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 (BAU) 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[1] provides incentives for firms and consumers to limit activities that produce GHGs, make long-lived investments in lower-carbon technologies, and stimulates innovation in the development of new low-carbon technologies.

Prices in existing cap-and-trade policies for GHGs, however, have at times been very volatile and, most recently, have been so low as to create little incentive to invest in GHG emissions reductions. 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[2] in early 2011 to below 4 euros in 2013. The EU-ETS responded in 2014 by reducing the emissions cap. The Regional Greenhouse Gas Initiative (RGGI), which covers electricity generators in the Northeastern U.S., has gone through a similar experience and administrative reduction in the emissions cap.[3]

In this paper, we study California's cap-and-trade market for GHGs. The market, which opened in 2013, is the broadest based GHG market in the world, covering nearly all anthropogenic emissions except for agriculture. The market includes GHG emissions from electricity generation, industrial production, and transportation fuels. Throughout the first five years, the program has seen prices at or very close to the administrative price floor. Our analysis suggests that in the absence of such administrative intervention, extremely low or high prices are the most likely outcomes. This is consistent with the experience in other existing cap-and-trade markets for GHG emissions.

Two factors drive this conclusion. First, there is a high level of *ex-ante* uncertainty in future emissions. "Business-as-usual" (BAU) GHG emissions are closely tied to 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.[4] These uncertainties have long been recognized as an issue when fore-

[1]The largest share of GHGs is CO_2, which we discuss broadly as "carbon emissions" and "carbon pricing" 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]As of the end of January 2018 , allowances in the EU-ETS were slightly below 9 euros per tonne and RGGI was slightly above $4 per tonne.

[4]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. Some of these policies are also designed to address other market failures, such as imperfect information or principal/agent conflicts in energy consumption.

casting both damages and mitigation cost,[5] 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 price responsiveness of GHG abatement is likely to be small compared to the uncertainty in emissions levels. In California, the price-inelasticity of GHG emissions abatement is exacerbated by the non-market "complementary" environmental policies, an effect that is likely to be present in other regions with GHG cap-and-trade markets. These policies steepen the abatement supply curve by mandating mitigation that would otherwise occur in response to a rising GHG price. The combination of a broad probability distribution of emissions outcomes before pricing effects, and relatively modest price-responsiveness of emissions, 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.[6] Such hybrid mechanisms can greatly reduce allowance price risk while ensuring a better match between *ex-post* costs and benefits (Pizer, 2003). While the EU-ETS has no such bounds, the trading system proposed under the never-enacted Waxman-Markey bill of 2010 included limited price collars, as does California's program. The fact that California's market has had the highest price among the major GHG cap-and-trade programs from its inception through 2018 is almost certainly due to its relatively high floor price.

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.[7] There is an auction reserve price (ARP) that sets a soft floor price for the market. 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.

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, as well as uncertainty and price-responsiveness of abatement. Our analysis of market equilibrium 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 probability density of future GHG emissions given the pre-existing trends in GHG drivers. Second, we account for GHG reductions from command-and-control regulations

[5]When discussing controversies about mitigation costs, Aldy et. al. (2009) 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."

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

[7]Legislation extending the program was passed in July 2017, as discussed in more detail below.

and other "non-market" factors outside the cap-and-trade program. These include the effects of complementary policies, exogenous energy price changes, reduced compliance obligation due to credit for emissions "offsets" (administratively verified reductions from emitters in locations or sectors not covered by the program), and activities that may not reduce actual total emissions, but reassign responsibility to entities outside the program, known broadly as "reshuffling." While incentives for reshuffling and offsets 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 auction reserve price. Third, we use a range of energy price elasticity estimates to account for the emissions abatement that could occur in response to the GHG price.

Combining these analyses, we estimate probabilities that the equilibrium allowance price will lie in four mutually-exclusive regions: (1) at (or very near) the price floor (auction reserve price), (2) above the price floor and below the lowest trigger price of the multi-step APCR (described in more detail below), (3) at or above the lowest trigger price of the APCR and at or below the highest trigger price of the APCR, and (4) above the highest trigger price of the APCR. At the time that the market opened, prices above the APCR were viewed as very unlikely, but if they did occur, most market participants believed they would very likely lead to further administrative intervention.

We find that uncertainties in BAU emissions and in the quantity of abatement available from non-market factors create much greater uncertainty in the amount of abatement needed to meet a cap than price-responsive abatement could plausibly provide within the politically 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 that set a floor or ceiling.[8]

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 95% probability the allowance market would clear at the price floor, with total emissions below the cap.[9] We find a less than 1% probability that the price would be in the interior equilibrium range, above the auction reserve price floor and below the lowest APCR trigger price. The remaining 4% probability weight is on outcomes in which the price is within the trigger prices of the APCR or above the highest trigger price.

