Stress-Testing Cap and Trade Markets

Frank A. Wolak
Director, Program on Energy and Sustainable Development (PESD)
Department of Economics
wolak@zia.stanford.edu
http://www.stanford.edu/~wolak
and
Member, Emissions Market Assessment Committee (EMAC)
California Air Resources Board

Cap and Trade Mechanisms

- Many jurisdictions are considering or have implemented cap and trade mechanisms to price greenhouse gas (GHG) emissions
  - European Union Emission Trading System (EU-ETS)
  - California
  - South Korea
  - Australia
  - Quebec
- Important to understand distribution of future allowance prices
  - Ensure that adequate safeguards are in place to prevent unacceptably high prices that may cause program to be shutdown
  - Assess likelihood prices end up at price floor or at zero
  - Example potential for privately profitable strategies that reduce market performance
    - Corner the market for allowances

Outline of Presentation

- Based on "Forecasting Supply and Demand Balance In California's Greenhouse Gas Emissions Cap and Trade Market," Emissions Market Assessment Committee (EMAC) report
- Report results of forecasting future distribution of GHG emissions allowance prices for California's Cap and Trade Mechanism
- California has a hybrid mechanism with
  - Price floor and
  - Price containment reserve (PCR)
- Market price of allowances determined by intersection of business-as-usual (BAU) emissions less emissions cap with supply curve of mitigation
- Considerable uncertainty over BAU emissions
  - High correlation between level of economic activity and emissions
- Results emphasize need for mechanism to defend maximum price

General Approach

- Estimate probability model for future business-as-usual (BAU) GHG emissions
  - BAU emissions minus cap is "demand" for abatement
- Consider scenarios of complimentary measure impacts
  - Measures that are *not* directly responsive to allowance prices
- Consider scenarios of abatement ``supply'' in response to varying allowance price levels
- Combine these to forecast distribution of future allowance prices
  - Probability of prices at floor
  - Probability above floor and below PCR price
  - Probability of prices in PCR
  - Probability at price above PCR price

Assumptions on Timing

- Main analysis assumes years/phases fully integrated over time through banking
- Banking—Allowances can be “banked” for later use
  - Inter-temporal arbitrage of allowance prices
- Aggregate emissions, complimentary measures, and abatement over 8 years
- All calculations based upon 8-year totals

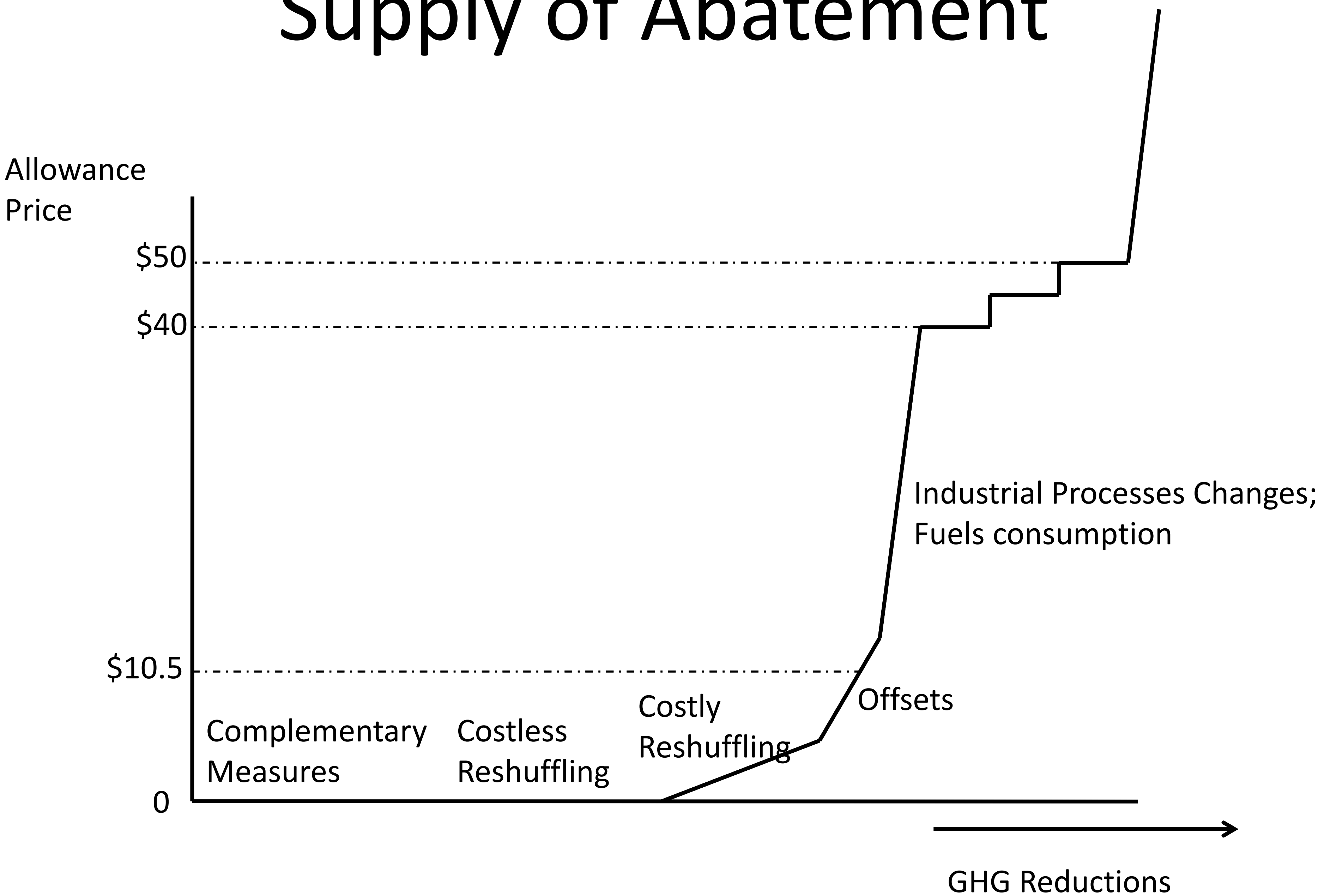
California's AB 32

- Statewide greenhouse gas emissions (GHGs) limit equivalent to 1990 emissions levels to be achieved by 2020
  - Controls all GHGs
  - Sets GHG limit in terms of annual maximum GHGs emissions in tons of carbon dioxide equivalents
    - Exchange rate to convert each GHG to carbon dioxide equivalent
  - Statewide GHG = total annual emissions in the state, including all emissions from *GHG from the generation of electricity delivered to and consumed in California*, accounting for transmission and distribution losses, whether the electricity generated in the state or imported
    - Raises issue of resource shuffling (more on this later)

California’s AB 32

- ARB may use market-based compliance mechanisms
  - Allows trading of GHGs emissions allowances
    - “Cap and Trade” mechanism for managing GHGs
  - Distribute emissions allowances “in a manner that is equitable, seeks to minimize costs and maximize the total benefits to California, and encourages early action to reduce GHGs emissions”
- California uses fractional output-based updating and periodic auctions of remaining allowances
  - Emitting 1 ton of CO_2 in year t entitles firm to X ($0 < X < 1$) allowances for year t+1
  - Magnitude of X is industry-specific and depends on degree of import competition faced by industry
  - Makes supply curve of mitigation more inelastic

