncertainty in emissions levels. In California, the typically-low elasticity of energy demand is lowered further by complementary policies, because they frequently mandate actions that consumers might otherwise have chosen to take in response to a higher GHG price, such as buying a more fuel-efficient car. These factors are likely to be present in other regions with GHG cap-and-trade markets, because each has adopted a cap-and-trade in concert with complementary policies to reduce capped emissions. The combination of a wide probability distribution of BAU emissions and relatively price-inelastic supply of emissions abatement results in outcomes skewed towards very high or very low prices.

In recognition of the problems created by uncertain allowance prices, economists have proposed hybrid mechanisms that combine emissions caps with administrative price collars that can provide both upper and lower bounds on allowance prices.[8] Such hybrid mechanisms can greatly reduce allowance price risk while ensuring a better match between *ex-post* costs and benefits (Pizer, 2002). The fact that California's allowance prices were higher than the other major GHG cap-and-trade programs from its inception through 2017 is almost certainly due to its relatively high price floor.

Using only information available prior to the commencement of California's market, we develop estimates of the distribution of potential allowance prices that account for uncertainty in BAU emissions, the effect of complementary policies and the price-responsiveness of abatement. Our analysis of the distribution of potential market equilibria proceeds in three stages. First, we estimate an econometric model of the drivers of BAU GHG emissions using time-series methods and use it to estimate the distribution of future BAU GHG emissions. Second, we account for GHG reductions from complementary policies and other "non-market" factors outside the cap-and-trade program. Third, we use a range of energy price elasticity estimates to account for the emissions abatement that could occur in response to the GHG emissions price.

Combining these analyses, we estimate the distribution of equilibrium allowance prices. We find that, due to uncertainties in BAU emissions and in the quantity of abatement available from non-market factors, the support of the distribution of abatement needed to meet an emissions cap is much broader than the amount of price-responsive abatement that could plausibly be provided within a politically

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Some of these policies are also designed to address other market failures, such as innovation incentives or principal/agent conflicts in energy consumption.

[7] When discussing controversies about mitigation costs, Aldy et. al. (2010) note that "[f]uture mitigation costs are highly sensitive to business-as-usual (BAU) emissions, which depend on future population and Gross Domestic Product (GDP) growth, the energy intensity of GDP, and the fuel mix."

[8] See, for instance, Jacoby and Ellerman, 2004, and Burtraw et al., 2009.

acceptable price range. Therefore, regardless of the level at which the emissions cap is set, there will be a low probability of an “interior equilibrium” in which price-responsive abatement equilibrates emissions with that cap. Rather, the outcome is very likely to be driven primarily by administrative interventions at pre-determined floor and ceiling prices.[9]

Based on the information available before the market opened, we find that the California's emissions cap for 2013-2020 was set at a level that implied a 94.3 percent probability the allowance market would clear at the price floor, with total emissions below the cap. We find a 1.1 percent probability that the price would be in the interior equilibrium range, above the price floor and below the market's soft price ceiling at which some additional allowances are released, described further below. The remaining 4.6 percent probability weight is on outcomes in which the price is at or above the soft price ceiling.

In July 2017, California adopted legislation extending the program to 2030 and setting much lower emissions targets for the additional decade. The legislation left many critical aspects of the extended program unsettled, including the price floor and ceiling mechanisms. Nonetheless, we also report results for a reasonable prototype of a program running through 2030. We find that the emissions cap proposed through 2030 is likely to yield substantially more balanced probabilities of outcomes at the price floor or price ceiling. Even in that analysis, however, we still find only a 20 percent probability of an interior equilibrium.

Unlike Weitzman's (1974) seminal work on prices versus quantities, and much of the analysis that has applied that framework to cap-and-trade markets for pollutants, ours is not a normative analysis.[10] Rather, our positive empirical analysis demonstrates the high likelihood of very high or very low prices in California's market for greenhouse gas emissions. While very high or low prices are not an economic impediment to the operation of cap-and-trade markets, they may be a political impediment, as they seem in practice likely to trigger *ex-post* administrative interventions. Moreover, significant uncertainty about the allowance price is unlikely to provide the most effective signal for long-term investments in GHG emissions abatement technologies.

The large uncertainty in the level of BAU emissions from which reductions must occur has not been explicitly recognized in previous studies of cap-and-trade market equilibria, which have tended to employ deterministic models.[11] To account for uncertainty in key parameters, such as energy prices and macroeconomic growth, modelers sometimes performed sensitivity analyses, but the choice

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[9] Or, in the case of EU-ETS and RGGI, *ex-post* emissions cap adjustments, an alternative administrative intervention.

[10] See Newell and Pizer (2003) for an application of Weitzman's analysis to a stock pollutant such as GHGs. See Newell, Pizer and Raimi (2014) and Schmalensee and Stavins (2017) for overviews of cap-and-trade programs in practice to date.

[11] To model equilibria in their respective markets RGGI used the Regional Economic Modeling, Inc. model (RGGI, 2005), the U.K. Department of Trade and Industry used ICF's Integrated Planning Model (U.K. DTI, 2006), and the California Air Resources Board (ARB) used ICF's Energy 2020 model (ARB, 2010a).

of which parameter values to include and the probability to assign to each parameter value has not been based on statistical distributions estimated from historical data, which limits analysts' ability to draw inferences about the relative likelihood of alternative scenarios. The most sophisticated of these studies is Neuhoff et al. (2006), which compares the EU ETS Phase-II cap level with 24 deterministic model-based projections. Assigning equal probabilities to each projection, the authors find that there is a significant chance that BAU emissions will fall below the cap. To limit the likelihood of a price collapse, they conclude that regulators should set a more stringent emissions cap. In contrast, we explicitly model uncertain abatement demand and supply, concluding that these uncertainties are quite large compared to likely levels of price-responsive abatement. This implies a low probability of an interior equilibrium regardless of the stringency of the cap.

The remainder of the analysis proceeds as follows. Section I introduces California's cap-and-trade market, and characterizes the set of possible market outcomes given the attributes of the supply and demand for GHG emissions abatement. Section II describes how we estimate the distribution of BAU GHG emissions over the 2013-2020 period using a cointegrated Vector Autoregression (VAR) model estimated using data from 1990 to 2010. In Section III, we explain how we incorporate the non-market factors that affect future GHG emissions. In Section IV, we analyze the likely impact that a GHG price would have on abatement. We present results in Section V under the baseline scenario for complementary policies and other non-market factors, and we also show how the cap-and-trade program might operate in the absence of complementary policies. Section VI briefly compares our estimated results to actual outcomes through 2015 and discusses analysis of an extended market out to 2030. We conclude in section VII.

I. The California Cap-and-Trade Market

California's cap-and-trade program was established as part of ARB's implementation of Assembly Bill 32, adopted in 2006. AB 32 also established a number of complementary policies and modified some existing programs, all in pursuit of reducing GHG emissions. California's first cap-and-trade allowance auction took place on November 14, 2012 and compliance obligations began on January 1, 2013. At the time, the quantity of available allowances was set for 2013-2020, after which the future of the program was uncertain.

We focus on estimating the potential range and uncertainty in allowance demand, abatement supply, and prices over the original 8-year span of the market. We carry out the analysis based on estimates of the distribution of future emissions using data through 2010. These were the most up-to-date data available by late 2012, months before the market commenced operation. Presumably, the GHG emissions cap would have to be set at least that far in advance of the start of any cap-and-trade market. Consequently, our analysis addresses the question of what distribution of market outcomes a regulator could reasonably expect at the time the emissions cap is set.[12]

The 8-year market was divided into three compliance periods: 2013-2014, 2015-2017, and 2018-2020. In the first compliance period, the market excluded tailpipe emissions from transportation and on-site emissions from small stationary sources (mostly residential and small commercial combustion of natural gas), known as "narrow scope" coverage. In the second compliance period, transportation and small stationary sources were also included, with the total known as "broad scope" coverage. In November of the year following the end of each compliance period, covered entities are required to submit allowances equal to their covered emissions for that compliance period. Banking allowances for later use is permitted with very few restrictions.