In July 2017, California adopted legislation extending the program to 2030 and

[8]Or *ex-post* emissions cap adjustments, an alternative administrative intervention that has been observed recently in the EU-ETS and RGGI, as noted earlier.

[9]Throughout this paper we refer to a single "allowance market." The trading of allowances and their derivatives takes place through several competing and coexisting platforms including quarterly auction of allowances by the State of California. We assume that prices between these markets are arbitraged so that all trading platforms reflect prices based upon the overall aggregate supply and demand of allowances and abatement.

setting much lower emissions targets for the additional decade. The legislation prescribed a hard price ceiling, but it left many critical aspects of the extended program unsettled, including the level and mechanism of the price ceiling, the price floor at which different shares of the allowance pool would be made available, and the allocation of free allowances to some emitters. 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 a substantially more balanced probability of an outcome at the price floor or price ceiling. Even in that analysis, however, we still find only a 20% 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.

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 of which parameter values to include has not been systematically informed by econometric analysis of the parameter distributions, 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 more ambitious targets. While we similarly find that BAU emissions are likely to fall below the emissions cap in California, we explicitly model uncertain abatement demand and supply, concluding that these uncertainties are quite large compared to likely levels of price-responsive abatement, yielding 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

[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 CARB used ICF's Energy 2020 model (CARB, 2010).

given the attributes of the supply and demand for GHG emissions abatement. Section II describes how we model the drivers of BAU GHG emissions over the 2013-2020 period using a cointegrated Vector Autoregression (VAR) model estimated using data from 1992 to 2010. In Section III, we explain how we incorporate the non-market factors that affect future GHG emissions. In Section IV, we discuss 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

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. Presumably, the GHG emissions cap would have to be set at least that long before any cap-and-trade market begins.[12] Consequently, our analysis addresses the question of what distribution of market outcomes a regulator could reasonably expect at the time the cap is set.

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. The auction has a reserve price, which was set at $10.50 in 2013 and has thereafter increased each year by 5% plus the rate of inflation in the prior year. A portion of the capped allowance quantity in the program are allocated to the Allowance Price Containment Reserve (APCR). 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

[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.

the APCR to be made available in equal proportions at allowance prices of $40, $45, and $50 in 2012 and 2013. These price levels increase annually by 5% 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 auction reserve price. What we loosely term "abatement supply" in this characterization includes both non-market and price-responsive emissions reductions among the covered entities. It also includes activities that arguably do not lower California GHG emissions – offsets and reshuffling – but an emitter can use to help meet its compliance obligation. For presentational clarity, we also include additional allowance supply that can be released from the APCR at higher prices as part of abatement supply.[14]

The analytical approach is illustrated in figure 1, which presents a hypothetical probability density function (PDF) of (price inelastic) abatement demand quantities along with one possible abatement supply curve. The supply curve includes non-market abatement along the horizontal axis, some very inexpensive abatement supply (mostly from offsets and reshuffling) likely cheaper than the auction reserve price, increasing abatement as price rises to the APCR, and then extra allowance supply from the APCR, 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 falls in the quantity of price responsive abatement between the floor and ceiling prices. The next section describes our methodology for estimating the PDF of the abatement demand, while section IV estimates the probability distribution of the quantity of non-market abatement and section V estimates the probability distribution of price-responsive abatement.

In its revised Scoping Plan of 2010, ARB's preferred model projected that 63% of emissions abatement would arise from complementary policies rather than from

[13]Borenstein, Bushnell, Wolak and Zaragoza-Watkins (2014) discusses the details of the compliance rules in more detail and the possibility of short-run allowance shortages.

[14]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.

