Environmental Market Design: Analyzing Impact of Regulatory Policy on Certificate Price Dynamics

Michael Coulon

University of Sussex

(from work with Rene Carmona & Daniel Schwarz...)

(... to work with Warren Powell & Javad Khazaei...)

(...and a bit with Michele Stua)

Workshop on Commodity Markets and their Financialization,

Los Angeles, LA

May 8th, 2015

Environmental Market Overview

Categories of typical environmental markets:

- Cap-and-trade for carbon allowances *(e.g. EU ETS, California, etc.)*
- Renewable energy certificates (RECs), i.e. green certificates *(e.g. many US states, Norway-Sweden, UK, Australia, India, etc.)*
- Credit markets for carbon *(e.g. CDM)*

Environmental Market Overview

Categories of typical environmental markets:

- Cap-and-trade for carbon allowances *(e.g. EU ETS, California, etc.)*
- Renewable energy certificates (RECs), i.e. green certificates *(e.g. many US states, Norway-Sweden, UK, Australia, India, etc.)*
- Credit markets for carbon *(e.g. CDM)*

A brief summary:

- In cap-and-trade, an allowance is a permit to emit one ton of CO_2, which polluters must submit each year to cover their emissions
- In REC markets, a certificate represents one MWh of electricity generated, needed by utilities to reach a required % of renewables.

Environmental Market Overview

Categories of typical environmental markets:

- Cap-and-trade for carbon allowances *(e.g. EU ETS, California, etc.)*
- Renewable energy certificates (RECs), i.e. green certificates *(e.g. many US states, Norway-Sweden, UK, Australia, India, etc.)*
- Credit markets for carbon *(e.g. CDM)*

A brief summary:

- In cap-and-trade, an allowance is a permit to emit one ton of CO_2, which polluters must submit each year to cover their emissions
- In REC markets, a certificate represents one MWh of electricity generated, needed by utilities to reach a required % of renewables.

Strong links between these markets, their design and price behaviour!

Environmental Market Overview

Why are these markets interesting / unusual?

- Market based alternative to carbon taxes, feed-in tariffs, etc.

Environmental Market Overview

Why are these markets interesting / unusual?

- Market based alternative to carbon taxes, feed-in tariffs, etc.
- Unlike other 'commodities', these are financial contracts!

Environmental Market Overview

Why are these markets interesting / unusual?

- Market based alternative to carbon taxes, feed-in tariffs, etc.
- Unlike other ‘commodities’, these are financial contracts!
- Either supply or demand is artificially set by regulators, along with various other key rules (e.g., penalty levels, banking / borrowing)

Environmental Market Overview

Why are these markets interesting / unusual?

- Market based alternative to carbon taxes, feed-in tariffs, etc.
- Unlike other 'commodities', these are financial contracts!
- Either supply or demand is artificially set by regulators, along with various other key rules (e.g., penalty levels, banking / borrowing)
- Price depends on a 'compliance event' leading to digital option like features (and inherent instability)

Environmental Market Overview

Why are these markets interesting / unusual?

- Market based alternative to carbon taxes, feed-in tariffs, etc.
- Unlike other ‘commodities’, these are financial contracts!
- Either supply or demand is artificially set by regulators, along with various other key rules (e.g., penalty levels, banking / borrowing)
- Price depends on a ‘compliance event’ leading to digital option like features (and inherent instability)
- However, underlying process for compliance event responds to price

Environmental Market Overview

Why are these markets interesting / unusual?

- Market based alternative to carbon taxes, feed-in tariffs, etc.
- Unlike other ‘commodities’, these are financial contracts!
- Either supply or demand is artificially set by regulators, along with various other key rules (e.g., penalty levels, banking / borrowing)
- Price depends on a ‘compliance event’ leading to digital option like features (and inherent instability)
- However, underlying process for compliance event responds to price
- Prices also linked to fundamentals (weather, energy prices, politics?)

Environmental Market Overview

Why are these markets interesting / unusual?

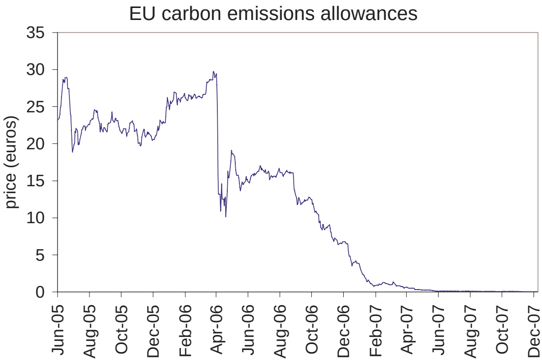
- Market based alternative to carbon taxes, feed-in tariffs, etc.
- Unlike other ‘commodities’, these are financial contracts!
- Either supply or demand is artificially set by regulators, along with various other key rules (e.g., penalty levels, banking / borrowing)
- Price depends on a ‘compliance event’ leading to digital option like features (and inherent instability)
- However, underlying process for compliance event responds to price
- Prices also linked to fundamentals (weather, energy prices, politics?)

Hence many interesting research questions emerge, with little literature:

- How to model prices? (and demand or supply)
- Optimal behaviour of participants? (e.g. abatement, new investment)
- Optimal behaviour by regulators? (e.g. interventions)
- Optimal market design?