Allowances are sold quarterly through an auction held by the ARB. There is an auction reserve price (ARP), which was set at \$10.50 in 2013 and has thereafter increased each year by 5 percent plus the rate of inflation in the prior year. There is also an allowance price containment reserve (APCR) designed to have some restraining effect at the high end of possible prices by adding a limited number of allowances to the pool if the auction price hits certain price trigger levels. Of the 2,508.6 million metric tonnes (MMT) of allowances in the program over the 8-year period, 121.8 MMT were assigned to the APCR to be made available in equal proportions at allowance prices of \$40, \$45, and \$50 in 2012 and 2013. After 2013, these price levels have increased annually by 5 percent plus the rate of inflation in the prior year.

Because of the relatively generous allowance quantities made available in the early year auctions, and the ability of the ARB to shift some additional allowances from later years, emissions during the first two compliance periods were very unlikely to exceed the allowances available. This implies that the eight years of the market were likely to be economically integrated. As a result, we examine the total supply/demand balance over the entire eight years of the program.[13]

As is standard in analyses of market mechanisms for pollution control, we present the market equilibrium as the outcome of a demand for and supply of emissions abatement. We define the demand for emissions abatement as the difference between BAU emissions and the quantity of allowances made available at the ARP.

What we term "abatement supply" in this characterization encompasses both price-responsive emissions reductions and reductions due to complementary policies. Also, we include reduced compliance obligations due to credit for emissions "offsets" (*i.e.,* administratively verified reductions from emitters in locations or

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[12] In late 2013, the ARB finalized plans to link California's cap-and-trade market with the market in Quebec, Canada as of January 1, 2014. Our analysis does not include Quebec, because the analysis is based on information available in 2012. Quebec, with total emissions of roughly 1/7 California's, was seen as a likely net purchaser of allowances, which would increase somewhat the probability of higher price outcomes.

[13] Borenstein, Bushnell, Wolak and Zaragoza-Watkins (2014) discusses the details of the compliance rules in more detail and the possibility of short-run mismatches between the release of allowances by ARB and the demand for allowances by compliance entities.

sectors not covered by the program). Finally, California regulators have recognized the potential for activities that do not reduce actual emissions, but just change contractual counterparties in a way that reassigns responsibility for emissions to entities not covered by the program, known broadly as "reshuffling."[14] We incorporate reshuffling in abatement supply as well. While incentives for offsets and reshuffling are affected by the price of allowances, previous analyses suggest that the bulk of this eligible activity would be realized at prices below or very close to the ARP. For presentational clarity, we also include additional allowance supply that can be released from the APCR at higher prices as part of abatement supply.[15]

The analytical approach is illustrated in Figure 1, which presents a hypothetical probability density function (PDF) of abatement demand quantities – BAU emissions minus allowances available below the APCR prices – along with one possible abatement supply curve. We present the abatement supply curve beginning at the ARP with a quantity at that price equal to the sum of non-market abatement, which occurs regardless of the allowance price, and some very inexpensive abatement supply (mostly from offsets and reshuffling) that is likely to be cheaper than the ARP. The supply then increases as price rises to the APCR. At three price levels, extra allowance supply from the APCR is released, followed by additional price-responsive abatement at prices above the APCR. In reality, the quantities in each component of the supply curve are uncertain so there is a probability distribution of abatement supply curves as well as abatement demand quantities. Nonetheless, this illustration demonstrates that the probability of an interior equilibrium depends upon the share of the area under the abatement demand PDF that overlaps with the interval under the (price-responsive) abatement curve between the floor and ceiling prices. The next section describes our methodology for estimating the PDF of the abatement demand, while section III describes our methodology for estimating the PDF of the quantity of price non-responsive abatement (*e.g.,* from complementary policies) and section IV describes our methodology for estimating the PDF of price-responsive abatement.

In its revised Scoping Plan of 2010, ARB's preferred model projected that 63 percent of emissions abatement would arise from complementary policies rather than from responses to the cap-and-trade program.[16] It is important to emphasize that these reductions are not costless; indeed many are likely to have abatement costs per tonne of GHG emissions greater than the allowance price. Rather, these reductions, and the accompanying costs, will be approximately independent of the level of the allowance price. Therefore, while these policies provide reductions, and contribute to the goal of keeping emissions under the cap, they do not provide the price-responsive abatement that could help mitigate volatility in allowance

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[14] See Bushnell, Chen and Zaragoza-Watkins (2014).

[15] Equilibrium is determined by the *net* supply of allowances, so including a particular factor as an increase in abatement supply or decrease in abatement demand will not alter the analysis.

[16] ARB (2010b) at page 38 (Table 10). This projection does not include the effects of exogenous energy price increases, reshuffling, or offsets.

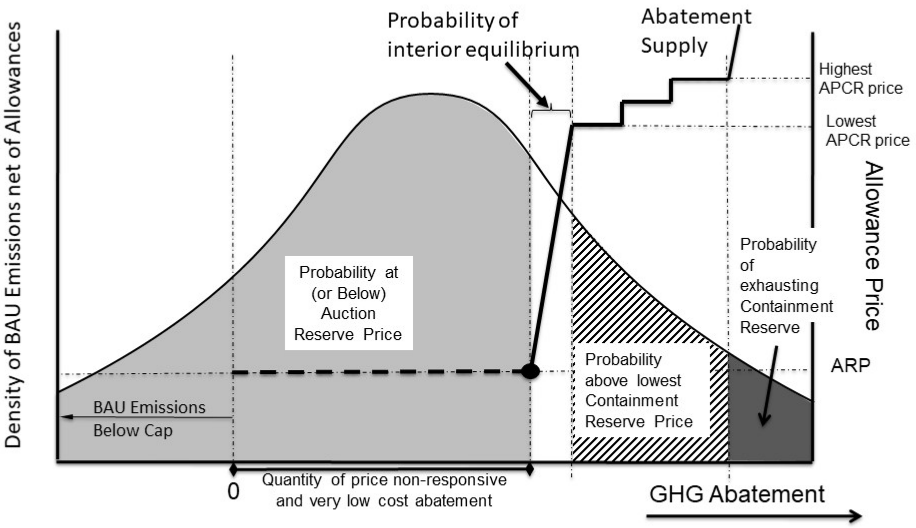

Figure 1. Hypothetical Distribution of Abatement Demand and Supply

prices.

The supply of price-responsive abatement is further limited by an allowance allocation policy designed to protect in-state manufacturers that are subject to competition from out-of-state producers. These "trade exposed" companies receive free allowances based on the quantity of output (not emissions) that the firm produces. Such output-based allocation reduces the firm's effective marginal cost of production and, thus, reduces the pass-through of the allowance price to consumers, and the associated reduction in consumption of these goods. But it does so while retaining the full allowance price incentive for the firm to adopt GHG-reducing methods for producing the same level of output.[17]

Large amounts of abatement from complementary policies and other very low-cost sources, combined with relatively modest price-responsive abatement, suggests a "hockey stick" shaped abatement "supply" curve, as illustrated in Figure 1.

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[17] For a detailed discussion of the economic incentives created by output-based allocation, see Fowlie (2012). If applied to a large enough set of industries or fraction of the allowances, Bushnell and Chen (2012) show that the effect can be to inflate allowance prices as higher prices are necessary to offset the diluted incentive to pass the carbon price through to consumers.

A. Price Evolution and Estimated Equilibrium Price in the Market

The analysis we present here models abatement supply and demand aggregated over the 8-year span of the market. We calculate the equilibrium as the price at which the aggregate demand for abatement over the 8 years is equal to the aggregate supply of abatement. Our primary analysis focuses on this program alone, assuming that the market is not integrated into a successor market or some geographically broader program. When the market commenced, there was no clarity on how the program would evolve after 2020 or other regional programs with which it might be merged.

Throughout this analysis, we assume that the emissions market is perfectly competitive. In Borenstein, Bushnell, Wolak and Zaragoza-Watkins (2014) we analyze the potential for exercise of market power given the characteristics of supply and demand in the market. While we find a potential for short-term exercise of market power, we do not find a plausible incentive to exercise market power in a way that would change the equilibrium price over the full 8-year course of the market.