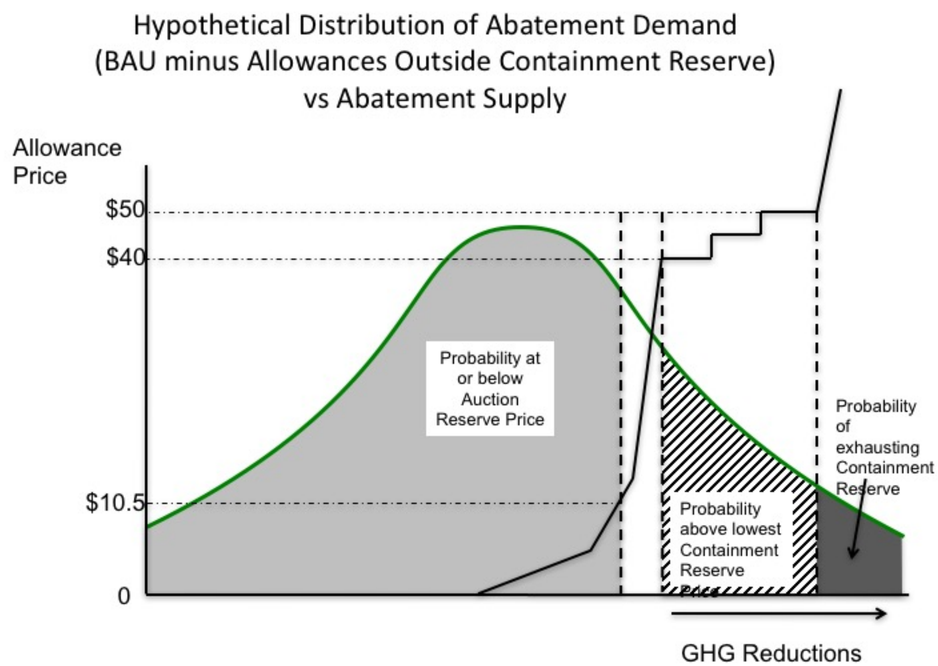

FIGURE 1. HYPOTHETICAL DISTRIBUTION OF ABATEMENT DEMAND AND SUPPLY

responses to the cap-and-trade program.[15] It is important to emphasize that these reductions are not costless; indeed many are likely to impose costs above the allowance price. Rather, these reductions, and the accompanying costs, will occur *approximately independently* 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 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

[15]See http://www.arb.ca.gov/cc/scopingplan/economics-sp/updated-analysis/updated_sp_analysis.pdf at page 38 (Table 10). This projection does not include the effects of exogenous energy price increases, reshuffling, or offsets.

GHG-reducing methods for producing the same level of output.[16]

The combination of large amounts of "zero-price" abatement, and relatively modest price-responsive abatement suggests a "hockey stick" shaped abatement "supply" curve, as illustrated in figure 1.

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 is of 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; no market participant is able to unilaterally, or collusively, change their supply or demand of allowances in order to profit from altering the price of allowances. In Borenstein, Bushnell, Wolak and Zaragoza-Watkins (2014) we analyze the potential for unilateral 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, 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, then intertemporal arbitrage will cause the *expected* price change over time to be equal to the nominal interest rate (or cost of capital).[17] 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.[18]

[16]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.

[17]This is the outcome envisioned when banking was first developed (Kling and Rubin, 1997). See also Holland and Moore (2013), for a detailed discussion of this issue. Pizer and Prest (2016) suggest that intertemporal arbitrage may also make cap-and-trade preferred to a tax under some circumstances where either type of program may be subject to updating.

[18]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 (December 31, 2020). 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 the prices of the APCR where additional supply is released and the level at which a hard price cap were set, if one were enacted. Thus, the price would either be approximately zero (if there is excess supply) or at one of the steps of the APCR or a hard price cap (if there is excess demand). Anticipating this post-

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). These types 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, 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 in 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 and eight-year period could require much more or less abatement than would be implied from considering only the expected BAU level.[19]

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 the Appendix.

To derive an estimate of the distribution of future GHG emissions covered by the program, we estimate a 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.[20] Due to the short time period for which the necessary

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.

[19]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.

[20]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.