Carbon Price Modelling

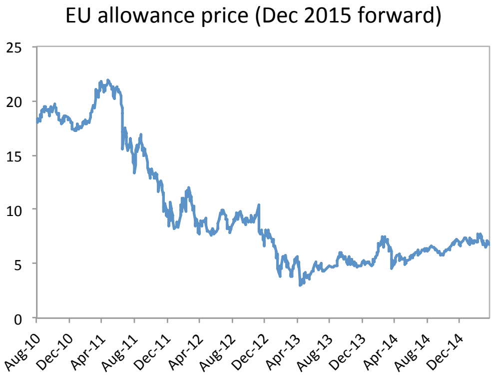
Early work (with limited history) proposed traditional price models like for equities. However, in the first EU-ETS trading period (Phase I, 2005-07):



Collapse of prices in 2006-07 was caused by the oversupply of credits, combined with the lack of banking to Phase II.

EU Carbon Prices

In recent years prices have again slumped, due partly to recession (lower than anticipated demand) and long-term political uncertainty.

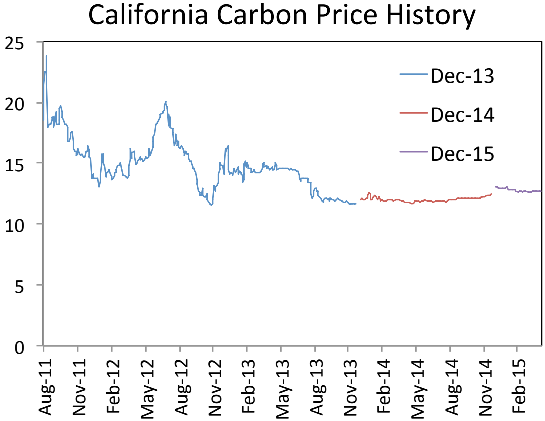


Low prices have led to some attempts to claw back oversupply, and to recent rule changes: the market stability reserve. (see Taschini *et al* 2014)

California Carbon Prices

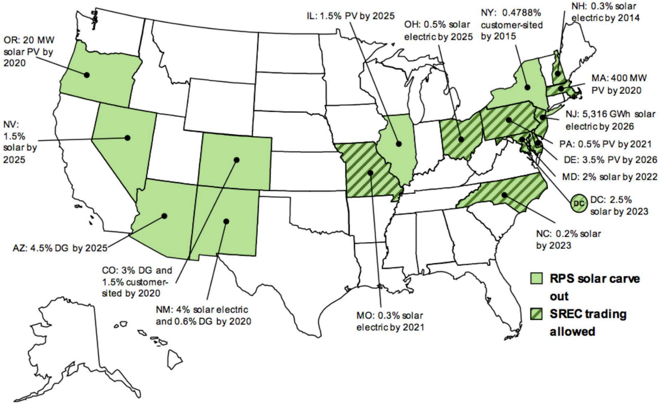
California Carbon Prices

The recently formed California (plus Quebec!) market as similarly slipped into a period of oversupply recently, with prices near 'auction reserve' price of about \$10-\$11 dollars (grows with inflation).



Renewable Energy Certificates (RECs)

In the US, about 30 states recently introduced a Renewable Portfolio Standard (RPS). About 10 have set up markets for tradeable certificates called SRECs (or more generally RECs) to achieve these RPS targets.

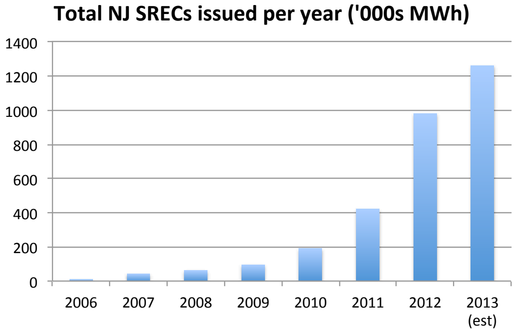


(map taken from: US DoE-NREL report by Bird, Heeter, Kreycik, 2011)

The New Jersey SREC market

The New Jersey SREC market is the biggest in the US (among about 10 states; similar markets for 'green certificates' also exist in Europe and Asia)

- Most ambitious target of over 4% solar energy by 2028.
- Highest recorded prices so far at about $700 per SREC.
- Rapid growth witnessed in solar installations in recent years.



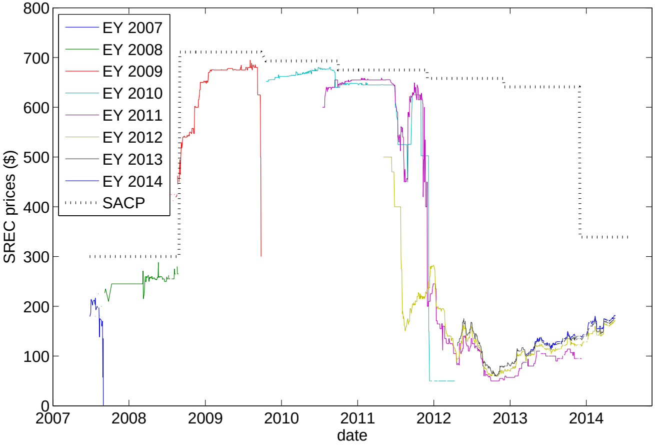
The New Jersey SREC market

The rules of the NJ market have been changed many times. Just a summary of the main ones here (penalty π, requirement R):