At any point in time, two conditions will drive the market price of an allowance, an intertemporal arbitrage condition and a long-run market equilibrium condition. If the markets for allowances at different points in time are competitive and well integrated, with a sufficient number of risk-neutral participants, then intertemporal arbitrage will cause the *expected* price change over time to be equal to the nominal interest rate (or cost of capital).[18] At the same time, the price *level* will be determined by the condition that the resulting expected price path – rising at the nominal interest rate until the end of 2020 – would in expectation equilibrate the total supply and demand for allowances for the entire program.[19]

Throughout the market's operation, new information will arrive about the demand for allowances (*e.g.,* weather, economic activity, and the energy intensity of Gross State Product (GSP) in California) and the supply of abatement (*e.g.,* supply of offsets, response of consumers to fuel prices, and the cost of new technologies for electricity generation). This sort of information will change expectations about the supply-demand balance in the market over the length of the program and thus change the current equilibrium market price. With risk neutral traders,

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[18] See Rubin (1996) and Holland and Moore (2013) for detailed analyses of this issue. Pizer and Prest (2016) show that with inter-temporal trading and policy updating, regulators can exploit the arbitrage condition to implement the first-best policy.

[19] Because of lags in information and in adjustment of emissions-producing activities, supply and demand will not be exactly equal at the end of the compliance obligation period. At that point, the allowance obligation of each entity would be set and there would be no ability to take abatement actions to change that obligation. The supply of allowances would have elasticity only at prices that trigger the APCR, where additional supply is released, and the level of a hard price cap, if one existed. Thus, the price would either be approximately zero (if there were excess supply) or at one of the steps of the APCR or the compliance penalty (if there were excess demand). Anticipating this post-compliance inelasticity, optimizing risk-neutral market participants would adjust their positions if they believed the weighted average post-compliance price outcomes were not equal to the price that is expected to equilibrate supply and demand. Such arbitrage activity would drive the probability distribution of post-compliance prices to have a (discounted) mean equal to the equilibrium market price in earlier periods.

the price at any point in time should be equal to the expected present discounted value of all the possible future prices that equilibrate the realized supply (plus allowances and offsets) and realized demand for abatement. As discussed below, we approximate this price evolution process by incorporating price-responsive abatement into the supply-demand analysis.

II. Estimating Business-as-Usual Emissions

The greatest source of uncertainty in the market's supply-demand balance is likely to be the level of emissions that would take place under BAU. Figure 2 presents annual covered GHG emissions in California in the four major sectors covered by the cap-and-trade program. The increased emissions during the 1995-2000 "dot com boom," as well as the drop that began with the 2008 financial crisis, illustrate both that emissions are correlated with the macro economy and that meeting an emissions goal over an 8-year period could require much more or less abatement than would be implied from considering only the expected BAU level.[20]

We construct an econometric model using historical emissions and other economic data to estimate the distribution of BAU emissions over the eight-year market period that accounts for both uncertainty in the parameters of our econometric model and uncertainty in the future values of the shocks to our econometric model using the two-step smoothed bootstrap procedure described in online appendix section A.1.

To derive our estimate of the distribution of future GHG emissions covered by the program, we estimate a cointegrated vector autoregression (VAR) model with determinants of the major components of state-level GHG emissions that are covered under the program and the key statewide economic factors that impact the level and growth of GHG emissions.[21] Due to the short time period for which the necessary disaggregated GHG emissions data have been collected, the model estimation is based on annual data from 1990 to 2010, which was the information that was available to policymakers in 2012, just before the market opened.

The short time series puts a premium on parsimony in the model. As a result, we use a 7-variable VAR model. We also impose the restrictions implied by cointegrating relationships between the elements of the 7-dimensional vector, which significantly reduces the number of parameters we must estimate to compute a distribution of future BAU values of these seven variables. The model includes three technical drivers of GHG emissions: in-state electricity production net of hydroelectricity production, vehicle-miles traveled (VMT), and the sum of non-electricity-generation natural gas combustion and industrial process GHG

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[20] In both 1997-2001 and 2007-2011 covered emissions changed by as much in absolute value as the entire emissions cap decline over 2013-2020.

[21] VARs are the econometric methodology of choice among analysts to construct estimates of the distribution of future values (from 1 to 10 time periods) of macroeconomic variables and for this reason are ideally suited to our present task. Stock and Watson (2001) discuss the successful use of VARs for this task in a number of empirical contexts.

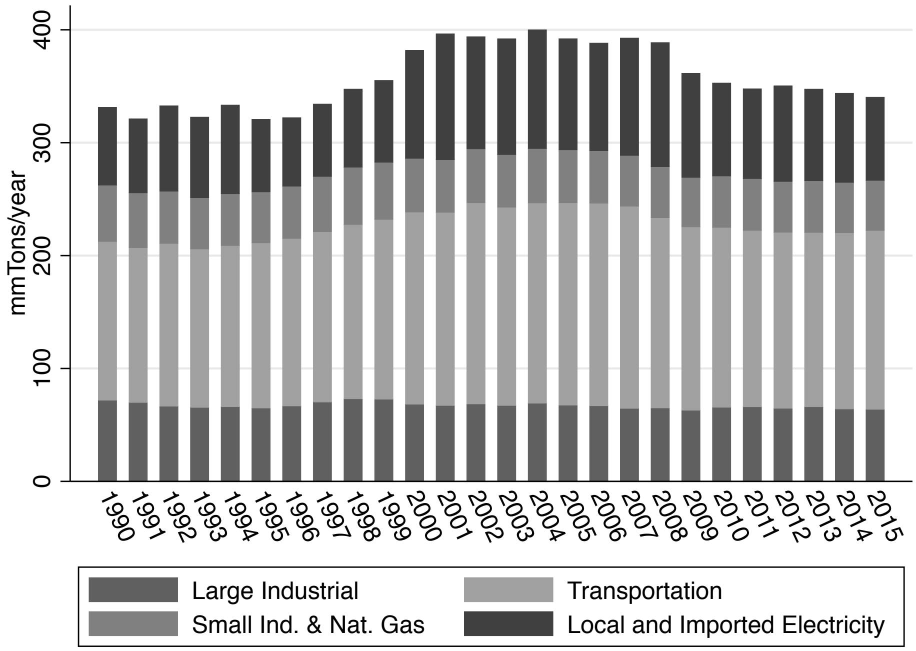

Figure 2. California Emissions from Capped Sectors

emissions.[22] The model also includes the two most important economic factors that influence emissions: real GSP and an index of the real price of gasoline in California. Finally, to facilitate the estimation of the BAU distribution of future GHG emissions in the transportation and electricity sectors under different sets of complementary policies for reducing GHG emissions in these sectors, we also model the behavior of the emissions intensity of the transportation sector and of fossil-fuel electricity generation in California. We simulate realizations from the distribution of BAU emissions from these two sectors as the product of a simulated value of sectoral emissions intensity and a simulated value of the economic driver of transportation (VMT) or electricity emissions (fossil-fuel electricity generation in California).

Summary statistics on the seven variables are presented in Table 1.

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[22] The electricity variable accounts for demand changes (after adjusting for imports as discussed below) as well as uncertainty and trends in hydroelectricity production, both of which are driven in part by variation and trends in weather. We account for other zero-GHG generation sources – wind, solar, and nuclear – explicitly, as discussed below.