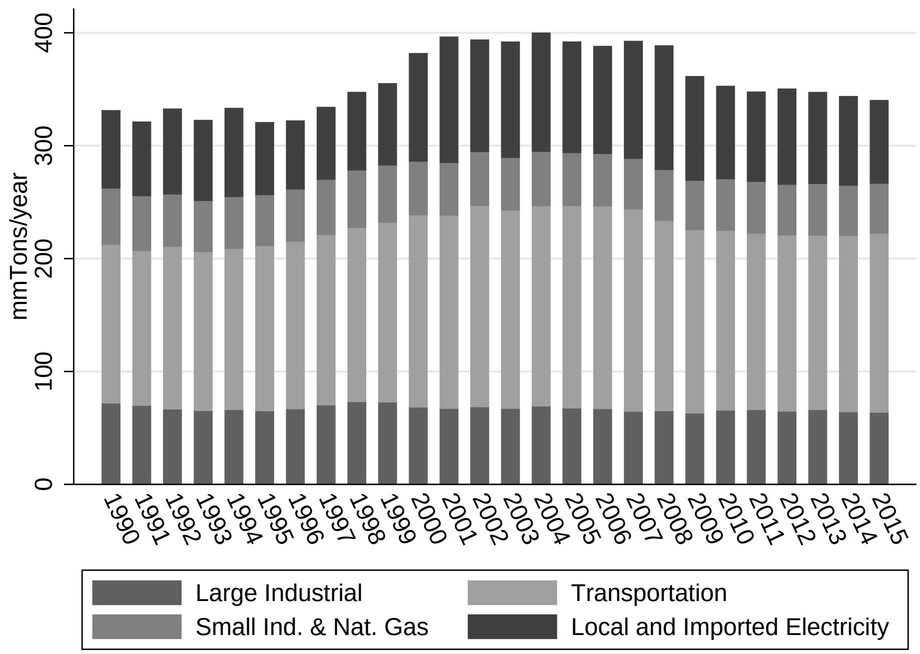

Figure 2. California Emissions from Capped Sectors

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 policy makers 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-dimensionsal vector, which significantly reduces the number of parameters estimated to compute our estimate of the distribution of future BAU values of these seven variables. The model includes three drivers of GHG emissions: in-state electricity production net of hydroelectricity production, vehicle-miles traveled (VMT), and non-electricity natural gas combustion and industrial process GHG emissions.[21] The model also includes the two most important economic factors that drive emissions: real GSP and the real price of gasoline in California. Finally, to facilitate the estimation of the 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

[21]The electricity variable accounts for demand changes (after adjusting for imports as discussed below) as well as uncertainty and trends in hydroelectricity production. We account for other zero-GHG generation sources – wind, solar, and nuclear – explicitly, as discussed below.

transportation sector and 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.

Table 1—Summary Statistics of Data for Vector Autoregression

	mean	S.D.	min	max	year min.	year max.
California Gen Net of Hydro (TWh)	159.3	16.5	133.5	185.6	1992	1998
Vehicle Miles Traveled (Billions)	299.7	27.0	258.0	329.0	1991	2005
Industry, Natural Gas & Other Emissions (MMT CO2e)	114.6	4.6	106.6	123.9	1995	1998
Gross State Product (Real Trillion $2015)	1.83	0.32	1.38	2.25	1990	2008
Wholesale SF Gasoline Price (Real ¢/gallon $2015)	198.83	42.05	146.88	300.09	1990	2008
In-state Electricity Thermal Intensity (CO2e tons/MWh)	0.462	0.056	0.372	0.581	2010	1993
Vehicle Emissions Intensity (CO2e tons/1000 VMT)	0.535	0.016	0.493	0.554	2010	1992

Note: Data are for 1990-2010

TABLE 2—SUMMARY STATISTICS OF SIMULATED VAR VARIABLES AND EMISSION

Year	California Electricity net of Hydro Twh	Vehicle Miles Traveled Million Miles	Nat. Gas, Ind. & Other MMT	Gasoline Price $2012	Gross St. Product $2012 Trillion	Therm. Intensity tons/ MWh	Trans. Intensity tons/1000 Miles	Broad Scope Emis. MMT	Cum. Emis. MMT
2013	179.2	331.2	108.7	2.71	2.28	0.360	0.485	355.7	150
	(21.5)	(12.9)	(10.2)	(0.75)	(0.24)	(0.043)	(0.027)	(20.4)	(11)
2014	181.3	334.9	108.4	2.78	2.33	0.355	0.482	356.5	301
	(24.8)	(14.7)	(11.1)	(0.83)	(0.28)	(0.045)	(0.030)	(23.0)	(22)
2015	183.4	338.5	108.0	2.84	2.39	0.350	0.480	357.1	658
	(25.9)	(16.6)	(11.9)	(0.90)	(0.31)	(0.049)	(0.034)	(24.5)	(42)
2016	186.0	342.5	107.5	2.90	2.44	0.346	0.479	358.6	1016
	(26.3)	(18.5)	(12.7)	(0.98)	(0.34)	(0.052)	(0.036)	(26.5)	(66)
2017	186.8	346.5	107.3	2.96	2.50	0.342	0.476	359.3	1376
	(28.6)	(20.0)	(13.6)	(1.05)	(0.38)	(0.055)	(0.039)	(28.3)	(92)
2018	189.6	350.5	107.0	3.01	2.56	0.338	0.475	361.2	1737
	(30.3)	(21.7)	(14.5)	(1.08)	(0.42)	(0.058)	(0.042)	(30.3)	(120)
2019	191.5	354.7	107.0	3.07	2.62	0.334	0.473	362.6	2099
	(31.1)	(23.8)	(15.2)	(1.19)	(0.45)	(0.062)	(0.044)	(32.5)	(150)
2020	193.4	359.0	106.9	3.13	2.68	0.330	0.471	364.0	2463
	(32.8)	(25.4)	(16.2)	(1.27)	(0.49)	(0.065)	(0.047)	(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 procedure we used to specify and estimate the cointegrated VAR and construct the estimate of the distribution of BAU emissions for the 2013 to 2020 time period are presented in the Appendix. In the Appendix, we also assess the impact of model uncertainty 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 the models.