Energy Year	True-up Period	Oldest Rules *(no banking)* R	π	2008 change *(3-year life)* R	π	2012 change *(5-year life)* R	π
2007	3 mon	32,743	300				
2008	3 mon	65,384	300				
2009	4 mon	130,266	300	130,266	711		
2010	4 mon	195,000	300	195,000	693		
2011	6 mon			306,000	675		
2012	6 mon			442,000	658	442,000	658
2013	6 mon			596,000	641	596,000	641
2014	6 mon			772,000	625	1,707,931	339
2015	6 mon			965,000	609	2,071,803	331
2016	6 mon			115,0000	594	2,360,376	323
2017	6 mon					2,613,580	315
2018	6 mon					2,829,636	308

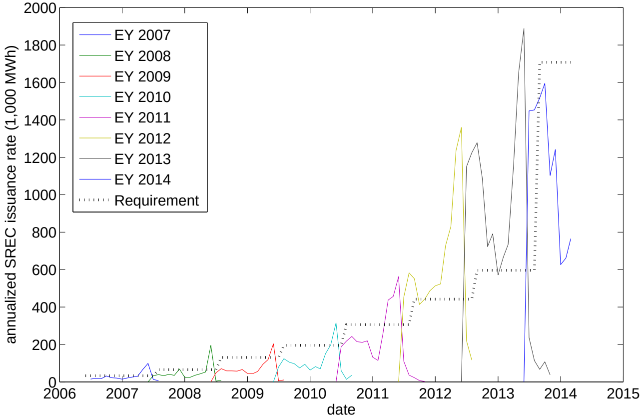
The New Jersey SREC market

What about historical prices? Very high (near penalty π) until recently...



The New Jersey SREC market

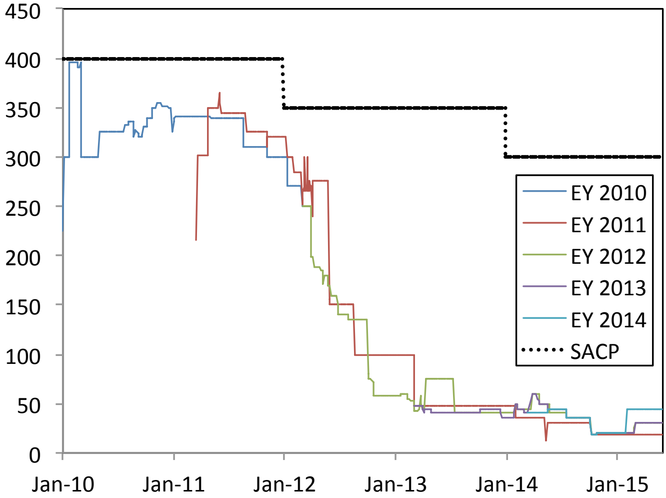
Historical (monthly) issuance data easily available online. Rapid growth in 2010-13 led to sudden swing from under to oversupply (and price collapse).



Was this just a Jersey thing?

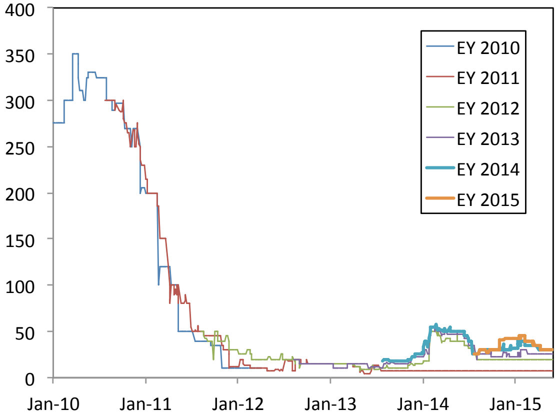
Was this just a Jersey thing?

Ohio SREC prices 2010-15:



Was this just a Jersey thing?

Pennsylvania SREC prices 2010-15:



Such sudden price swings are worrying for solar investors and regulators.

Carbon / REC Price Modeling - Basics

How to model allowance / certificate price P_t? Exogenously? Lognormally?

Carbon / REC Price Modeling - Basics

How to model allowance / certificate price P_t? Exogenously? Lognormally?

- Convenient as input for other problems (derivatives, optimization, etc.)
- Some (carbon) literature applying classical models from finance

However, such 'reduced-form' approaches ignore:

Carbon / REC Price Modeling - Basics

How to model allowance / certificate price P_t? Exogenously? Lognormally?

- Convenient as input for other problems (derivatives, optimization, etc.)
- Some (carbon) literature applying classical models from finance

However, such 'reduced-form' approaches ignore:

1. Structure of the market, including rules and rule changes
2. Equilibrium produced by the feedback of price on market behaviour:

Carbon / REC Price Modeling - Basics

How to model allowance / certificate price P_t? Exogenously? Lognormally?

- Convenient as input for other problems (derivatives, optimization, etc.)
- Some (carbon) literature applying classical models from finance

However, such 'reduced-form' approaches ignore:

1. Structure of the market, including rules and rule changes
2. Equilibrium produced by the feedback of price on market behaviour:

- *For carbon*, P_t is increasing in emissions level E_t (relative to cap $K(T)$), **but** higher P_t slows the growth of E_t.
- *For RECs*, P_t is decreasing in generation level g_t (relative to requirement $R(T)$), **but** higher P_t encourages growth of g_t.

Carbon / REC Price Modeling - Basics

How to model allowance / certificate price P_t? Exogenously? Lognormally?