Table 1—Summary Statistics of Data for Vector Autoregression

	mean	S.D.	min	max	year min.	year max.
California Generation Net of Hydro (TWh)	159.3	16.5	133.5	185.6	1996	2007
Vehicle Miles Traveled (Billions)	299.7	27.0	258.0	329.0	1991	2005
Industry, Nat Gas & Other Emissions (MMT CO_2e)	114.6	4.6	106.6	123.9	2009	1998
Gross State Product (Real Trillion $2015)	1.83	0.32	1.38	2.25	1992	2007
Wholesale SF Gasoline Price (Real index)	198.83	42.05	146.88	300.09	1998	2008
In-state Elec Thermal Intensity (CO_2e tons/MWh)	0.462	0.056	0.372	0.581	2010	1993
Vehicle Emissions Intensity (CO_2e tons/1000 VMT)	0.535	0.016	0.493	0.554	2010	2000

Note: Data are for 1990-2010

Table 2—Summary Statistics of Simulated VAR Variables

Year	Calif. Elec. Net of Hydro Twh	Vehicle Miles Traveled Mill. Miles	Nat. Gas, Ind. & Other MMT	Gasoline Price Real Index	Gross St. Product $2015 Trillion	Therm. Intensity tons/ MWh	Trans. Intensity tons/1000 Miles
2013	179.2	331.2	108.7	2.71	2.28	0.360	0.485
	(21.5)	(12.9)	(10.2)	(0.75)	(0.24)	(0.043)	(0.027)
2014	181.3	334.9	108.4	2.78	2.33	0.355	0.482
	(24.8)	(14.7)	(11.1)	(0.83)	(0.28)	(0.045)	(0.030)
2015	183.4	338.5	108.0	2.84	2.39	0.350	0.480
	(25.9)	(16.6)	(11.9)	(0.90)	(0.31)	(0.049)	(0.034)
2016	186.0	342.5	107.5	2.90	2.44	0.346	0.479
	(26.3)	(18.5)	(12.7)	(0.98)	(0.34)	(0.052)	(0.036)
2017	186.8	346.5	107.3	2.96	2.50	0.342	0.476
	(28.6)	(20.0)	(13.6)	(1.05)	(0.38)	(0.055)	(0.039)
2018	189.6	350.5	107.0	3.01	2.56	0.338	0.475
	(30.3)	(21.7)	(14.5)	(1.08)	(0.42)	(0.058)	(0.042)
2019	191.5	354.7	106.99	3.07	2.621	0.334	0.473
	(31.1)	(23.8)	(15.16)	(1.19)	(0.452)	(0.062)	(0.044)
2020	193.4	359.0	106.92	3.13	2.684	0.330	0.471
	(32.8)	(25.4)	(16.22)	(1.27)	(0.495)	(0.065)	(0.047)

Note: Estimates are mean values of 1000 draws.
Values in parenthesis are the standard deviations of 1000 draws.

Table 3—Simulated Emissions

Year	Broad Scope Emissions MMT	Cumulative Cappped Emissions MMT
2013	355.7	150
	(20.4)	(11)
2014	356.5	301
	(23.0)	(22)
2015	357.1	658
	(24.5)	(42)
2016	358.6	1016
	(26.5)	(66)
2017	359.3	1376
	(28.3)	(92)
2018	361.2	1737
	(30.3)	(120)
2019	362.6	2099
	(32.5)	(150)
2020	364.0	2463
	(34.5)	(183)

Note: Estimates are mean values of 1000 draws. Values in parenthesis are the standard deviations of 1000 draws.

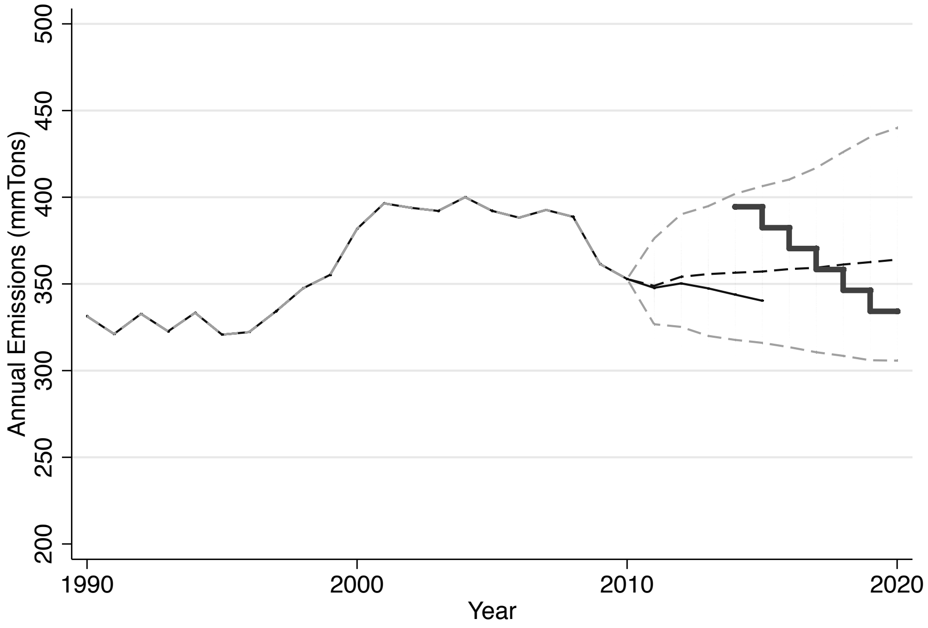
The data sources and the details of the cointegrated VAR specification are presented in online appendix sections A.1.2, A.1.3 and A.1.4. Our procedure for constructing the estimate of the distribution of BAU emissions for the 2013 to 2020 time period is presented in online appendix section A.1.5. We investigate the impact of model uncertainty in online appendix section A.1.6 by comparing the results of using different econometric models for historical GHG emissions to construct our estimate of the distribution of future GHG emissions. We obtain very similar mean forecasts and similar size confidence intervals for BAU emissions from 2013 to 2020 across all of the models.

A. Results

The parameter estimates for the 7-variable VAR are shown in online appendix Table A.5. Table 2 presents the means and standard deviations of the estimated distribution of the seven elements of the VAR for each year from 2013 to 2020.

For each draw from this estimated distribution, we calculate annual GHG emissions from each sector category: transportation, electricity, and natural gas/industrial. Transportation emissions are the product of estimated VMT and estimated GHG intensity of VMT. Electricity emissions require adjusting estimated in-state generation net of hydro for generation from other zero-GHG sources – renewables (solar, wind, and geothermal) and nuclear power – as described in online appendix section A.2.1.1, then multiplying the remainder, which is in-state fossil-fuel generation, by the thermal intensity of fossil-fuel generation. Natural gas/industrial emissions are taken directly from the draw.

The resulting realizations of emissions based upon the variable estimates in Table 2 are summarized in Table 3. Emissions from all sources in the program are shown in the "Broad Scope Emissions" column of Table 3. The final column presents the cumulative emissions covered under the cap-and-trade program, accounting for the fact that transportation emissions and some natural gas/industrial emissions were not included under the narrow scope emissions covered in 2013 and 2014.[23]



Solid line shows actual values; Stairstep line shows annual broad scope cap level

Figure 3. California Broad Scope Mean Emissions Forecast and Confidence Intervals, 2011-2020 (Actual Data, 1990-2015)

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[23] In online appendix section A.1.2, we explain how we decompose the natural gas/industrial emissions category to approximate the share of emissions from this category that is covered in 2013-2014.

Figure 3 illustrates the actual values for broad scope emissions through 2015 and the estimated mean, 2.5th, and 97.5th percentile from the distribution of emissions from 2011 through 2020, based on data through 2010. The vertical dots show the distribution of simulation outcomes. The stair-step line in Figure 3 shows the emissions cap for each year of broad scope coverage, 2015-2020. For the two years of narrow-scope coverage, 2013 and 2014, the emissions cap was within 10 MMT of our mean BAU estimate of those emissions. As can be seen from Figure 3, many realizations fall below the level of capped emissions out to 2020. This is a large contributing factor to the expectation of low allowance prices.

In the next two sections, we describe how we combine these estimates of BAU emissions with abatement opportunities to estimate the distribution of the supply-demand balance in the cap-and-trade market.

III. Impact of Price Non-Responsive Abatement

This section describes how we model a number of possible effects of other state energy policies and other activities that were expected to change covered emissions independent of the price in the cap-and-trade market. For each policy, we assume that abatement will fall within a specific range between a more effective abatement case and a less effective abatement case. We then sample from a symmetric $\beta(2,2)$ distribution to create a random draw of abatement for each policy from within our assumed range.[24] The resulting range of potential price non-responsive abatement from each source is shown in the lower panel of Table 4. We combine each of the 1000 realizations from the BAU emissions distribution from the VAR with a simulated outcome of the price non-responsive abatement to derive a distribution of 1000 emissions outcomes before price-responsive abatement.