A. Results

The parameter estimates for the 7-variable VAR are shown in Appendix A. Table 3 presents the means and standard deviations of 1000 simulated values of each element of the VAR for each year from 2013 to 2020.

From each simulation of the seven variables through 2020, 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 the Appendix, 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 estimate in the VAR.

The resulting measure of emissions from all sources in the program is shown in the "Broad Scope Emissions" column of table 2. 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.[22]

Figure 3 illustrates the actual values for broad scope emissions through 2015 and the estimated median, 5th, and 95th 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 median 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 potential supply-demand balance in the cap-and-trade market.

[22]In the Appendix, 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.

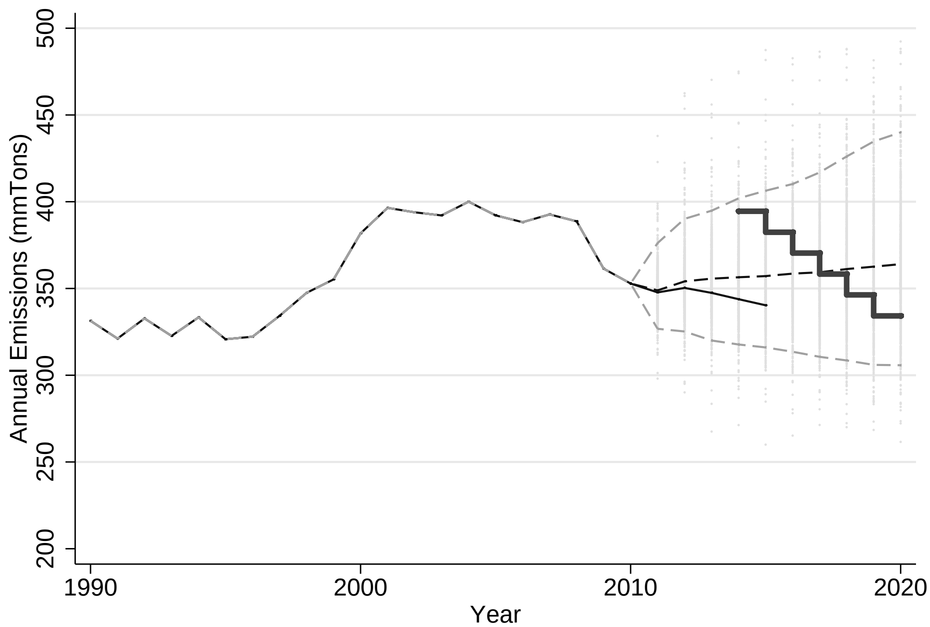

Figure 3. California Broad Scope Mean Emissions Forecast and Confidence Intervals, 2011-2020 (Actual Data, 1990-2015)

III. Impact of Price-Inelastic Abatement

This section models 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.[23] Throughout this discussion we characterize "low" and "high" scenarios, with "low" referring to cases in which the result is more likely to be a low allowance price (*i.e.,* more effective abatement), and "high" referring to cases more likely to lead to a high allowance price (*i.e.,* less effective abatement). We combine each of the 1000 realizations from the BAU emissions distribution from the VAR with a simulated outcome of the price-inelastic abatement to derive a distribution of 1000 emissions outcomes before price-responsive abatement.

[23]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.

A. Zero-Carbon Electricity Generation and Energy Efficiency

In the case of electricity, the main complementary policies are the the Renewables Portfolio Standard (RPS) – which in 2011 was increased to mandate that 33% of California electricity supply must come from 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 future deviations from trend in renewable electricity. These potential deviations from trend are based on external data sources discussed in the Appendix. 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-fuel 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 forecast the BAU emissions. As discussed in the Appendix, we therefore make no further adjustments in addition to energy efficiency effects already integrated into our forecasts.

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 the Appendix, the low end of this range of emissions intensity is based on a forecast from EMFAC 2011, which is the model ARB used to forecast the impact of GHG policies on fleet composition and fuel economy in the transportation sector. The high end of this range incorporates both the EMFAC 2011 forecast and the BAU emissions intensity forecast 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 for each of the 1000 simulated BAU draws.