- Convenient as input for other problems (derivatives, optimization, etc.)
- Some (carbon) literature applying classical models from finance

However, such 'reduced-form' approaches ignore:

1. Structure of the market, including rules and rule changes
2. Equilibrium produced by the feedback of price on market behaviour:

- *For carbon*, P_t is increasing in emissions level E_t (relative to cap $K(T)$), **but** higher P_t slows the growth of E_t.
- *For RECs*, P_t is decreasing in generation level g_t (relative to requirement $R(T)$), **but** higher P_t encourages growth of g_t.

As usual when matching supply and demand, an equilibrium results! :)

Carbon/REC Price Modelling - Basics

Key features for carbon:

- Financial contract, unlike other commodities $\implies$ $\mathsf{e}^{-rt}P_t$ martingale
- Derivative on total emissions $E_t = \int_0^t X_u du$ ('emissions rate' $X_t \geq 0$)
- In a single period, with cap K, penalty π:

$$P_t = \mathsf{e}^{-r(T-t)}\mathbb{E}_t^{\mathbb{Q}}\left[\pi 1_{\{E_T > K\}}\right]$$

Carbon/REC Price Modelling - Basics

Key features for carbon:

- Financial contract, unlike other commodities $\implies$ $\mathrm{e}^{-rt}P_t$ martingale
- Derivative on total emissions $E_t = \int_0^t X_u du$ ('emissions rate' $X_t \geq 0$)
- In a single period, with cap K, penalty π:

$$P_t = \mathrm{e}^{-r(T-t)}\mathbb{E}_t^{\mathbb{Q}}\left[\pi 1_{\{E_T > K\}}\right]$$

Key features for SRECs (analagously):

- Financial contract, unlike other commodities $\implies$ $\mathrm{e}^{-rt}P_t$ martingale
- Derivative on total generation $b_t = \int_0^t g_u du$ ('generation rate' $g_t \geq 0$)
- In a single period, with requirement R, penalty π:

$$P_t = \mathrm{e}^{-r(T-t)}\mathbb{E}_t^{\mathbb{Q}}\left[\pi 1_{\{b_T < R\}}\right]$$

Key Observation: X_t and g_t should be dependent on P_t (decreasing for former, increasing for latter), due to the feedback effect.

Carbon Price Modelling - One Period

Higher carbon price P_t reduces emissions X_t via two forms of abatement:

- 'Immediate' abatement in power sector due to the merit order.
- Longer-term abatement due to incentives to use clean technology, etc.

Carbon Price Modelling - One Period

Higher carbon price P_t reduces emissions X_t via two forms of abatement:

- 'Immediate' abatement in power sector due to the merit order.
- Longer-term abatement due to incentives to use clean technology, etc.

The power stack model can give us $X_t(P_t)$ to capture the first effect. Then

$$P_t = \mathrm{e}^{-r(T-t)} \pi \mathbb{P}_t^{\mathbb{Q}} \left\{ \int_0^T X_u(P_u) du > K \right\},$$

How to solve?:

Carbon Price Modelling - One Period

Higher carbon price P_t reduces emissions X_t via two forms of abatement:

- 'Immediate' abatement in power sector due to the merit order.
- Longer-term abatement due to incentives to use clean technology, etc.

The power stack model can give us $X_t(P_t)$ to capture the first effect. Then

$$P_t = \mathrm{e}^{-r(T-t)} \pi \mathbb{P}_t^{\mathbb{Q}} \left\{ \int_0^T X_u(P_u) du > K \right\},$$

How to solve?:

- Discretize and solve backwards via dynamic programing (fixed point problem at each gridpoint)
- In continuous time, drift of E_t dependent on P_t (and other factors):

$$dE_t = \mu_e(P_t, C_t, G_t, D_t) dt \qquad \text{(possibly } + \sigma_e dW_t)$$

FBSDE is needed (Carmona *et al.* (2012), Howison/Schwarz (2012))

Carbon Price Modelling - FBSDE

Combining the processes for demand, fuels (using $\mathbf{S}_t = (C_t, G_t)$), cumulative emissions and allowance price leads to the FBSDE below:

$$\begin{cases} dD_t = \mu_d(t, D_t)dt + \sigma_d(D_t)d\tilde{W}_t^0, & D_0 = d_0 \in (0, \bar{\xi}), \\ d\mathbf{S}_t = \mu_s(\mathbf{S}_t)dt + \sigma_s(\mathbf{S}_t)d\tilde{\mathbf{W}}_t, & S_0 = s_0 \in \mathbb{R}_{++}, \\ dE_t = \mu_e(D_t, P_t, \mathbf{S}_t)dt, & E_0 = 0, \\ dP_t = rP_t dt + Z_t^0 d\tilde{W}_t^0 + Z_t \cdot d\tilde{\mathbf{W}}_t, & P_T = \pi 1_{\{E_T > K\}}. \end{cases}$$

- $(D_t, \mathbf{S}_t, E_t)$ - forward part
- (P_t) - backward part,
- (Z_t) - generator

We solve for $P_t = f(t, D_t, E_t, \mathbf{S}_t)$ numerically via the corresponding non-linear PDE. Can then (e.g. Carmona Coulon Schwartz 2012):

- price derivatives (eg, spread options) by simulation (or via a 2nd PDE).
- compare impact of cap-and-trade with a carbon tax (fixed P_t).