A. Zero-Carbon Electricity Generation and Energy Efficiency

In the case of electricity, the main complementary policies are the Renewables Portfolio Standard (RPS) – which in 2011 was increased to mandate that 33 percent of California's electricity consumption must come from qualified renewable sources by 2020 – and energy efficiency (EE) investments. We treat the RPS as reducing the *quantity* of carbon-emitting electricity generation, rather than the carbon *intensity* of generation. In the same way as described in the previous section, we adjust the realization of in-state electricity generation net of hydro to account for the expected increase in renewable generation required to meet the 33 percent RPS. The expected impacts of expanding the RPS on renewable generation in future years are based on external data sources discussed in online

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[24] A $\beta(2,2)$ distribution looks like an inverted "U" with endpoints, in this case, at the low and high scenario abatement levels. The $\beta(2,2)$ is symmetric between the endpoints. We have also experimented with the assumption that the abatement follows a triangular distribution with the low and high ends of the support at the low and high abatement scenarios and the mode at the average of the low and high scenario. The results differed very little from using the $\beta(2,2)$ distribution.

appendix section A.2.1.2. We multiply the value of in-state, fossil-fueled electricity generation net of this realization of renewable generation by the realization from our estimated distribution of the emissions intensity to obtain a realization of the GHG emissions from fossil-fueled generation units located in California.

There is a strong pre-existing trend of energy efficiency improvements already present in the time-series data we used to simulate the distribution of future BAU emissions. As discussed in online appendix section A.2.1.2, we therefore make no further adjustments to account for increased energy efficiency beyond those effects already (implicitly) integrated into our estimate of the BAU emissions distribution.

B. Transportation

We incorporate the impact of stricter GHG policies in the transportation sector – improved vehicle fuel economy and increases in the use of biofuels – through adjustments to the emissions intensity of VMT realization from the estimated distribution. As described in online appendix section A.2.1.3, the low end of this range of emissions intensity is based on a model that ARB used to forecast the impact of GHG policies on vehicle fleet composition and fuel economy. The high end of this range incorporates both ARB's 2011 forecast and the BAU emissions intensity estimation from the VAR. A random draw of emissions intensity from this range, using a $\beta(2,2)$ distribution, is then multiplied by the realization of VMT from our estimated distribution to arrive at a BAU realization of emissions from the transportation sector.

C. Energy Price Changes Exogenous to Cap-and-Trade

We also account for the effects on emissions of two potential energy price changes not attributable to the cap-and-trade program. Real prices of electricity in California were expected to rise over the 2013-2020 period due to capital expenditures on transmission and distribution, increased use and integration of renewable energy, and other factors. We take a 2012 forecast of those increases and apply a range of own-price elasticity assumptions, as discussed in online appendix A.2.1.4. The real price of transportation fuels was also likely to rise due to the cost of using more renewable fuels, as mandated under the LCFS. We consider a range of possible estimates of this effect. Our estimates do not explicitly anticipate the 2014-15 collapse of oil prices and the associated decline in transport fuel prices, but our estimate of the distribution of BAU gasoline prices implies a wide range of possible prices, as shown in Table 2.

D. Emissions Offsets

As in nearly all GHG cap-and-trade programs in the world, California covered entities are allowed to meet some of their compliance obligations with offset credits. Each entity can use offsets to meet up to eight percent of its obligation in each compliance period. In theory, this means that over the 8-year program, up to 218 MMT of allowance obligations could be met with offsets.[25] In online appendix section A.2.1.5, however, we discuss the difficulty of getting approval for offset projects and the fact that the 8 percent share is not fungible across firms or time, both of which are likely to lead to substantially lower use of offsets. We account for the uncertainty in the quantity of offsets likely to be available over the course of the program by taking draws from our best estimate of the range of possible values of offsets.

E. Imported Electricity and Reshuffling

California's cap-and-trade program attempts to include all emissions from out-of-state generation of electricity delivered to and consumed in the state. However, due to the physics of electricity and the extent of the Western electricity grid – which includes states from the Pacific Ocean to the Rocky Mountains – it is not possible to identify the specific generation resource supplying imported electricity. Depending on how the GHG content of imports is administratively determined, electricity importers have an incentive to engage in a variety of trades that lower the reported GHG content of their imports, a class of behaviors broadly labeled reshuffling, as discussed earlier.[26] As explained in online appendix section A.2.1.6, we use information on long-term contracts with out-of-state coal plants to determine the range of possible reshuffling and its impact on allowance demand to cover imported electricity.

IV. Price-Responsive Abatement

In online appendix section A.2.2, we discuss in detail the potential abatement from higher allowance prices. These assessments rely in part on regulatory decisions that affect how allowance prices will be passed through, as well as on previous estimates of demand elasticities for goods and services that produce GHG emissions. Here, we summarize the range of potential impacts we consider and discuss them briefly. The underlying assumptions are shown in more detail in Table A.15 of the online appendix. It is clear from this discussion that the uncertainty in BAU emissions, as well as in the price non-responsive abatement possibilities, are much larger than the potential impact from demand response to cap-and-trade allowance prices.

To evaluate the impact of allowance prices on the demand for GHG emissions, it is important to recognize that the actual allowance price path will evolve over

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[25] Because the offset rule allows 8 percent of total obligation to be met with offsets, it effectively expands the cap to solve the equation $C - 0.08C = 2508.6MMT$. This implies that $C = 2726.7$ and the total offsets allowed would be $2726.7 - 2508.6 = 218.1$.

[26] Also known as "contract reshuffling" or "resource shuffling." Reshuffling, an extreme form of emission leakage, refers to cases in which actual economic activity doesn't change, but generation from a cleaner source is reassigned by contract to a buyer that faces environmental regulation, while generation from a dirtier source is reassigned to a buyer that does not.

time as more information arrives about whether the market is likely to have insufficient or excess allowances over the 8-year life of the program, as mentioned in section I. Even if very high or low prices were to eventually occur, they may not be observed until much later in the program, when participants are fairly certain of whether the market will be short or long allowances. The price in each year will reflect a weighted average of the probabilities of different equilibrium outcomes, eventually ending at the aggregated equilibrium price. In online appendix section A.2.2.1, we present the method we use to account for this price evolution. In brief, for all draws, the price at the beginning of the program is assumed to equal the probability-weighted average of the distribution of (discounted) 2020 equilibrium prices. For each individual draw, the price is assumed to follow a linear path from the weighted-average starting price (*i.e.,* in 2013) to the 2020 equilibrium price associated with that draw.

For gasoline and diesel price response, we assume 100 percent allowance price pass-through based on many papers that study pass-through of tax and crude oil price changes (see, for example, Marion and Muehlegger (2011)). We use an elasticity assumption that is below most long-run elasticity estimates, because improved vehicle fuel economy is a large part of the difference between long-run and short-run elasticity estimates. Fuel economy standards, however, already induce higher fuel economy than consumers would otherwise choose. For natural gas, elasticities estimates are taken from the recent literature. The pass-through of allowance prices to retail natural gas was still unclear in 2012, but seemed likely to be well below 100 percent. Still, we present results assuming 100 percent pass-through, because less-than-complete pass-through may be politically untenable in the longer run, and because even with this upper bound case, price-responsive abatement is relatively small. For electricity, elasticities are also taken from the literature, but pass-through seemed likely in 2012 to be quite complicated, with residential customers protected from these costs and commercial and industrial customers absorbing greater than 100 percent pass-through to cover the shortfall, as discussed in online appendix section A.2.2.3. The effect on abatement, however, is nearly the same as imposing 100 percent pass-through on all customers, so for simplicity we do so.[27]

In online appendix section A.2.2.6, we also discuss possible changes in industrial emissions and explain why – due to a combination of low own-price demand elasticities and policies designed to lower pass-through of the allowance price by industrial emitters – these changes are likely to be very small.