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

We also account for the effect on emissions from 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 the Appendix. 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 cap-and-trade programs for GHGs 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.[24] In the Appendix, however, we discuss the difficulty of getting approval for offset projects and the fact that the 8% 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 amount 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 nature of the Western electricity market – which includes states from the Pacific Ocean to the Rocky Mountains – it is generally not possible to identify the specific generation resource supplying imported electricity. Electricity importers therefore 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.[25] As explained in the Appendix, we use information on long-term contracts with coal plants to determine the range of possible reshuffling and its impact on allowance demand to cover imported electricity.

[24] Because the offset rule allows 8% 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 $2726.7 - 2508.6 = 218.1$.

[25] 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 at all, 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.

IV. Price-Responsive Abatement

In the Appendix, 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, shown in table 3, and discuss them briefly. It is clear from this discussion that the uncertainty in BAU emissions, as well as in the price-inelastic 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 time as more information arrives about whether the market is likely to have insufficient or excess allowances over the life of the eight-year program, as mentioned in section I. Even if very high 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 the Appendix, we present the method we use to account for this price evolution. In brief, the price at the beginning of the program is assumed to represent the probability-weighted average of possible final prices, and then is assumed to evolve linearly over the course of the program to the aggregated equilibrium outcome that is ultimately realized.

For gasoline and diesel price response, we assume 100% 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. Complementary policies, however, are already requiring higher fuel economy than consumers would 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%. Still, we present results assuming 100% 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-elastic 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% pass-through to cover the shortfall, as discussed in the Appendix. The effect on abatement, however, is nearly the same as imposing 100% pass-through on all customers, so for simplicity we do so.[26]

In the Appendix, 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 the cost of cap-and-trade for industrial emitters – these changes are likely to be very small.

Table 3—Summary of Abatement Supply (MMT)

	Abatement over 8 Years				Annual
	Mean	S.D.	5%	95%	Average
Electricity					
Price Response (floor)	3.4	0.5	2.5	4.2	0.4
Price Response (ceiling)	9.7	1.4	7.3	12.0	1.2
Transport					
Price Response (floor)	3.6	0.5	2.7	4.4	0.7
Price Response (ceiling)	12.2	1.8	9.3	15.0	2.4
Natural Gas					
Price Response (floor)	11.1	2.5	7.1	15.1	2.2
Price Response (ceiling)	31.6	6.9	20.4	42.7	6.3
Exogenous Elec.					
rate effects	17.5	2.1	14.0	21.0	2.2
Fuel Economy & LCFS	79.2	47.6	11.0	163.8	9.9
Renewable Portfolio Std.	63.0	10.2	47.3	80.5	7.9
Electricty Imports	62.8	20.8	29.2	97.4	7.8
Offsets	98.0	14.3	75.4	122.2	12.2
Total at Price Ceiling	373.9				50.0
Total at Price Floor	338.6				43.4

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.

[26]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.

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 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 GHG intensity of VMT is multiplied by the realization of BAU VMT to obtain the realization of transportation GHGs. Similarly, GHG emissions from electricity generation in each draw are the interaction of the realization of thermal intensity and the realization of kWh of thermal generation, after deducting the realization of renewable generation.

Given the very short data series and outside sources for much of the abatement assumptions, basing correlations of these parameter draws on empirical analysis isn't likely to be credible. Nor, unfortunately, are even the signs of these correlations clear.[27] Thus, we append an independently distributed draw of each additional abatement source to each realization of BAU emissions.

We consider four mutually exclusive and exhaustive potential market clearing price ranges, as was illustrated in figure 1: (1) at or near the auction reserve price, 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 auction reserve price, though without accessing any of the allowances in the allowance price containment reserve (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.[28]

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 5% and 95% bounds on the curve. Our results suggest a 95.1% probability of the price equilibrating at or very near the auction reserve price, implying that the emissions cap was set high relative to the expected emissions due to business as usual, complementary policies, and the

[27]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.

[28]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.