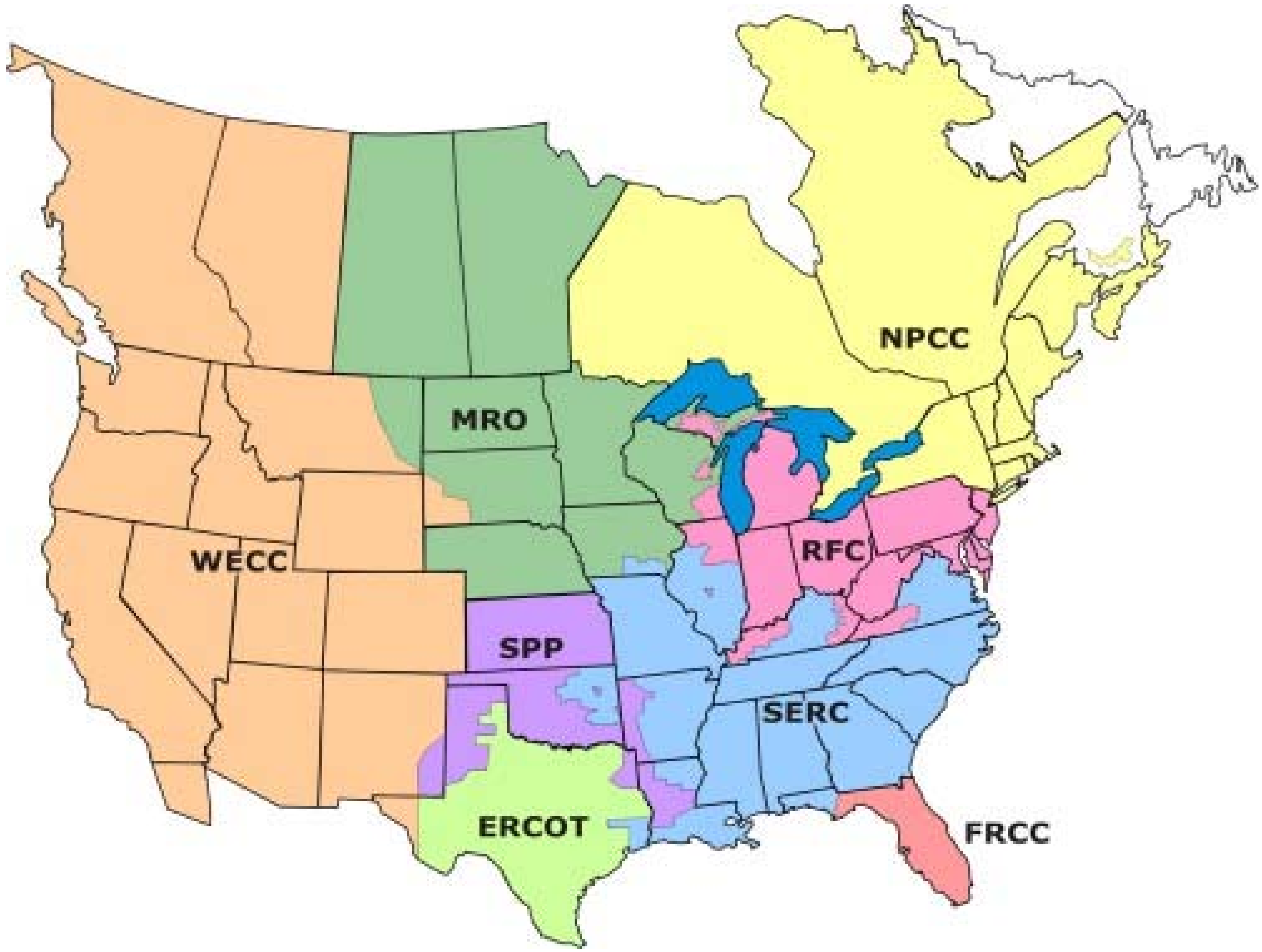
Supply of Abatement



Reshuffling of GHG Emissions

- Stylized facts about electricity in California
  - California obtains more than 25% of its energy from imports
  - California is part of electrically interconnected Western Electricity Coordinating Council (WECC)
- Physics of electricity delivery implies that it is impossible to tell which plant is selling to which customer
  - Electricity injected into network flows according to path of least resistance
  - Supply must equal demand at every instance in time and at every location in network
    - Automatic Generation Control (AGC) units ensure this is the case
- Bathtub model of electricity network
  - Suppliers inject electricity into network
  - Consumers withdraw electricity from network

NERC Regional Reliability Councils



California Electricity Facts

- Many ways to create “source of electricity” consumed by a specific customer
- Historically generation unit “selling energy” to customer is created by a forward financial contract
  - Buy 200 MWh contract from generation unit
  - Verify that generation unit produced at least 200 MWh during that hour
  - Generation unit is deemed to have delivered 200 MWh of electricity to customer

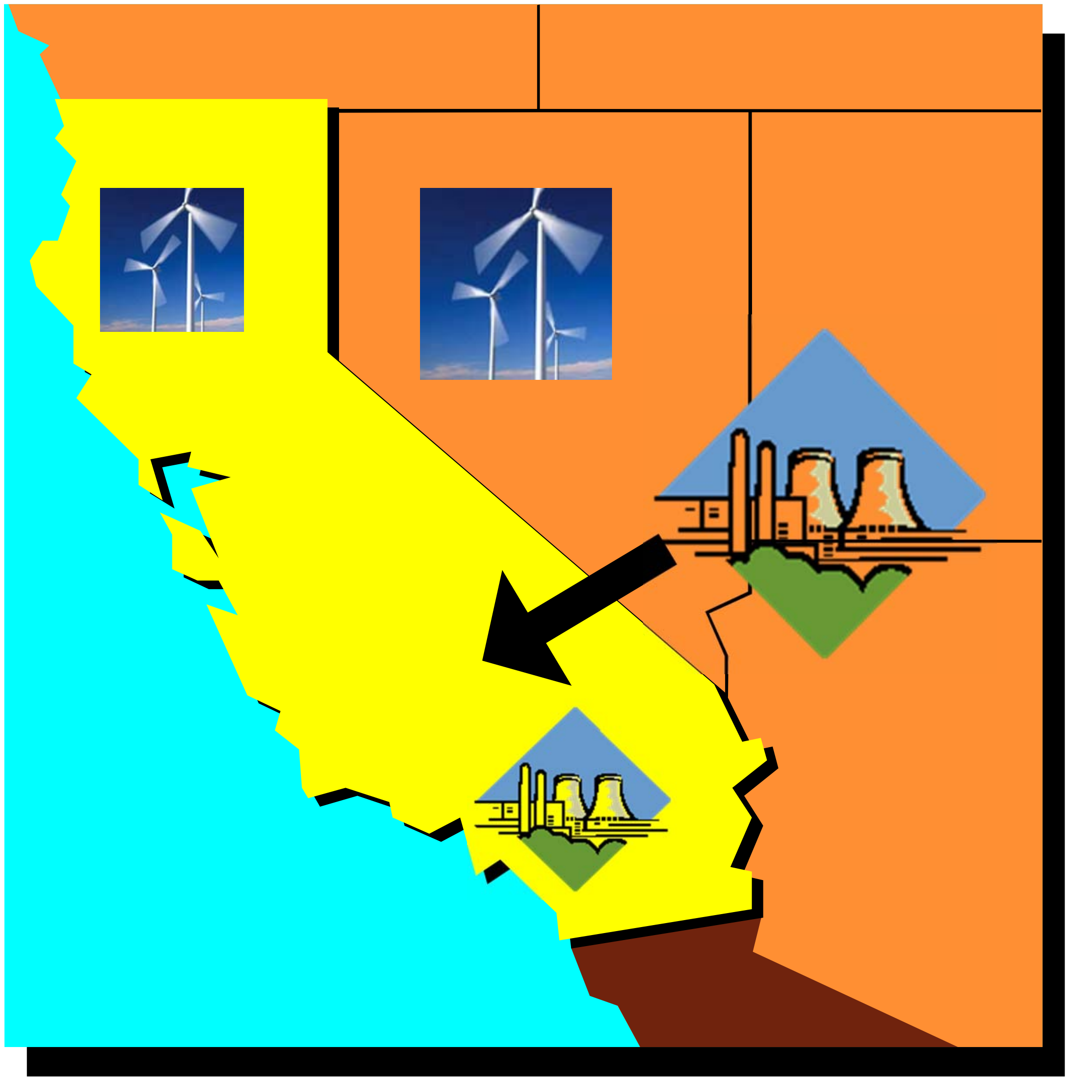
Reshuffling of GHG Emissions

- How would reshuffling occur?
  - In response to price of carbon, California load-serving entities sign long-term supply arrangements with green and high-efficiency fossil fuel suppliers in and outside of California
- Utilities outside of California need to purchase electricity to sell to their consumers
  - They are not restricted in purchases from brown suppliers
    - Brown suppliers face less demand and sell at lower prices
- Virtually all of generation capacity in WECC is needed to meet annual demand peaks
  - Less than 200 MW of spare capacity was available in entire WECC during July 2006 heat storm in California