Our analysis of price-responsive abatement incorporates a wide range of possible demand elasticities for electricity, transportation fuels, and natural gas used in residential, commercial, and industrial settings. It does not, however, explicitly account for price-responsive technological breakthroughs in low-GHG energy

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[27] This would not be the case if residential customer demand were much more or less elastic than demand from commercial and industrial customers. There is not, however, consistent evidence in either direction.

sources. Such innovation is one compelling argument for a GHG price, but there are no credible estimates of the magnitude of the innovation price response. Moreover, while a GHG price would likely increase R&D budgets for low-GHG technologies, the outcome of increased research expenditures is highly unpredictable. It could lead eventually to a breakthrough that could displace fossil fuels even at a very low GHG price, but it could instead lead to little significant progress. Finally, the innovation pathway for a GHG price response is very likely to have long lags, which would mean little significant GHG emissions reduction during the 8-year market period that we study. For these reasons, we do not attempt to explicitly incorporate price-responsive technological breakthroughs. By omitting this effect, our results are likely overstating the probability of very high prices, but for the market and timespan we study, the omission is not likely to have a large effect.

The potential range of abatement from each category of price-responsive and price non-responsive sources are shown in Table 4. To put these figures in context, it is useful to recall from Table 3 that the standard deviation of simulated covered BAU emissions over the 8-year program is 183 MMT. By comparison, the mean of our simulated total price-responsive abatement due to an allowance price increase from the floor (APR) to the ceiling (highest tier of the APCR) is 35.1 MMT, about one-fifth of one standard deviation of the BAU distribution.

Table 4—Summary of Abatement Supply

	Abatement over 8 Years			
	Mean	S.D.	2.5%	97.5%
Allowance Price Responsive Abatement				
Electricity				
Price Response (floor)	3.4	0.5	2.5	4.3
Price Response (ceiling)	9.7	1.4	7.2	12.3
Transport				
Price Response (floor)	3.6	0.5	2.6	4.5
Price Response (ceiling)	12.1	1.8	9.0	15.5
Natural Gas				
Price Response (floor)	11.2	2.4	6.6	15.6
Price Response (ceiling)	31.6	6.7	18.9	44.1
Price Non-Responsive Abatement				
Zero-Carbon Electricity & Energy Efficiency	63.1	10.2	43.4	84.7
Transportation	77.9	47.0	4.2	179.6
Exog Elec Price Effects	9.6	1.4	7.0	12.2
Emissions Offsets	97.8	14.6	71.2	124.9
Elec Imports & Reshuffling	63.2	20.7	27.0	101.2
Total at Price Ceiling	365.0			
Total at Price Floor	329.7			

Notes: Price responsive abatement based upon a $\beta(2,2)$ distribution where the endpoints are determined by elasticities of -0.1 to -0.2 for electricity and gasoline, and -0.1 to -0.3 for natural gas.

V. Estimated Market Clearing in the Cap-and-Trade Market

To estimate the distribution of possible price outcomes in the allowance market, we combine the 1000 realizations from the distribution of BAU emissions with 1000 realizations from the distribution of additional abatement sources discussed in sections III and IV. Each of the abatement effects is drawn independently. However, the two largest sources of complementary policy-driven abatement – GHG abatement from vehicles and electricity generation – are positively correlated with BAU emissions by construction. In the case of vehicles, this is because the GHG intensity of VMT is multiplied by the realization of BAU VMT to obtain the realization of transportation GHG emissions. Similarly, GHG emissions from electricity generation from each draw are the interaction of the realization of thermal intensity and the realization of kilowatt-hours of thermal generation, after deducting the realization of renewable generation.

Given the very limited amount of data available on abatement activities and our use of sources from the literature for many of the abatement assumptions, basing correlations of BAU emissions and GHG abatement on empirical analysis isn't likely to be credible. Nor, unfortunately, are even the signs of these correlations clear.[28] Thus, from each realization of BAU emissions, we subtract an independently distributed draw from the assumed distribution of each source of additional abatement.

We consider four mutually exclusive and exhaustive potential market clearing price ranges, as was illustrated in Figure 1: (1) at or near the ARP, with all abatement supply coming from price-inelastic and very low-cost abatement, plus offset supply (some of which may require a price slightly above the auction reserve), (2) noticeably above the ARP, though without accessing any of the allowances in the APCR, with marginal supply coming from price-elastic sources, (3) at or above the lowest trigger price of the APCR, but at or below the highest APCR trigger price, and (4) above the highest price of the APCR.[29]

Based on the 1000 realizations from the distribution of BAU emissions, complementary policies, offsets, reshuffling, and price-responsive abatement, Figure 4 presents our estimate of the PDF of the abatement demand quantity and an estimated abatement supply curve, along with 2.5 percent and 97.5 percent bounds on the curve. This is effectively the empirical implementation of Figure 1. Our results suggest a 94.3 percent probability of the price equilibrating at or very near the ARP, implying that the emissions cap was set high relative to our estimated distribution of BAU emissions, complementary policies, and the offsets and reshuffling that would likely take place at very low prices. Of the remaining probability, we estimate a 1.1 percent chance of a price below the lowest APCR trigger price, what we have referred to as an interior solution. We estimate a 3.4 percent chance of a price within the APCR price range, and a 1.2 percent probability of a price above the highest APCR trigger price. Thus, while the likelihood is low, if emissions were high enough to drive the market off the floor, the price would be more than twice as likely to end up in or above the APCR than at an interior equilibrium, where price equilibrates a fixed supply with demand.

Of course, the low probability of an interior solution results to some extent from the emissions cap being set very high relative to the distribution of BAU emissions net of price-inelastic policies. This likely was not intentional. As of late 2010, after the state's emissions reductions targets had been set, ARB still projected emissions from capped sectors during the decade of 2010-2020 to remain level at about 400 MMT per year absent expanded policy intervention (ARB,

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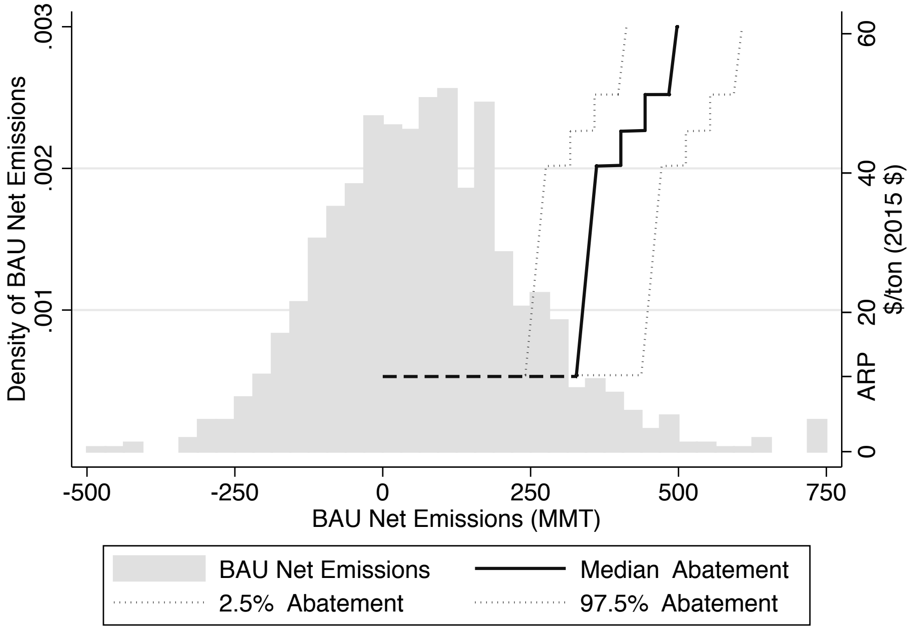
[28] For instance, lax offset policy could be positively correlated with lax policy towards reshuffling, or an inability to control reshuffling could lead to a looser allowance market and put less pressure on regulators to approve controversial offset applications. Similarly, it is unclear whether higher BAU emissions associated with a strong economy would be positively or negatively correlated with the willingness of utilities (and their regulators) to reshuffle contracts or the willingness to accept a higher level of offsets.