Summary Comparison: Carbon vs RECs

Clearly many similarities with cap-and-trade, but also key differences:

Feature	**Cap-and-trade**	**NJ SREC market**
Banking	(typically) unrestricted	finite # of times (eg. 4)
Borrowing	within trading periods	none
'Withdrawal'	Penalty plus debt	Penalty (SACP) only
Periodicities	none significant	solar generation seasonal
Feedback	power sector fuel switching	new construction of solar generation
Available data?	challenging at EU level	easy (at monthly freq)
Correlated with?	power, gas, coal, etc	relatively separate *for now!*

Summary Comparison: Carbon vs RECs

Clearly many similarities with cap-and-trade, but also key differences:

Feature	Cap-and-trade	NJ SREC market
Banking	(typically) unrestricted	finite # of times (eg. 4)
Borrowing	within trading periods	none
'Withdrawal'	Penalty plus debt	Penalty (SACP) only
Periodicities	none significant	solar generation seasonal
Feedback	power sector fuel switching	new construction of solar generation
Available data?	challenging at EU level	easy (at monthly freq)
Correlated with?	power, gas, coal, etc	relatively separate *for now!*

However, many other rule variations. For example, in Scandinavia:

- Unlimited banking (until market ends in 2035)
- **But,** no new supply allowed after 2020! (a 'creative' design)
- **And,** penalty resets to 1.5 times previous year's price! ('interesting')

Back to NJ SRECs - Multi-period model

We must include τ years of banking, such that a vintage y SREC is valid at

$$t \in \{y, y+1, \ldots, y+\tau\}$$

Back to NJ SRECs - Multi-period model

We must include τ years of banking, such that a vintage y SREC is valid at

$$t \in \{y, y+1, \ldots, y+\tau\}$$

Then the price today is a max over all future shortage probabilities:

$$p_t^y = \max_{v \in \{\lceil t \rceil, \lceil t \rceil + 1, \ldots, y+\tau\}} e^{-r(v-t)} \pi_t^v \mathbb{E}_t \left[1_{\{b_v = 0\}} \right]$$

where b_t is the accumulated SREC supply (this year's plus banked):

Back to NJ SRECs - Multi-period model

We must include τ years of banking, such that a vintage y SREC is valid at

$$t \in \{y, y+1, \dots, y+\tau\}$$

Then the price today is a max over all future shortage probabilities:

$$p_t^y = \max_{v \in \{\lceil t \rceil, \lceil t \rceil + 1, \dots, y+\tau\}} e^{-r(v-t)} \pi_t^v \mathbb{E}_t \left[1_{\{b_v = 0\}} \right]$$

where b_t is the accumulated SREC supply (this year's plus banked):

$$b_t = \begin{cases} \max\left(0, b_{t-1} + \int_{t-1}^{t} g_u \mathrm{d}u - R_t^t\right) & t \in \mathbb{N}, \\ b_{\lceil t \rceil - 1} + \int_{\lceil t \rceil - 1}^{t} g_u \mathrm{d}u & t \notin \mathbb{N}. \end{cases}$$

Back to NJ SRECs - Multi-period model

We must include τ years of banking, such that a vintage y SREC is valid at

$$t \in \{y, y+1, \ldots, y+\tau\}$$

Then the price today is a max over all future shortage probabilities:

$$p_t^y = \max_{v \in \{\lceil t \rceil, \lceil t \rceil + 1, \ldots, y+\tau\}} e^{-r(v-t)} \pi_t^v \mathbb{E}_t \left[1_{\{b_v = 0\}} \right]$$

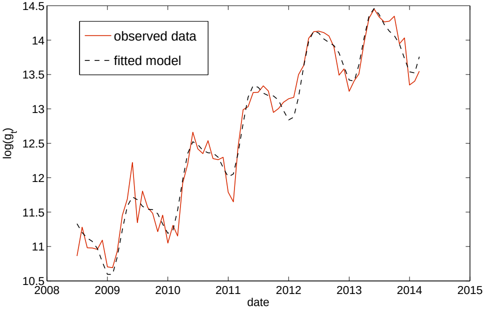
where b_t is the accumulated SREC supply (this year's plus banked):

$$b_t = \begin{cases} \max\left(0, b_{t-1} + \int_{t-1}^{t} g_u \mathrm{d}u - R_t^t\right) & t \in \mathbb{N}, \\ b_{\lceil t \rceil - 1} + \int_{\lceil t \rceil - 1}^{t} g_u \mathrm{d}u & t \notin \mathbb{N}. \end{cases}$$

Note: Extending to multi-period in carbon similar but 'withdrawal' rule $\Longrightarrow$ price is a sum, not a max! (e.g., Hitzemann Uhrig-Homburg 2014)

NJ SREC issuance data

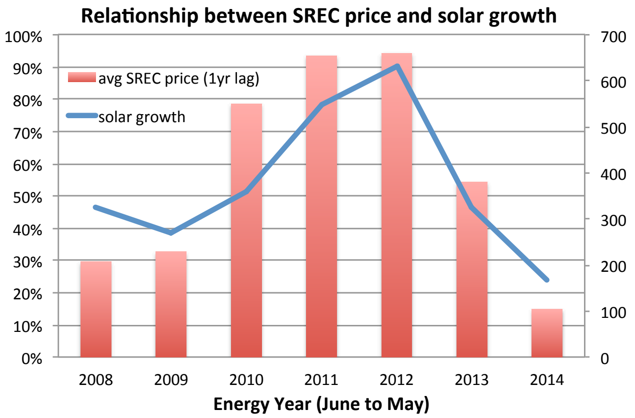
Lastly, a stochastic model for solar generation rate g_t. Log of monthly SREC issuance shows some noise, seasonality and a clear upwards trend:



Like for electricity demand, perhaps model g_t with an OU process plus a trend and cosines? Anything missing? (notice recent flattening)

NJ SREC issuance data

Looking more closely at SREC generation growth (and in recent data):



Clear relationship between growth rate and (1yr lagged) price!