Reshuffling of GHG Emissions

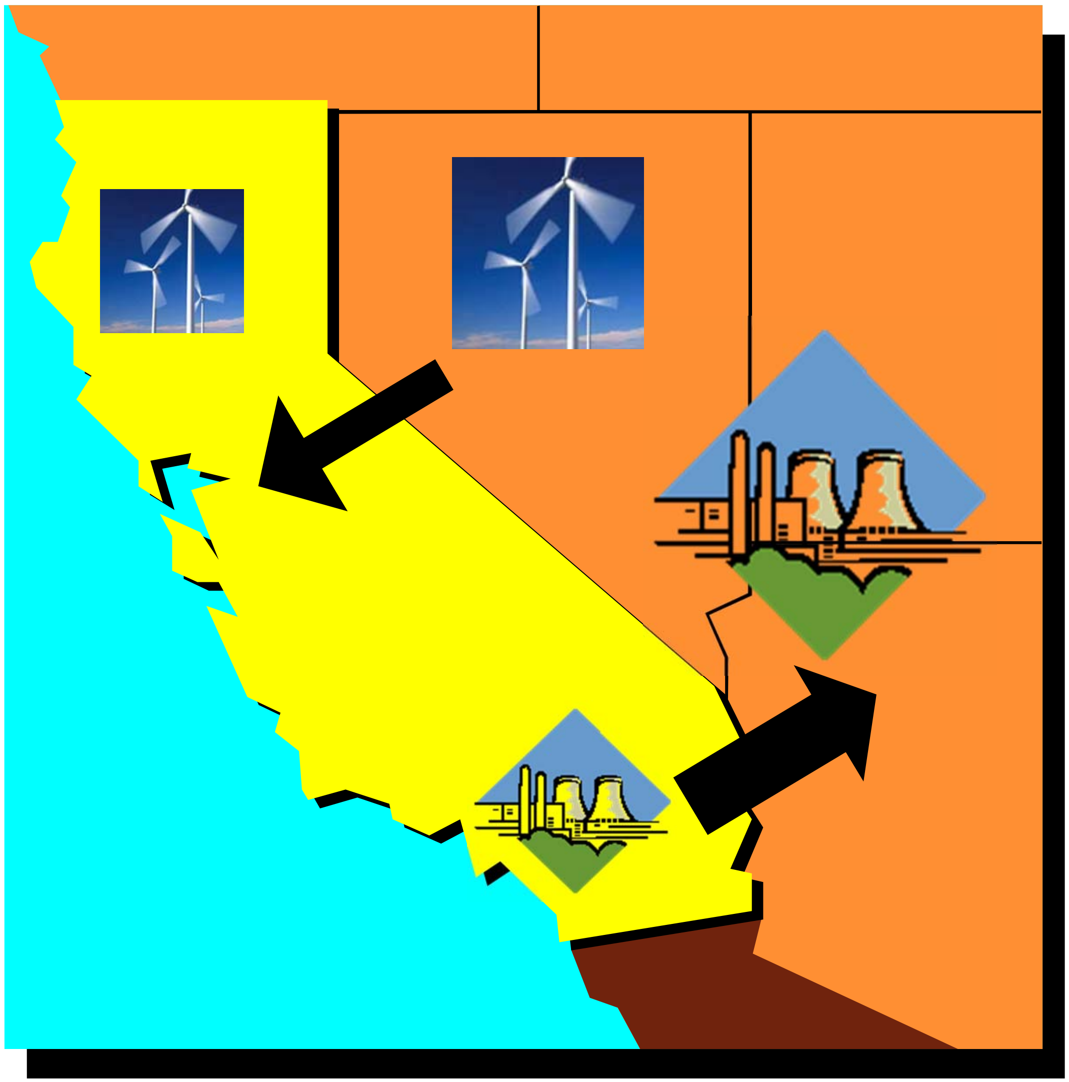
- Implications of above facts--If there is sufficient green and high-efficiency fossil fuel to capacity in WECC to meet California's 1992 GHG emissions then contract reshuffling could be complete
  - Same WECC generation units operate and same GHGs produced, but California just pays higher price for electricity than surrounding states
  - Higher GHG emissions are also possible because of inefficient dispatch of generation resources in WECC

Load-Based--Before Cap



- CA demand
  - 750
- Rest of West demand
  - 1500
- CA supply
  - 250 brown
  - 250 green
- Rest of West supply
  - 1250 brown
  - 500 green
- Currently CA buys
  - 250 brown from CA
  - 250 green from CA
  - 250 brown from ROW

Load-Based--After Cap



- CA buys
  - 250 green from CA
  - 500 green from ROW
- ROW buys
  - 250 brown from CA
  - 1250 brown from ROW
- No change in GHG emissions in WECC
  - Reshuffling complete

Reshuffling of GHG Emissions

Summary of Capacity and Generation Supply and Demand Able to Meet California GHG Cap			
	Annual MWh	**MW of Capacity**	**Excess clean supply (MWh)**
Total WECC Supply	582,000,000	112,222.80	
Total WECC Supply Able to Meet GHG Cap	325,000,000	77,925.69	
Average Demand CA	289,000,000	32,968.73	36,000,000
Average Demand Rest of WECC	490,000,000	55,898.54	
Total Demand WECC	779,000,000	88,867.27	

Electricity Supply in Rest of WECC

- Unless California GHG emissions policies can influence operation of generation units outside of state, they will have no impact on GHG emissions in rest of WECC
- Coal is low variable cost source of electricity relative to natural gas-fired units at current natural gas prices
  - Will operate if rest of WECC does not adopt GHG policies that price GHG emissions
- Nuclear and renewables will operate if available
- California cannot impact which natural gas and oil-fired units operate outside of California?
  - These are under control of vertically-integrated utility
- Extent of reshuffling is major source “mitigation supply” uncertainty

Figure 1
Supply of Abatement

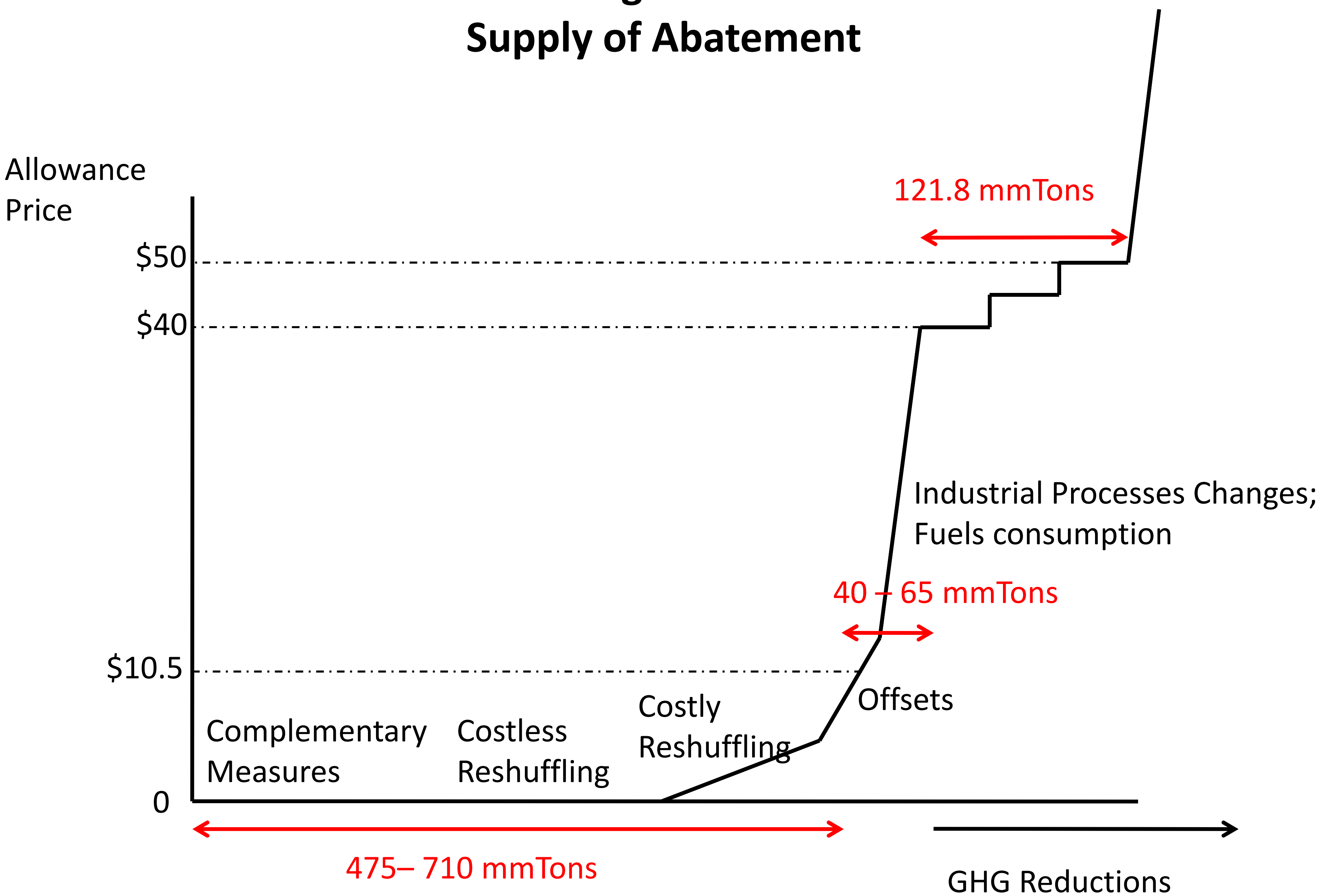


Figure 2
Hypothetical Distribution of Abatement Demand (BAU minus Allowances Outside Containment Reserve) vs Abatement Supply