[29] California considered program modifications to address the possibility of the price containment reserve being exhausted, but none was adopted prior to the launch of the program. We do not address how high the price might go in case (4). This would be difficult to do even in the absence of this policy uncertainty, because it will be greatly influenced by the state's other policy responses. We simply report the estimated probability of reaching this case and note that prices could be much higher than the highest APCR price.



BAU net emissions are (2013-2020) BAU emissions less allowances not in APCR

Figure 4. Net Emissions and Abatement Supply (2013-2020)

2010c).[30] One might ask how high the probability of an interior solution could have been if the cap were set at a lower level. We investigated this question by re-running our analysis at every integer cap level between 2000 and 3000 MMT to find the cap level that would yield the highest probability of an interior solution. We found that occurred at an emissions cap of 2391 MMT (about 295 MMT lower than the actual cap), resulting in a 9.2 percent probability of an interior solution with the remaining probabilities fairly balanced between lower and higher priced outcomes.[31] In other words, due to the relatively low price responsiveness of abatement, particularly in the presence of complementary policies, and the wide support of the probability density of the BAU emissions, we estimate that no emissions cap level would yield even a 10 percent probability of an interior solution.

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[30] To construct their forecast of 2020 BAU emissions, ARB combined sector-specific average annual emissions levels for the three most recent years for which the GHG Emissions Inventory data were available (2006-2008) with sector-specific growth projections from the California Energy Commission's 2009 Integrated Energy Policy Report. Therefore, ARB's methodology explicitly omitted BAU uncertainty and implicitly supposed that the emissions intensity of activity in each sector would, absent further policy intervention, remain constant through 2020.

[31] A 42 percent probability of an outcome at or near the ARP, a 35 percent probability of an outcome in the APCR, and a 16 percent probability above the APCR.

A. How much difference do complementary policies make?

As section III discussed, we make a number of assumptions about complementary policies in order to adjust the BAU estimates to reflect changes that are likely to occur during 2013-2020. An important question, motivated by the results just discussed, is how much the probability distribution of equilibrium allowance prices would change if complementary policies were not present and the cap-and-trade program were relied upon as the primary mechanism for reducing GHGs.

Removing complementary policies has two significant effects on the analysis. First, it lowers the level of price non-responsive abatement, which in this case causes the price-responsive region of the abatement supply curve to coincide with a higher probability region of the BAU emissions distribution. Second, it increases the price-elasticity of abatement supply by removing the dampening effects of the complementary policies, as discussed earlier.

In this subsection, we re-estimate the distribution of possible outcomes under a counter-factual without complementary policies. To do this, we make assumptions about alternative paths of regulatory rules – such as the RPS mandate and automotive fuel-economy standards. We also make assumptions about price-responsive consumption changes that would result if complementary policies were not pursued. Thus, we are assessing a more idealized implementation of California's cap-and-trade program, with no other programs to reduce GHG emissions, but all sectors fully exposed to the price of allowances.

To implement this approach, we make the following changes in abatement assumptions:

1) Renewable electricity output is frozen at its 2012 level;[32]

2) No effect of complementary or other policies on the realization of vehicle emissions intensity from the VAR;

3) No LCFS, so no impact of the LCFS on the price of fuels;

4) Higher price elasticity of response of energy demand to energy price changes.[33]

The effects of assumptions 1 through 3 are indicated in the first three lines of the lower panel of Table 4, which presents the magnitudes of these shifts of abatement supply that are removed. The effects of assumption 4 are slightly more complicated and amount to roughly doubling the price responsiveness of abatement. The details are described more completely in section A.3.1 of the online appendix.

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[32] This is based on forecasts of renewable generation costs as of 2012, which suggested that neither wind nor solar would be cost competitive during 2013-2020, even with a GHG price in the range of the APCR.

[33] More specifically, elasticities for transportation fuels, natural gas, and electricity are all drawn from a distribution that ranges from -0.3 to -0.5.

Under this scenario with no complementary policies, our BAU distribution estimate yields a substantially smaller chance of the market clearing at or very close to the price floor, 83.1 percent vs. 94.3 percent, and a larger probability of an interior solution in which the market clears at a price above the ARP but still below the APCR, 6.2 percent vs. 1.1 percent under the baseline scenario. The probability of very high prices more than triples, with a 7.4 percent probability of settling in the APCR, and a 3.3 percent probability of exhausting the APCR.

While eliminating complementary policies substantially changes the probabilities, it does not change our fundamental finding that the great majority of the probability distribution lies outside the area of an interior equilibrium. Over 90 percent of the outcome distribution still occurs at the administratively-determined price floor and ceiling constraints on price, or above the APCR in a range that is likely to be politically unacceptable.

VI. Market Performance To Date and Program Extension

Since the first allowance auction in November 2012, the market performance has been consistent with expectations of excess allowance supply. In the 21 quarterly auctions through 2017, the allowance price averaged \$0.67 above the floor, and 5 auctions (February 2016 through February 2017) failed to sell all of the allowances on offer, setting the price at the floor.[34] This softness in the allowance market reflects the gap between the reported actual emissions under the program in its first years of operation and the level of the cap.

In Table 5, we take a closer look at the emissions results for the year 2015. The top panel of Table 5 compares our estimated distribution to 2015 reported values for the seven variables in the VAR of BAU emissions. The bottom panel combines our estimates of abatement with our BAU projections to compare our distribution of forecast emissions after abatement with the actual measured emissions by sector. These values reflect the distribution of projected BAU emissions, less exogenous and price-responsive abatement, as described in the previous section. Note that offsets, which are not directly attributable to any of these specific sectors, are not captured here.

Table 5 indicates that despite the perception of a soft emissions market, 2015 emissions were slightly above our mean estimate. In fact, the upper panel shows that other than VMT being slightly lower than our mean forecast, all other variables in the VAR deviated from the mean forecast in the direction that would increase GHG emissions.[35] The bottom panel shows that every sector except one, electricity import emissions (which include both real reductions and reshuffling), produced net emissions (after abatement) above our mean forecast. The low allowance price and total emissions relative to the cap do not seem to be a result

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[34] These statistics describe the front-year allowance auctions. Auctions for later-year allowances, which take place at the same time, have generally yielded lower prices.

[35] The "NA" for the industry, natural gas and other category reflects the fact that we do not observe the counterfactual omissions from these sources without abatement.

Table 5—Actual vs. Forecast Values of Model Variables for 2015

	2015 Actual	mean forecast	2.5% forecast	97.5% forecast
California Generation Net of Hydro (TWh)	182201	183360	139447	246703
Vehicle Miles Traveled (Billions)	335	338	308	372
Gross State Product (Real Trillion $2015)	2.48	2.39	1.85	3.03
Wholesale SF Gasoline Price (Real index)	229.02	284.06	157.27	475.91
In-state Electricity Thermal Intensity (tons/MWh)	0.364	0.350	0.265	0.457
Industry, Natural Gas, other (MMT before abatement)	NA	107.955	87.359	134.235
Vehicle Emissions Intensity (tons/1000 VMT)	0.473	0.460	0.425	0.488
Transport Emissions (MMT after abatement)	158.5	155.6	130.9	181.6
In-state Electricity Emissions (MMT after abatement)	43.0	39.1	21.8	64.7
Industry, Nat. Gas, other (MMT after abatement)	108.0	106.1	85.5	132.2
Electricity Import Emissions (MMT after abatement)	30.7	32.5	27.7	37.2
Total Broadscope Emissions (MMT after abatement)	340.3	333.3	296.8	377.6

of emissions outcomes below expectations.