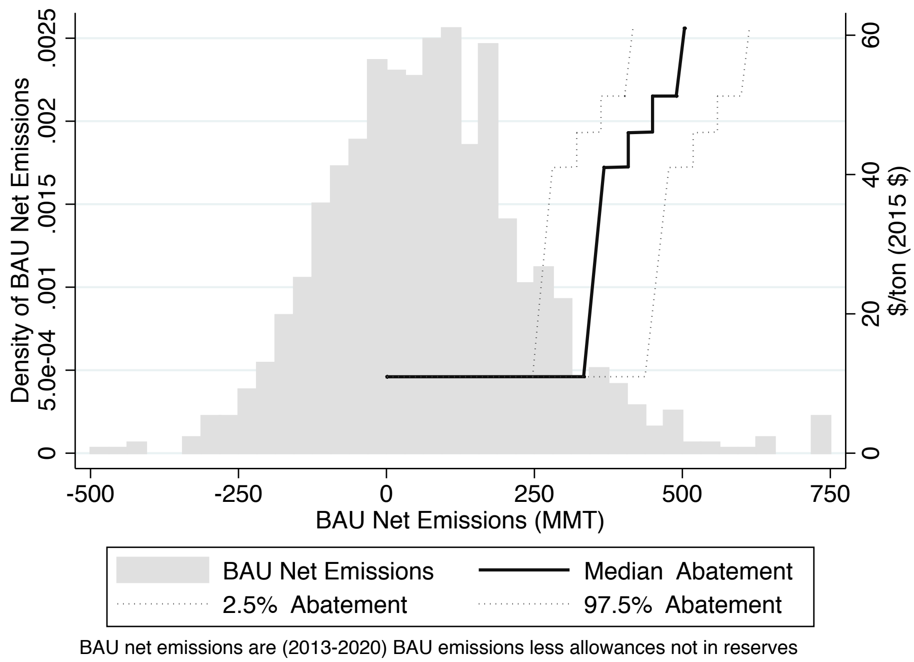

Figure 4. Net Emissions and Abatement Supply (2013-2020)

offsets and reshuffling that would take place at very low prices. Of the remaining probability, we estimate a 0.9% chance of a price below the lowest APCR trigger price, what we have referred to as an interior solution. We estimate a 2.9% chance of a price within the APCR price range, and a 1.1% 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 primarily from the emissions cap being set very high relative to the distribution of BAU emissions net of price-inelastic policies. One might ask how high the probability of an interior solution could have been if the cap were set at a different level. We investigated this question by rerunning 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 2416 MMT (about 290 MMT lower than the actual cap), resulting in an 8.1% probability of an interior solution with the remaining probabilities fairly balanced between lower and higher priced outcomes.[29] 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% probability of an interior solution.

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 suggested by the results just discussed is how much they would change if complementary policies are not present and cap-and-trade is 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-inelastic abatement, which in this case causes the price-elastic region of the abatement supply curve to coincide with a higher probability region of the BAU emissions PDF. Second, it increases the price-elasticity of abatement supply by removing the dampening effects that were caused by 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 cap-and-trade, 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;[30]

2) No complementary or other policies impact the realization of vehicle emission intensity from the VAR;

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

4) Higher price elasticity of response to energy price changes.[31]

[29]A 50% probability of an outcome at or near the auction reserve price, a 26.5% probability of an outcome in the APCR, and a 15.4% probability above the APCR.

[30]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.

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

The effects of assumptions 1 through 3 are indicated in table 3. These shifts of abatement supply are removed. The effects of assumption 4 are slightly more complicated and amount to roughly doubling of the price responsiveness. The details are described more completely in the Appendix.

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, 79.4% vs. 95.1%, and a much larger probability of an interior solution in which the market clears at a price above the ARP but still below the APCR, 8.3% vs. 0.9% under the baseline scenario. The probability of very high prices more than doubles, with an 8.5% probability of settling in the APCR, and a 3.8% 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% of the outcome distribution still occurs at administratively-determined 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

California's AB 32 was passed in 2006, just as emissions from capped sectors were reaching their peak of roughly 400 MMT/year, as shown in figure 2. As of late 2008, ARB projected emissions from capped sectors during the decade of 2010-2020 to remain level at about 400 MMT, absent policy intervention.

Since the first allowance auction in November 2012, the market has performed in a manner that is consistent with these reduced expectations. In the 21 quarterly auctions through 2017, the allowance price has 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.

The softness in the allowance market reflects the reported emissions under the program in its first years of operation. The solid line in figure 3 illustrates annual reported emissions through 2015. Reported broad scope emissions have been below our median forecast level in every year, producing a cumulative 30 MMT lower emissions than our median forecast for the years 2013-2015. In table 4 we compare our estimated distribution to reported values for all variables in our VAR through 2015. Emissions have fallen to these relatively lower levels despite other factors that might otherwise be expected to increase emissions. For example, California GSP was 4% higher in 2015 than our median forecast and 2015 gasoline prices were almost 25% below our median forecast for that year. Despite these seemingly stimulative factors, Californians drove fewer miles and used less fuel per mile in 2015 compared to our median BAU forecast.