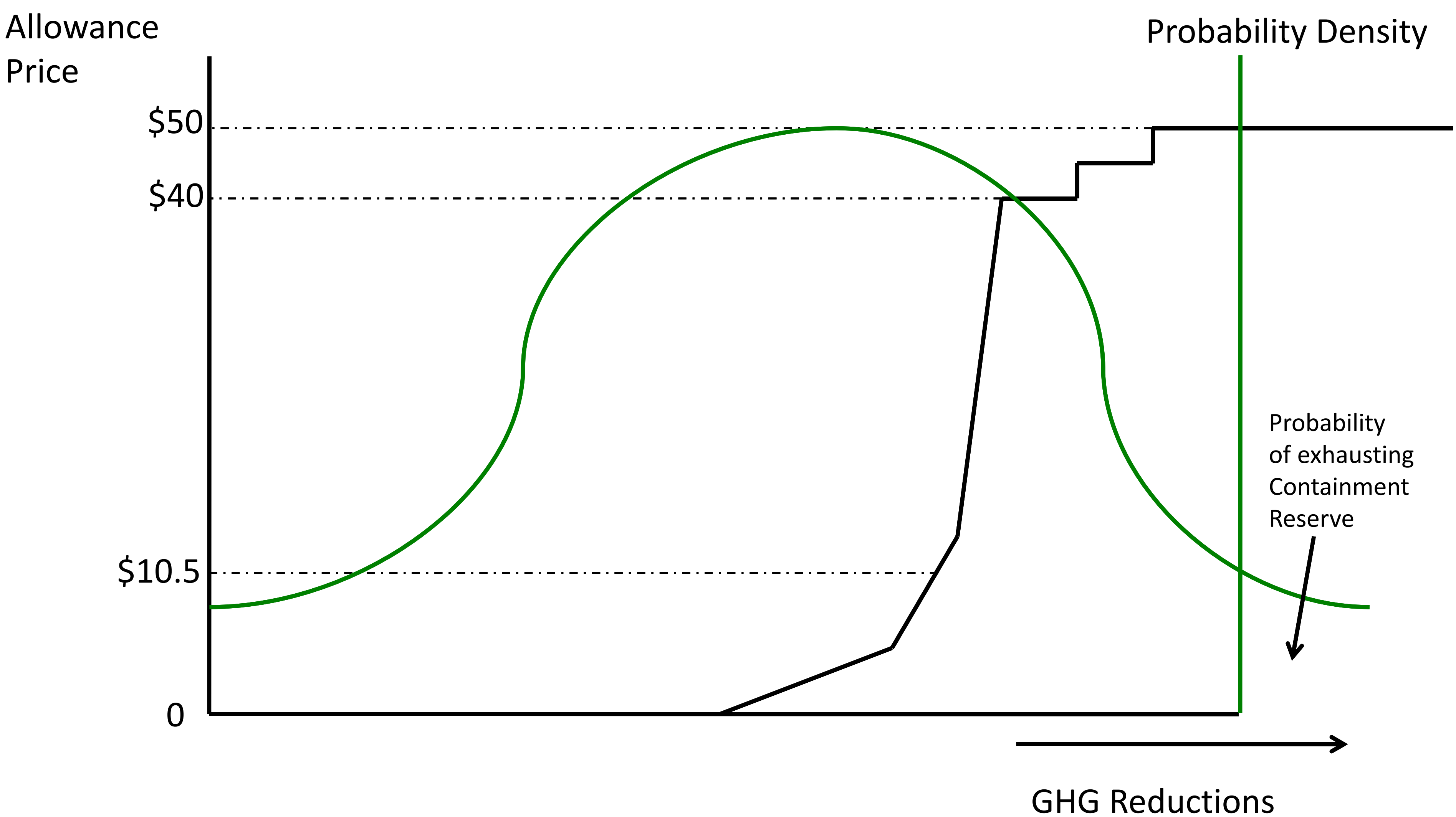


Figure 2
Hypothetical Distribution of Abatement Demand (BAU minus Allowances Outside Containment Reserve) vs Abatement Supply

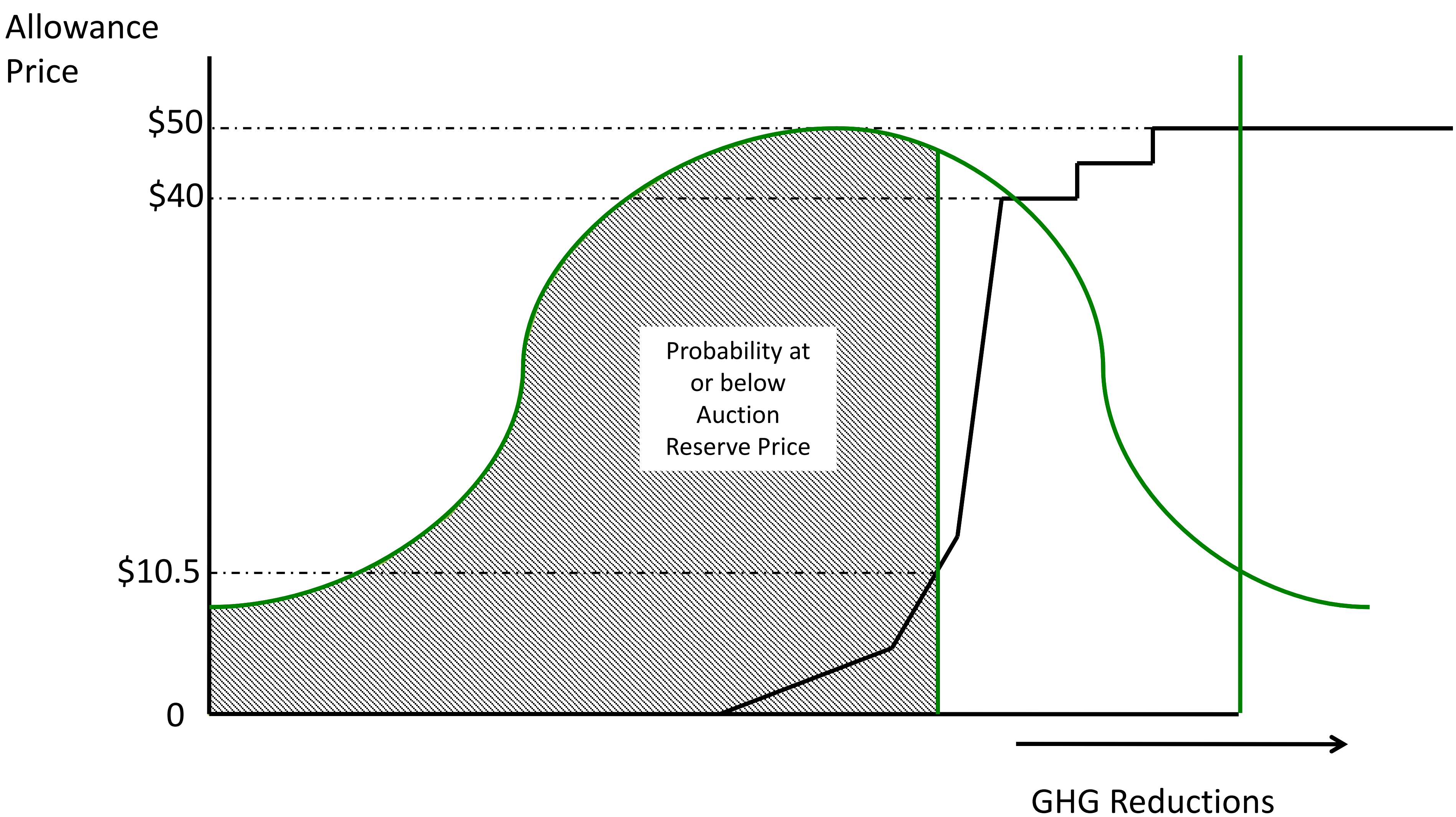


Figure 2
Hypothetical Distribution of Abatement Demand (BAU minus Allowances Outside Containment Reserve) vs Abatement Supply