A. *Extension of Program through 2030*

In July 2017, California adopted Assembly Bill 398, extending the current cap-and-trade program through 2030. Several details of the new program remain unresolved at the time of this writing, but the annual emissions cap will be reduced from 330 MMT in 2020 to 200 MMT by 2030. In an extension of this paper, Borenstein, Bushnell and Wolak (2017) apply the same approach to estimating the supply-demand relationship under rules that are likely close to those that will govern the extension of the market out to 2030, utilizing the data on market outcomes through 2015 and estimating market outcomes for 2016-2030. They find that the emissions cap through 2030 lies much closer to the center of the "adjusted" BAU distribution (*i.e.,* after adjusting the distribution for complementary policies, exogenous energy price changes, offsets, and reshuffling). As a result, under the primary analysis with a hard price ceiling of $85 in 2030 (in 2015 dollars), they estimate a 46 percent probability of the equilibrium price being at the price floor, a 34 percent probability of the price ceiling, and a 20 percent probability of an outcome between the floor and the ceiling. The higher estimated probability of an interior equilibrium results from a combination of the cap level being close to the center of the "adjusted" BAU distribution and an assumption of higher price elasticities due to estimating over a time period that is nearly twice as long as the originally-legislated 8-year market.

The outcome of that analysis again makes clear that the probability of an interior equilibrium depends very much on the level of the cap compared to the adjusted BAU distribution. Still, the analysis through 2030 demonstrates that even if the cap lies very close to the center of the adjusted BAU distribution and abatement is much more price-elastic, the probability of an interior solution remains low.

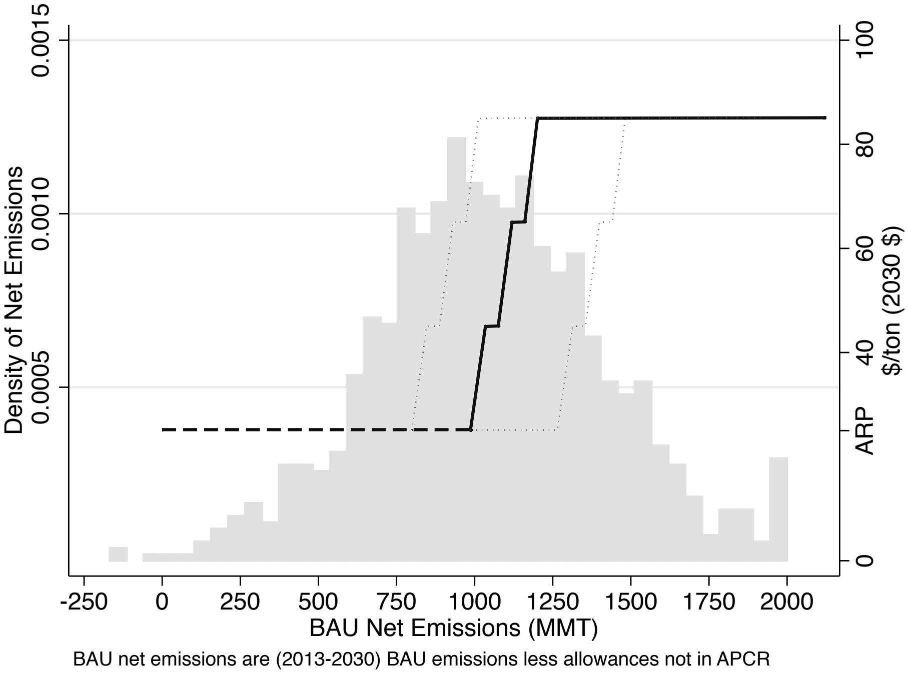

Figure 5. Net Emissions and Abatement Supply (2013-2030)

VII. Conclusion

If cap-and-trade programs for greenhouse gases are to successfully expand around the world, it is important to understand the possible outcomes of these markets. We have analyzed supply and demand in the California cap-and-trade market over its first authorized period, 2013-2020, in order to estimate the distribution of possible price outcomes and the factors that could drive those outcomes. We find that great uncertainty associated with BAU emissions creates a wide range of possible allowance demands. Combining this with a steep supply curve of abatement creates an inflexible net allowance supply. These two findings suggest that absent administrative restrictions, the price of allowances in the market would likely be extremely low or high.

Our analysis has demonstrated two implications of using cap-and-trade mechanisms for addressing GHG emissions that do not seem to have been widely appreciated. First, there is substantial uncertainty in the BAU emissions from which any assessment of needed abatement must start. Typically, analyses of targets for GHG reduction programs have taken BAU emissions as a known quantity. Our analysis suggests that BAU uncertainty is likely to be at least as large as uncertainty about the effect of abatement measures. Second, over the range of prices that have been considered politically acceptable, at least in California, there is likely to be relatively little price elasticity of emissions abatement. This is due in part to the demand for emitting GHGs and the lack of scalable cost-effective abatement technologies, but exacerbated by the complementary policies – such as the renewable portfolio standard and auto fuel-economy standards – that have been adopted by California. These complementary policies, analogues of which exist in all other regions with cap-and-trade markets, effectively mandate many of the changes that consumers and producers might otherwise have made in response to an emissions price.

The "hockey stick" shape of the abatement supply curve – driven by the large quantity of abatement required by complementary policies and then the inelasticity of additional supply beyond that – combined with significant uncertainty in the demand for abatement – driven by uncertainty in BAU emissions – implies that extreme prices (both high and low) are most likely. Using the information available at the time the market began, we find a 94.3 percent probability that the market would have excess allowances, leaving the price at or very close to the administrative floor. But we also find about a 4.6 percent chance that the price would rise to the point of triggering regulatory intervention to contain further increases. We estimate only a 1.1 percent probability of the market clearing in an intermediate region that is not primarily determined by the price containment policies. These results might be interpreted as demonstrating only that California's emissions cap was set "too high," thereby driving prices to the floor. However, our sensitivity analysis demonstrates that even if the cap were set with a goal of maximizing the likelihood of an intermediate price, such an outcome would arise with less than a 10 percent probability.

Some might also infer that the likelihood of extreme-price outcomes would be greatly reduced if the cap-and-trade market were established for a much longer period, such as many decades, because the elasticity of abatement supply is likely to be larger over a longer period of time. While this view of abatement supply elasticity is almost surely correct, two factors suggest that prices in a longer cap-and-trade market may not be less extreme. First, a cap-and-trade market established for a longer period of time is likely to face greater uncertainty about whether politicians will be willing to stick with a given capped quantity throughout the market period.[36] Second, although the abatement supply elasticity would likely be greater over a longer period, so would the uncertainty of BAU emissions. California's program has now been extended to the year 2030, with much more ambitious reduction targets. Still, even with the tighter cap and longer time horizon for price-responsive abatement to work, Borenstein et al (2017) estimates only a 20 percent chance of an intermediate price outcome by 2030.

While California may be somewhat unusual in factors that make its abatement supply curve inelastic, our analysis in Borenstein et al (2016) suggests that other

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[36] Such uncertainty seems well-founded given recent emissions cap reductions in both RGGI and EU-ETS.

cap-and-trade markets for GHGs could potentially face similar concerns. Other regions do have access to larger amounts of GHG abatement with costs ranging from \$20 to \$60/tonne, primarily through the ability to switch electricity production from coal to natural gas or renewable sources. However these regions also face significant uncertainty in BAU emissions that it seems could exceed the range of price-responsive abatement supply. A detailed empirical analysis of these other markets is beyond the scope of this paper, but is a potentially valuable exercise. The relevance of our findings to cap-and-trade markets for other pollutants, such as SO_2 or NO_x, is simply that it is critical to understand the *ex ante* uncertainty in emissions in comparison to the potential for price-responsive abatement. In the cases of SO_2 and NO_x there was greater availability of cost-effective abatement technologies at a politically acceptable cost than is currently the case for GHGs.

Another reaction to our findings has been to conclude that pricing greenhouse gases is an ineffective policy as compared to technology standards and direct regulation. Our work does not support this inference. Pricing GHGs creates incentives for technological advance, and could create large incentives for switching from high-GHG to low-GHG technologies as their relative costs change. The magnitudes of these effects could be quite large, but they are extremely uncertain, consistent with our conclusion that the probability of an interior solution in a cap-and-trade market is quite low. Furthermore, while we demonstrate that one should expect large uncertainty in the implied allowance prices from a cap-and-trade mechanism, there is also substantial uncertainty about the effectiveness and the costs of non-market-based regulations directed at reducing carbon emissions.

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