It is important to recognize that our forecasts are of BAU, while reported 2015 values reflect not only BAU but also the aggregate impact of both price-responsive abatement and other mandated abatement measures. We do not attempt to

Table 4—Actual vs. Forecast Values of Model Variables for 2015

	2015 Actual	mean forecast	5% forecast	95% forecast
Broad Scope Emissions (MMT)	340	352	316	390
California Gen Net of Hydro(TWh)	182201	183311	145427	227433
Vehicle Miles Traveled (Billions)	335	338	314	364
Industry, Natural Gas & Other Emissions (MMT CO2e)	108	108	91	127
Gross State Product (Real Trillion \$ 2015)	2.48	2.38	1.94	2.85
Wholesale SF Gasoline Price (Real ¢/gallon \$ 2015)	229.02	285.61	171.70	445.46
In-state Electricity Thermal Intensity (tons/MWh)	0.364	0.351	0.280	0.435
Vehicle Emissions Intensity (tons/1000 VMT)	0.473	0.481	0.429	0.537
Electricity Import Emissions (MMT CO2e)	30.7	40.17	40.17	40.17

disentangle the relative contribution of low BAU emissions and active abatement in contributing to the low allowance prices to date, but rather report these values to provide some context for assessing the market's performance to date. While transportation and electricity emissions have declined slightly, the great majority of reductions in capped emissions since 2012 have come from imported electricity.

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 emissions under the 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. One significant difference in that analysis is 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 our primary analysis with a hard price ceiling of $85 in 2030 (in 2015 dollars), we estimate a 46% probability of the equilibrium price being at the price floor, a 34% of the price ceiling, and a 20% 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

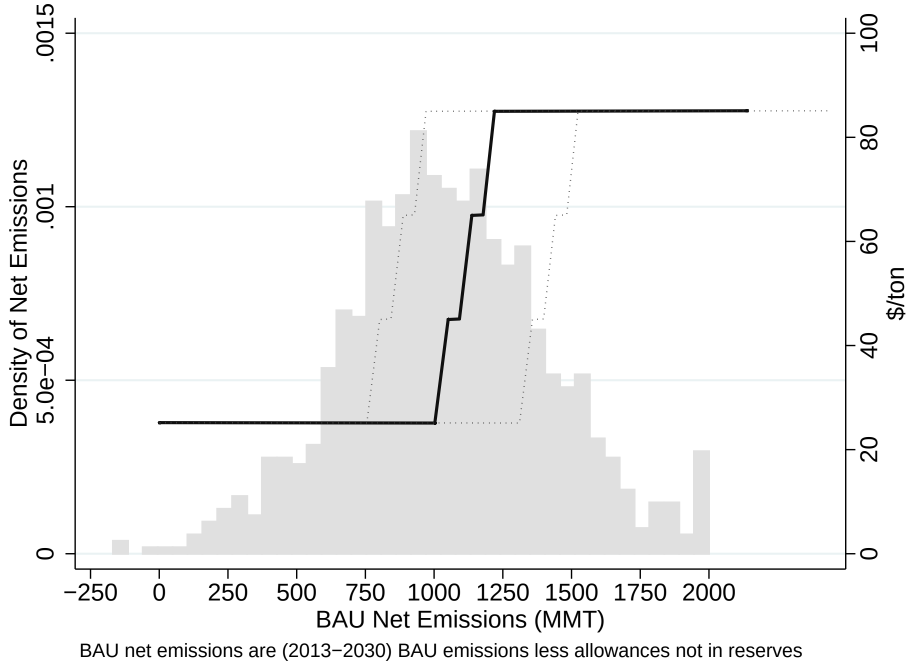

FIGURE 5. NET EMISSIONS AND ABATEMENT SUPPLY (2013-2030)

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.

VII. Conclusion

If cap-and-trade programs for greenhouse gases are to successfully expand around the 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 costs-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 95% 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% chance that the price would rise to the point of triggering regulatory intervention to contain further increases. We estimate less than a 1% 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 9% 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.[32] Second, though 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

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

for price-responsive abatement to work, we estimate only a 20% 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 BBWZ (2016) suggests that other cap-and-trade markets for GHGs could face similar concerns. Other regions do have access to larger amounts of CO2 abatement with costs ranging from \$20 to \$60/ton, 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 applicability of our findings to cap-and-trade markets for other pollutants, such as SO_2 or NO_x, is simply to point out that it is critical to understand the *ex ante* uncertainty in emissions in comparison to the potential for price-responsive abatement. The latter will depend very much on the availability of abatement technologies that are cost-effective within a politically acceptable price range.

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 prices from a cap-and-trade scheme, 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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