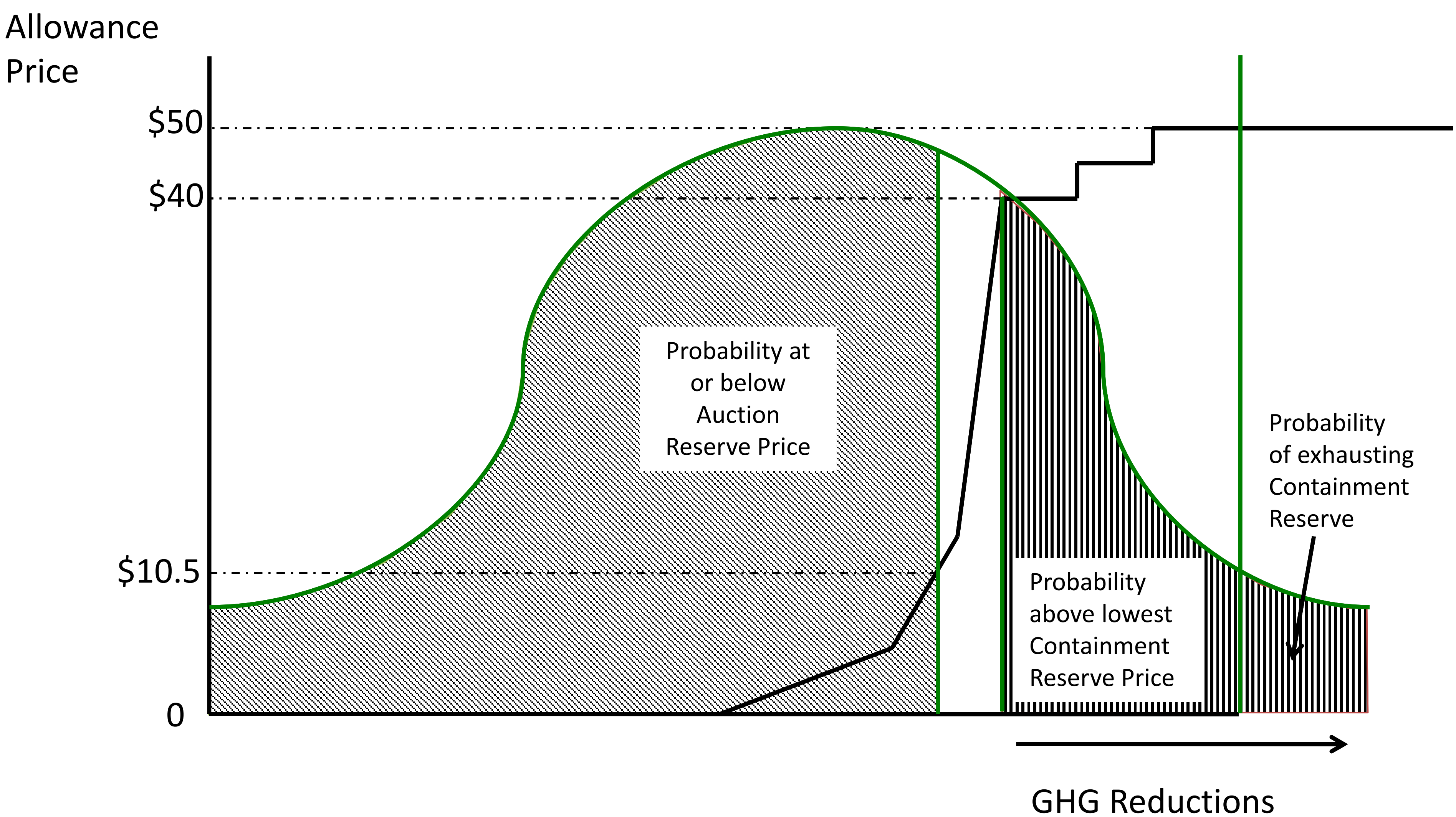


Figure 2
Hypothetical Distribution of Abatement Demand (BAU minus Allowances Outside Containment Reserve) vs Abatement Supply

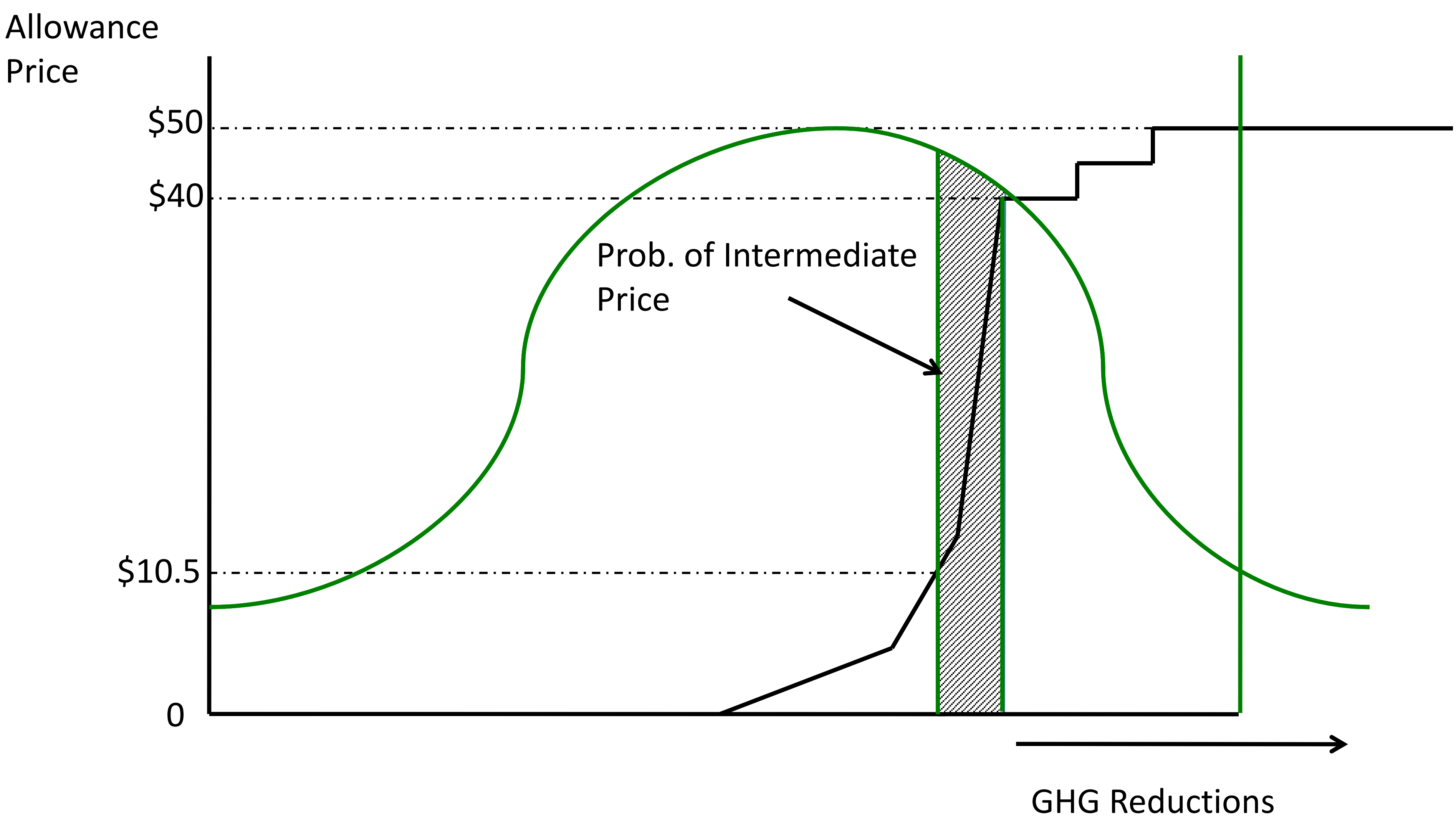
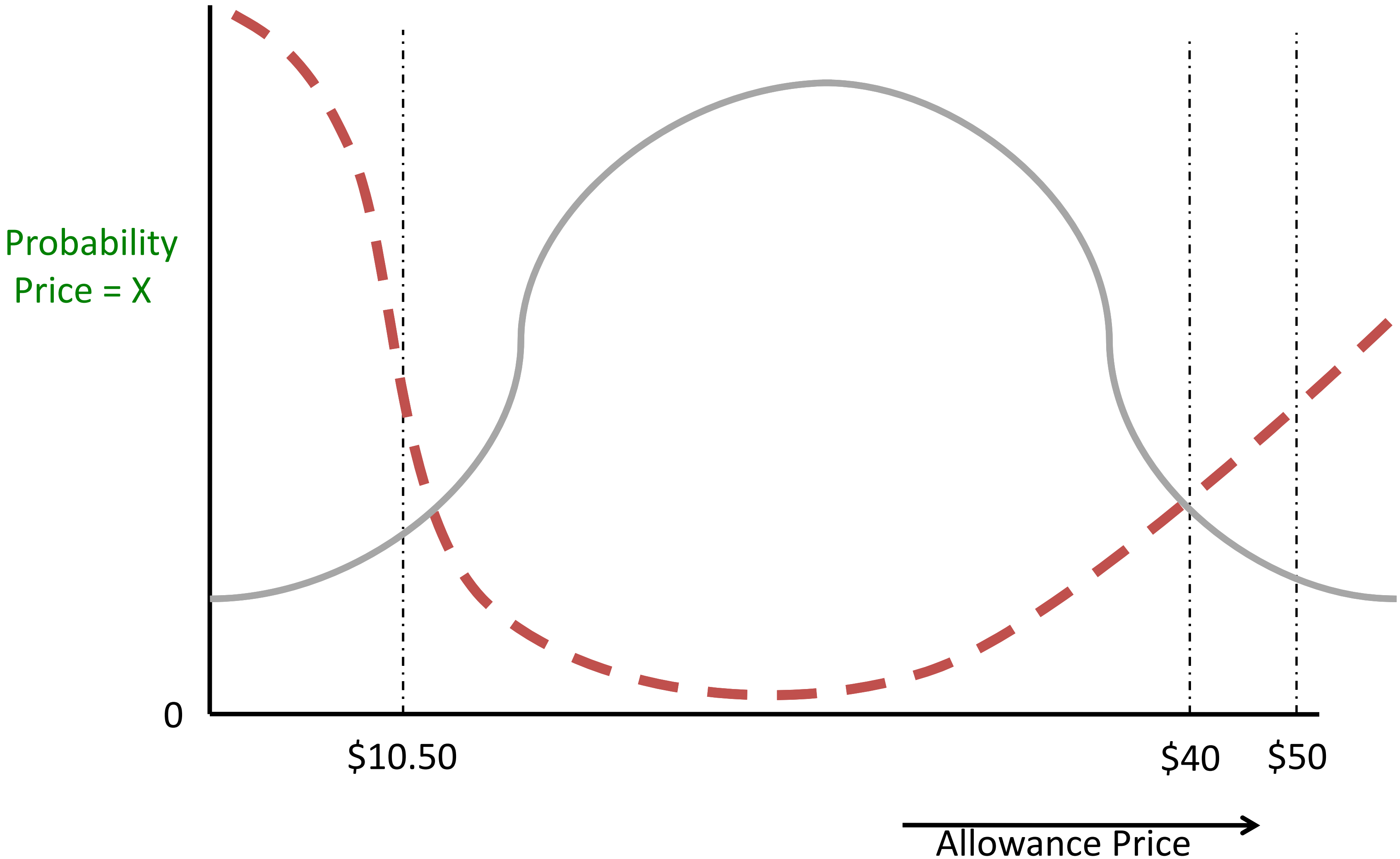


Figure 3
Possible Density Functions of Allowance Price



Model for BAU Emissions

- Estimate time series model of drivers of sectoral greenhouse gas (GHG) emissions and sectoral emissions intensity
  - Model allows for economic activity in sector to increase yet GHG intensity of sector to fall
- Use model to construct a distribution of future GHG emissions from 2013 to 2020 that accounts for
  - Uncertainty in econometric model parameter estimates
    - Estimation Error
  - Uncertainty in future values of unobservables in econometric model
    - Prediction Error
- Model assumes all variables are 2^{nd}-order stationary in growth rates but allows for linear combinations of elements of model to be stationary
  - Co-integration restrictions imposed in estimation and simulation that reflect "equilibrium" relationships between variables in model
  - Imposing these restrictions improves forecasting accuracy of model
  - Model uncertainty is a third source of uncertainty
    - Not explicitly taken into account in distribution of future GHG emissions, but estimated distributions are very similar across a wide range of models that assumed variables are 2^{nd}-order stationary in growth rates

Model for BAU Emissions

Let $X_t = (X_{1t}, X_{2t}, \ldots, X_{9.t})'$ denote the vector composed of the nine annual magnitudes included in the VAR for year t, t=1990, 1991,…,2010. The elements of X_t are:

Three Measures of GHG Intensity per Unit of Economic Activity

X_{1t} = [(Industrial GHG Emissions+Natural Gas and Other GHG Emissions)/Real State GSP]

X_{2t} = [Transportation Sector GHG Emissions/Total Vehicle Miles Traveled]

X_{3t} = [In-state Electricity Sector GHG Emissions/Total Instate Electricity Production]

Three Measures of Economic Activity

X_{4t} = [Real State GSP]

X_{5t} = [Total Vehicle Miles Traveled]

X_{6t} = [Total In-state Electricity Production in Terawatt-hours]

Two Drivers of Economic Activity

X_{7t} = [Real Oil Price in dollars per barrel]

X_{8t} = [In-state Electricity Consumption in Terawatt-hours]

Allocating Emissions Across Sectors

X_{9t} = [(Industrial GHG Emissions)/(Natural Gas and Other GHG Emissions)]

All real dollar magnitudes are expressed in 2005 dollars.

All GHG emissions are in Tons of CO_2-equivalents.

Model for BAU Emissions

Define $Y_{it} = \ln(X_{it})$ for $i=1,2,\ldots,9$ and $Y_t = (Y_{1t}, Y_{2t}, \ldots, Y_{9,t})'$.

Econometric model specified in terms of Y_t because $R_{it} = Y_{it} - Y_{it-1}$ is continuously compounded growth in X_i during period t

Vector Autoregression Regression (VAR) that is stationary in first-differences can be written as

$$Y_t = \Theta_1 Y_{t-1} + \Theta_2 Y_{t-2} + \varepsilon_t$$

where each Θ_i $(i=1,2)$ is a (9x9) matrix of constants, and ε_t is a (9x1) white noise sequence with mean μ and covariance matrix Ω.

Recall that ε_t $(t=1,2,\ldots,T)$ being a white noise sequence implies that realizations of ε_t are uncorrelated over time

Co-integration implies that $(I - \Theta_1 - \Theta_2) = \gamma\alpha'$ where both γ is (9 x r) and α are (9 x r) rank r $(0 < r < 9)$ matrices and I is a (9x9) identity matrix

Model for BAU Emissions

Preliminary data analysis finds that null hypothesis that r = 4 cannot be rejected

Four stationary linear combinations of elements of Y_t

Four "long-run equilibrium" relations between elements of Y_t

We impose these restrictions on elements of Θ_1 and Θ_2 in model estimation and to construct distribution of $(Y_{T+1,}Y_{T+2,}....Y_{T+9,}Y_{T+10})$ for T=2010, so that T+1 = 2011 and T+10 = 2020

Account for two sources of uncertainty in value of $(Y_{T+1,}Y_{T+2,}....Y_{T+9,}Y_{T+10})$

Uncertainty in values of Θ_1, Θ_2, μ and Ω because these are estimated from historical data

Uncertainty in realizations of ε_t given values of μ and Ω

Use 2-step smoothed bootstrap approach to compute estimate of $F(Y_{T+1,}Y_{T+2,}....Y_{T+9,}Y_{T+10})$

Have information on real California Gross State Product (GSP) for 2011 and 2012

Compute $F[(Y_{T+1,}Y_{T+2,}....Y_{T+9,}Y_{T+10})|GSP(2011),GSP(2012)]$, distribution of $(Y_{T+1,}Y_{T+2,}....Y_{T+9,}Y_{T+10})$ conditional on actual values of GSP(2011) and GSP(2012)

Model for BAU Emissions

From $F[(Y_{T+1,}Y_{T+2,}....Y_{T+9,}Y_{T+10})|GSP(2011),GSP(2012)]$ can apply change of variables to compute an estimate of distribution of state-wide GHG emissions for

Phase I = electricity and industrial processes for 2013, 2014

Phase II = Phase I + transportation and natural gas for 2015 to 2020

Cap three emissions intensity measures at in-sample median, 75th percentile, or maximum in constructing future GHG emissions

If realized value of intensity is greater than cap, then re-set value to equal cap and multiply by economic activity measure to obtain sectoral GHG emissions

Compute distribution of cumulative GHG emissions covered by cap for 2013 through 2020

Sum of GHG emissions covered from start of program though end of each year

Report E(Cumulative Sum of Covered GHG Emissions| GSP(2011),GSP(2012)] for each year from 2013 to 2020

Compute pointwise (for each year) upper and lower 95% confidence intervals for each conditional expectation of cumulative annual GHG emissions

Figure 4a
Estimated Business-As-Usual Emissions
(with GHG Ratios to Other Factors Bounded Above at Median Levels)

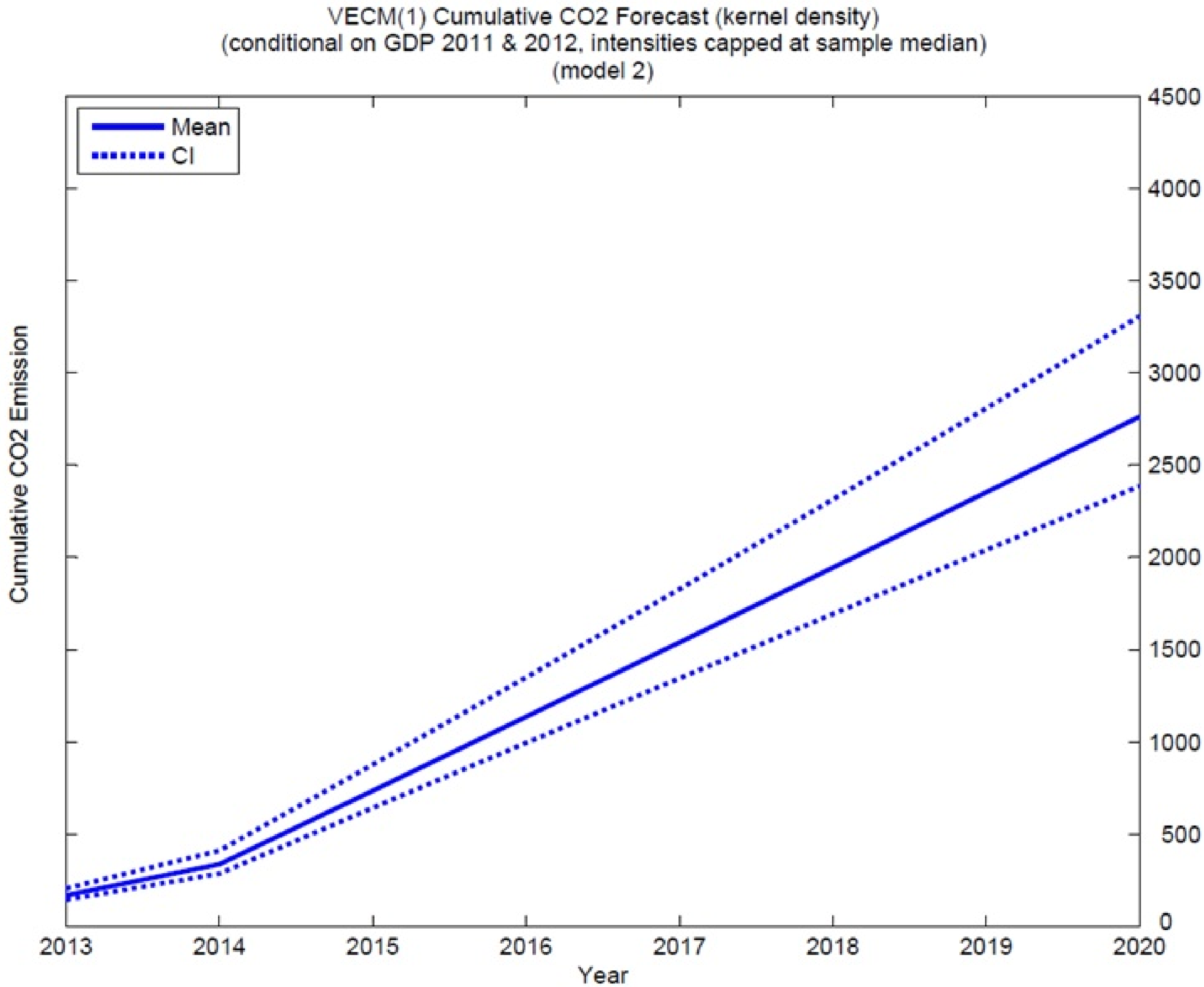


Figure 4b
Estimated Business-As-Usual Emissions

(GHG Ratios to Other Factors Bounded Above at 75th Percentile)

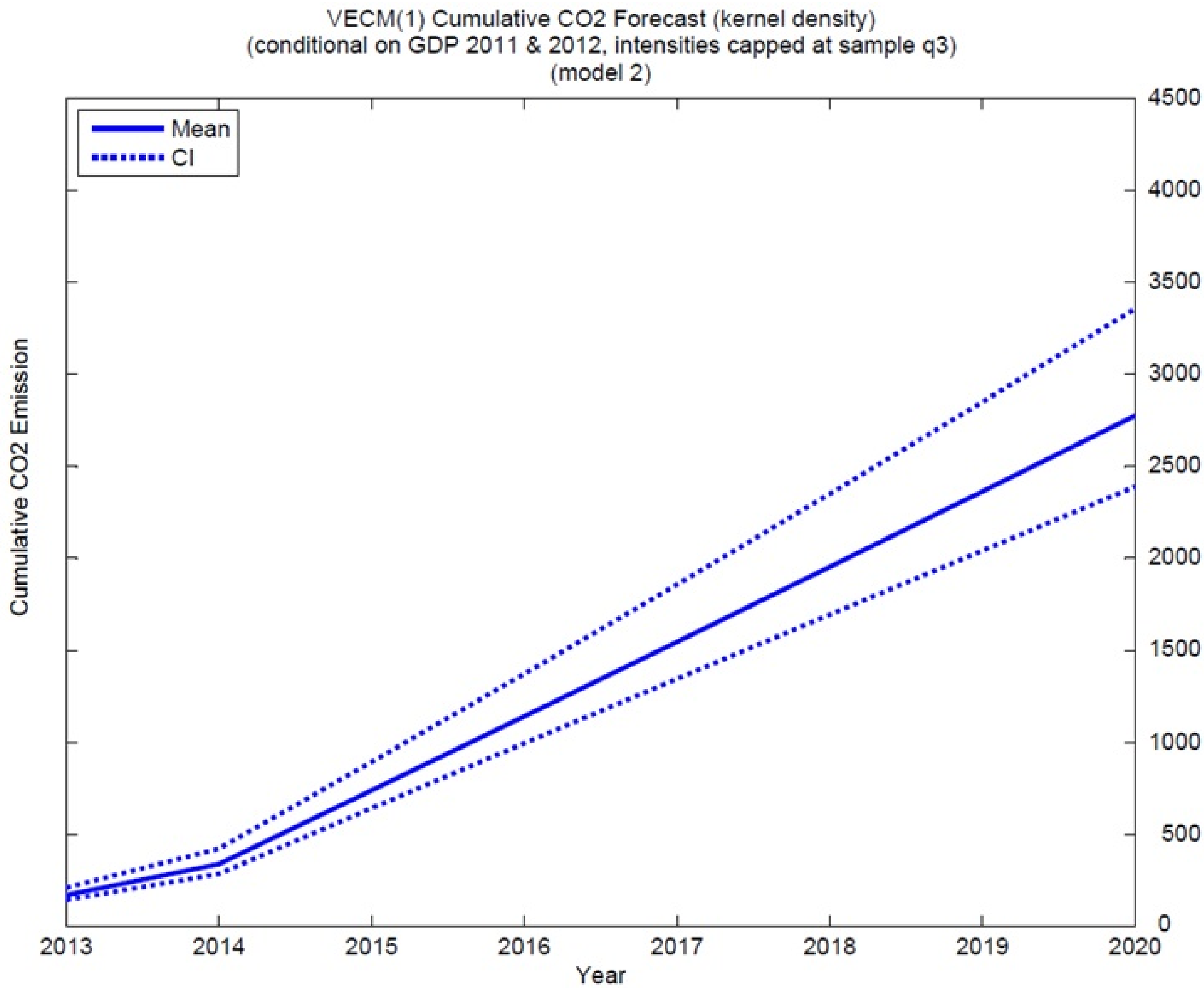
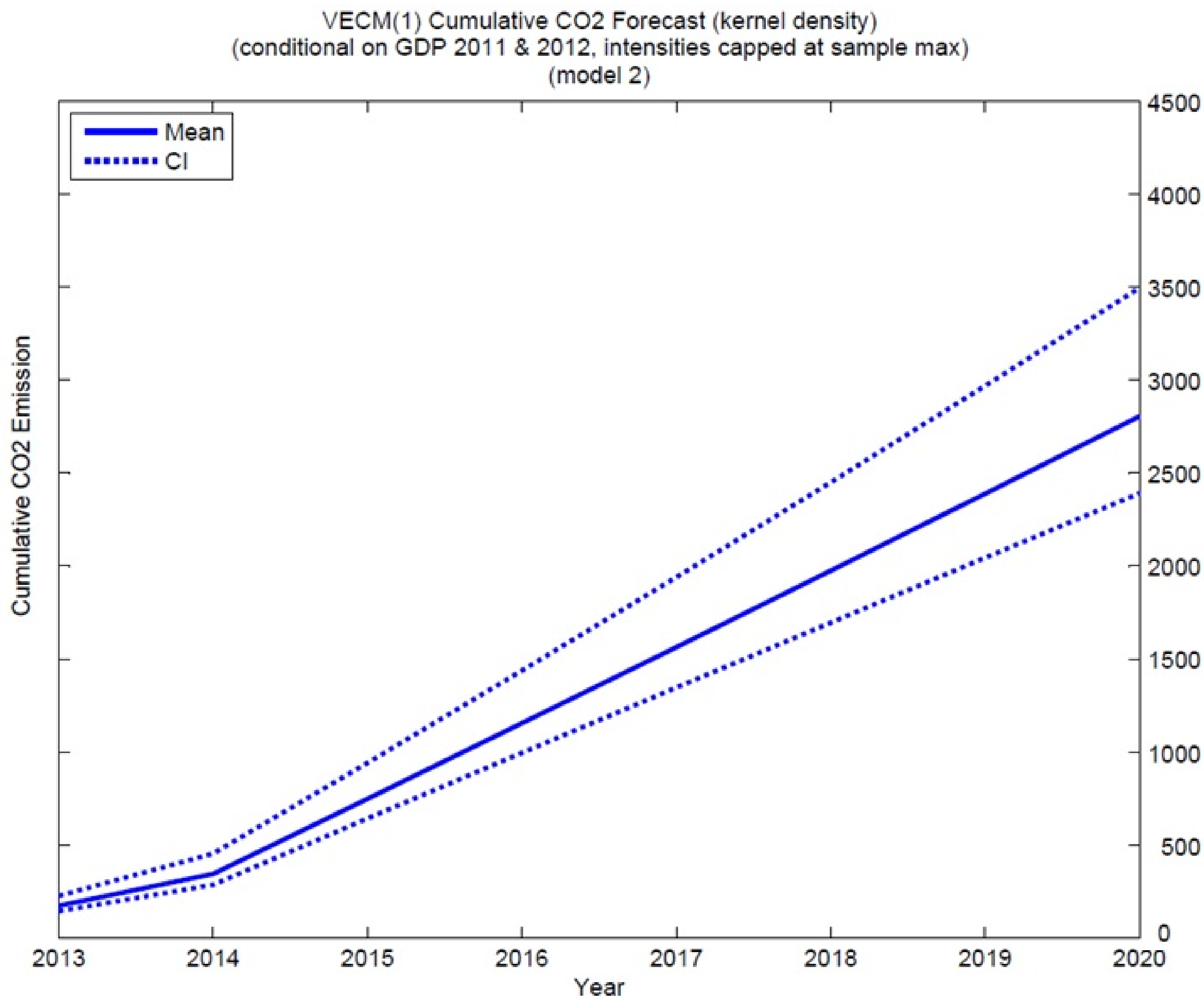


Figure 4c
Estimated Business-As-Usual Emissions

(GHG Ratios to Other Factors Bounded Above at Maximum)



Supply of Abatement

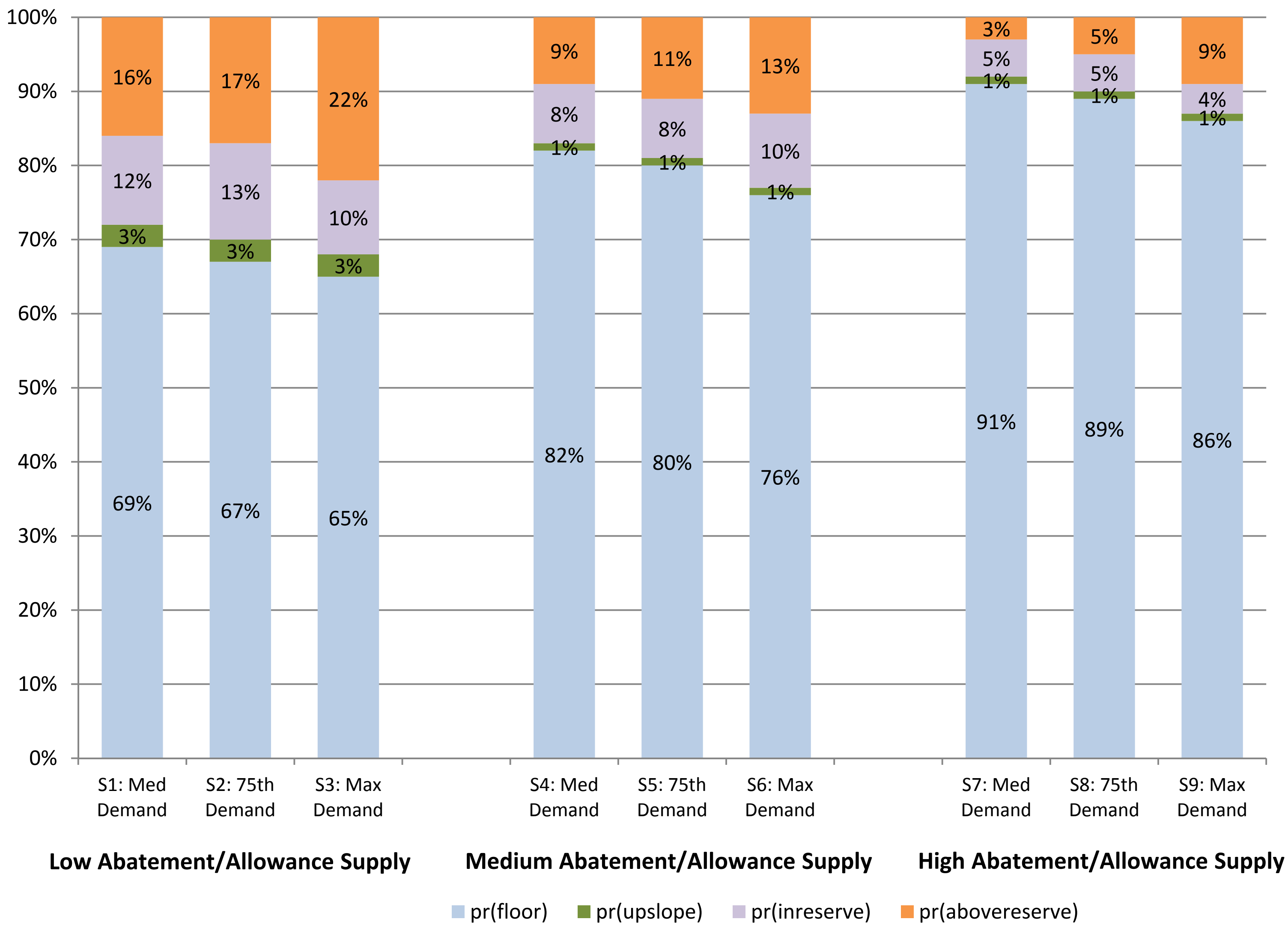
Table 1: Potential Emissions Reductions from Complementary Policies

Category	**Measure**	**Average Annual Reductions**	**Years Under Cap**	**Total Aggregate Reductions**
Complimentary Measures	20% and 33% RPS	7.8 – 12.4 MMT	2013 – 2020	62.4 – 98.8 MMT
	Auto Standards	9.3 – 16.2 MMT	2015 – 2020	74.2 – 129.8 MMT
	LCFS	0 – 10.3 MMT	2015 – 2020	0 – 61.9 MMT
	Energy Efficiency	0 – 3.4 MMT	2013 – 2020	0 – 27 MMT
	Other transport	0 – 1.5 MMT	2015 – 2020	0 – 12.4 MMT
Low-price Responses	Offsets	9.4 – 17.4 MMT	2013 – 2020	75 - 139 MMT
	Reshuffling	15 – 45 MMT	2013 – 2020	120 – 360 MMT
Price-Responsive (at $50/ton)	Gasoline		2015 - 2020	13.4-26.7 MMT
	Natural Gas		2015 - 2020	18.5-35.8 MMT
	Electricity		2013 - 2020	15-25 MMT
Totals				**378.5 – 916.4**

Three Abatement Scenarios

- Low Availability:
  - 475 MMT from comp. and low price policies
  - Medium price response
- Medium Availability:
  - 583 MMT from comp. and low price policies
  - Low price response
- High Availability:
  - 710 MMT from comp. and low price policies
  - Medium price response

Figure 5
Allowance Price Probabilities by Scenario



General Points

- Very skewed distribution of possible prices
  - High probability on low and high prices
  - Virtually no probability on intermediate prices
  - Non-trivial probability of exhausting allowance reserve
  - Steeper abatement curves and fatter tails on expected emissions magnify this effect
- Without allowance banking, ``width'' of the segments from the abatement supply curve narrow
  - Prices would not be the same every year
  - Probability of extreme prices in any given year increase

Policy Implications

- Allowance revenues could fall well below previous forecasts.
  - Floor price most likely outcome
  - Lower sales needed to maintain floor price
- Small, but real chance of reaching and exhausting allowance reserve before end of 2020.
  - Specific policies to respond to potential exhaustion of reserve are needed
  - EMAC Recommendation—Borrow reserves from future post-2020 compliance period to defend $50/Ton maximum allowance price
- Prices could be volatile as market updates to new information
  - Small swings in BAU or abatement could lead to large prices swings
  - Credible hard defense of price ceiling could limit attempts of market participants to create artificial scarcity of allowances to raise prices
    - Limits price upside of these strategies

Questions/Comments

For more information:

http://wolak.stanford.edu/~wolak