Structural model for SREC prices

Indeed, **feedback** of SREC prices on generation growth is crucial!

Structural model for SREC prices

Indeed, **feedback** of SREC prices on generation growth is crucial!

- We first fit seasonality and Gaussian noise term ε_t:

$$g_t = \hat{g}_t(p) \exp\left(a_1 \sin(4\pi t) + a_2 \cos(4\pi t) + a_3 \sin(2\pi t) + a_4 \cos(2\pi t) + \varepsilon_t\right),$$

Structural model for SREC prices

Indeed, **feedback** of SREC prices on generation growth is crucial!

- We first fit seasonality and Gaussian noise term ε_t:

$$g_t = \hat{g}_t(p) \exp\left(a_1 \sin(4\pi t) + a_2 \cos(4\pi t) + a_3 \sin(2\pi t) + a_4 \cos(2\pi t) + \varepsilon_t\right),$$

- We then assume that the average annual generation rate $\hat{g}_t$ grows as:

$$\frac{d}{dt}\left(\ln(\hat{g}_t)\right) = a_5 + a_6 \bar{p}_t, \qquad \text{for } a_5 \in \mathbb{R}, a_6 > 0$$

where a_6 captures sensitivity to prices (degree of feedback).

Structural model for SREC prices

Indeed, **feedback** of SREC prices on generation growth is crucial!

- We first fit seasonality and Gaussian noise term ε_t:

$$g_t = \hat{g}_t(p) \exp\left(a_1 \sin(4\pi t) + a_2 \cos(4\pi t) + a_3 \sin(2\pi t) + a_4 \cos(2\pi t) + \varepsilon_t\right),$$

- We then assume that the average annual generation rate $\hat{g}_t$ grows as:

$$\frac{d}{dt}\left(\ln(\hat{g}_t)\right) = a_5 + a_6 \bar{p}_t, \qquad \text{for } a_5 \in \mathbb{R}, a_6 > 0$$

  where a_6 captures sensitivity to prices (degree of feedback).

- $\bar{p}_t$ allows for dependence on *historical* prices, e.g. a lagged EWMA:

$$\bar{p}^y_t = \delta p^y_{t-\gamma} + (1-\delta)\bar{p}^y_{t-\Delta t} \qquad \text{(where} \quad \bar{p}^y_{t_0} = p^y_{t_0-\gamma}\text{)}.$$

Structural model for SREC prices

Indeed, **feedback** of SREC prices on generation growth is crucial!

- We first fit seasonality and Gaussian noise term ε_t:

$$g_t = \hat{g}_t(p) \exp\left(a_1 \sin(4\pi t) + a_2 \cos(4\pi t) + a_3 \sin(2\pi t) + a_4 \cos(2\pi t) + \varepsilon_t\right),$$

- We then assume that the average annual generation rate $\hat{g}_t$ grows as:

$$\frac{d}{dt}\left(\ln(\hat{g}_t)\right) = a_5 + a_6 \bar{p}_t, \qquad \text{for } a_5 \in \mathbb{R}, a_6 > 0$$

  where a_6 captures sensitivity to prices (degree of feedback).

- $\bar{p}_t$ allows for dependence on *historical* prices, e.g. a lagged EWMA:

$$\bar{p}^y_t = \delta p^y_{t-\gamma} + (1-\delta)\bar{p}^y_{t-\Delta t} \qquad (\text{where} \quad \bar{p}^y_{t_0} = p^y_{t_0-\gamma}).$$

This completes the model. We now solve by dynamic programming.
(Between years $p^y_t = \mathrm{e}^{-r\Delta t}\mathbb{E}^{\mathbb{Q}}_t[p^y_{t+\Delta t}]$, while jumps can occur at $t \in \mathbb{N}$.)

Summary of the Algorithm

Recall: Firstly the price today as a maximum over expected payoffs:

$$p_t^y = \max_{v \in \{\lceil t \rceil, \lceil t \rceil + 1, \ldots, y+\tau\}} e^{-r(v-t)} \pi_t^v \mathbb{E}_t \left[1_{\{b_v = 0\}} \right].$$

Discretize and initialize $p_T^y(b_T, \hat{g}_T) = 1_{\{b_T=0\}}$ at $T = y + \tau$. Then:

Summary of the Algorithm

Recall: Firstly the price today as a maximum over expected payoffs:

$$p_t^y = \max_{v \in \{\lceil t \rceil, \lceil t \rceil + 1, \ldots, y+\tau\}} e^{-r(v-t)} \pi_t^v \mathbb{E}_t \left[1_{\{b_v = 0\}} \right].$$

Discretize and initialize $p_T^y(b_T, \hat{g}_T) = 1_{\{b_T=0\}}$ at $T = y + \tau$. Then:

- For $t \notin \mathbb{N}$, solve $p_t^y = \mathrm{e}^{-r\Delta t} \mathbb{E}_t^{\mathbb{Q}}[p_{t+\Delta t}^y]$, a fixed point problem with

$$p_t^y \uparrow \implies \hat{g}_{t+\Delta t} \uparrow \implies b_{t+\Delta t} \uparrow \implies \text{RHS} \downarrow.$$

- For $t \in \mathbb{N}$, solve $p_t^y = \max\left(\pi_t^t 1_{\{b_t=0\}}, \mathrm{e}^{-r\Delta t} \mathbb{E}_t^{\mathbb{Q}}[p_{t+\Delta t}^y]\right)$

Summary of the Algorithm

Recall: Firstly the price today as a maximum over expected payoffs:

$$p_t^y = \max_{v \in \{\lceil t \rceil, \lceil t \rceil + 1, \ldots, y+\tau\}} e^{-r(v-t)} \pi_t^v \mathbb{E}_t \left[1_{\{b_v = 0\}} \right].$$

Discretize and initialize $p_T^y(b_T, \hat{g}_T) = 1_{\{b_T=0\}}$ at $T = y + \tau$. Then:

- For $t \notin \mathbb{N}$, solve $p_t^y = \mathrm{e}^{-r\Delta t} \mathbb{E}_t^{\mathbb{Q}}[p_{t+\Delta t}^y]$, a fixed point problem with

$$p_t^y \uparrow \Longrightarrow \hat{g}_{t+\Delta t} \uparrow \Longrightarrow b_{t+\Delta t} \uparrow \Longrightarrow \text{RHS} \downarrow .$$

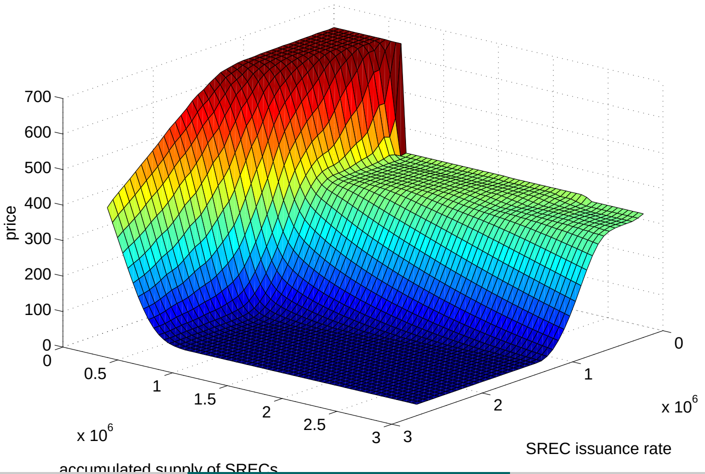
- For $t \in \mathbb{N}$, solve $p_t^y = \max \left(\pi_t^t 1_{\{b_t=0\}}, \mathrm{e}^{-r\Delta t} \mathbb{E}_t^{\mathbb{Q}}[p_{t+\Delta t}^y] \right)$

Notes:

- Expected price drops at compliance dates (breaking martingale condition) but this captures when all certificates should be used up.
- BSDE to PDE approach can also be applied here, with (trivial) 'exercise' condition each compliance date (like a Bermudan option).

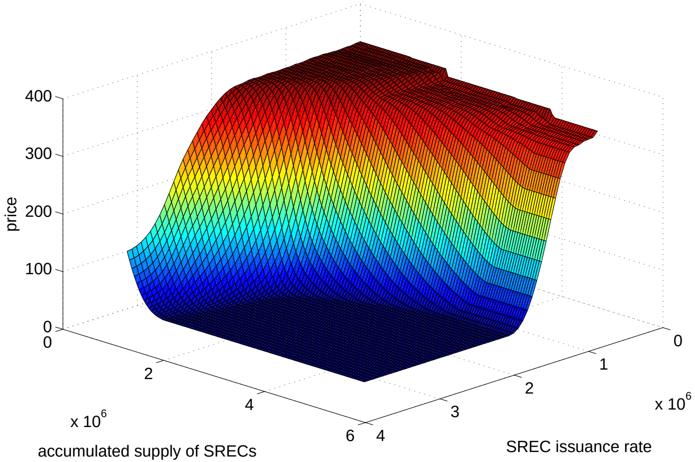
Results of structural model

Solving algorithm produces a surface $P_t(b_t, \hat{g}_t)$ for each time.
For 2013 SRECs near the end of the first year:



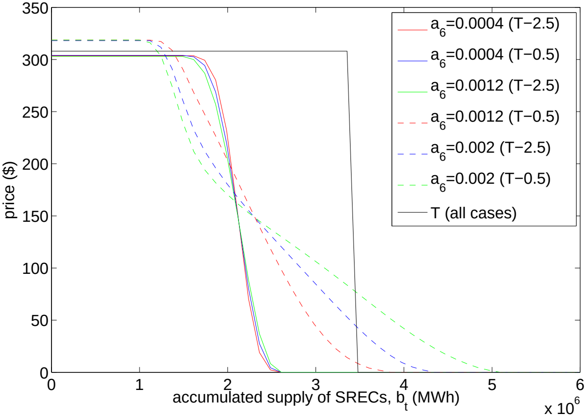
Results of structural model

Same price surface but six months later:



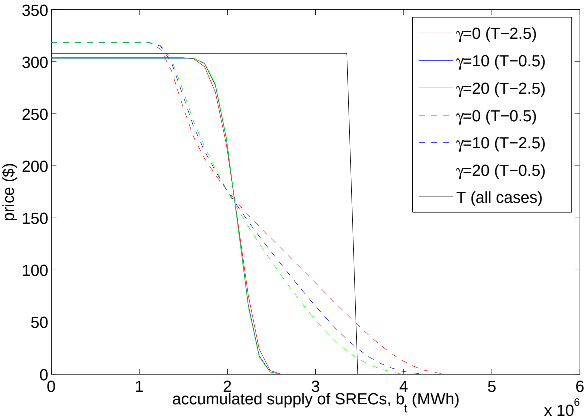
Results of structural model

Sensitivity to feedback parameter a_6:



Results of structural model

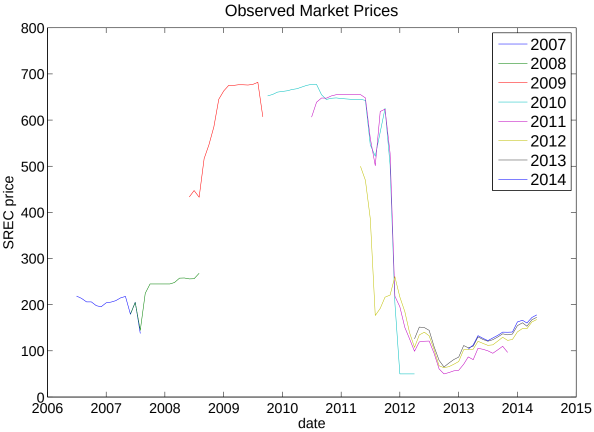
Sensitivity to feedback lag parameter γ:



Comparison to history

After fitting parameters, we compare historical market vs model prices:

- Overall price behaviour through history reasonably encouraging
- Also, provides further evidence about nature of feedback in market



Comparison to history

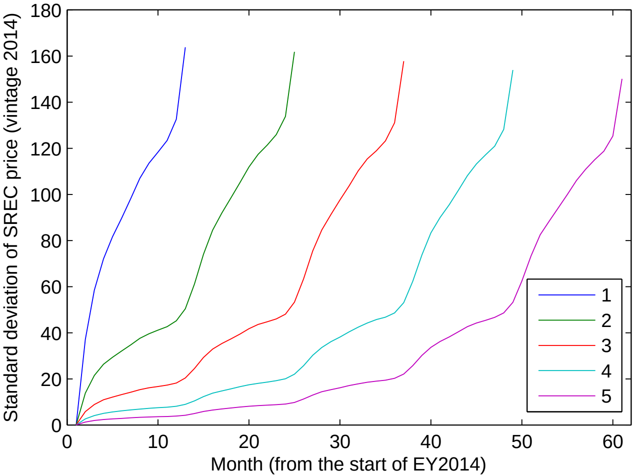
Feedback parameter found to be $a_6 = 1.3 \times 10^{-3}$. With lag $\gamma = 5/12$:

Comparison to history

With larger time lag $\gamma = 10/12$, recent price drop is more dramatic:

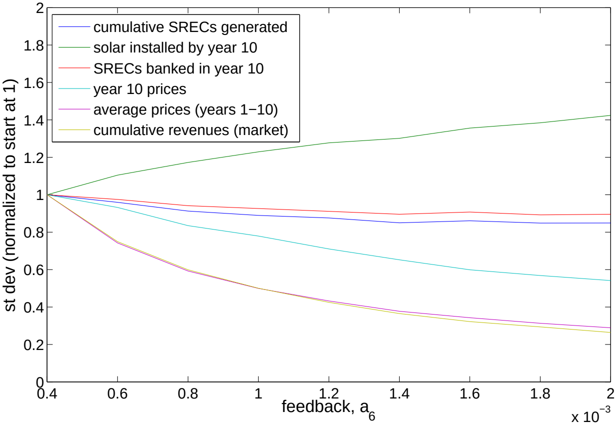
Impact of Banking

A larger number of banking years clearly produces greater price stability:



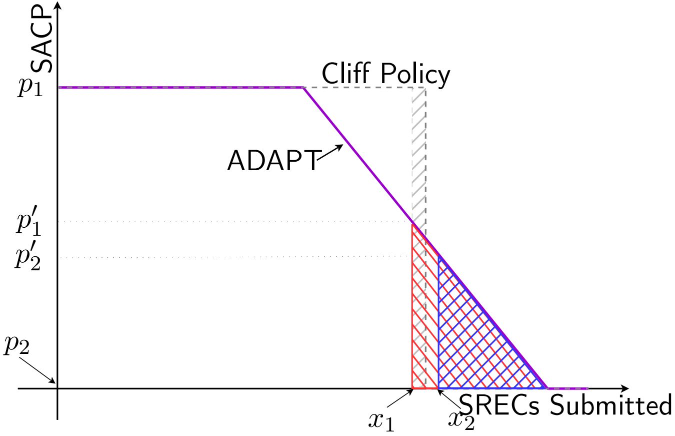
Impact of Feedback

An increase in feedback a_6 also stabilizes prices. However, can come at the expense of quantity uncertainty (top line in plot below):



Policy Analysis - Other Ideas?

Inherent instability (in both REC and carbon markets) is due to the digital payoff functions... why not try something smoother? (eg, slope below)



(Example prices for submitted SRECs x_1 and x_2. Shaded triangles = penalty paid.)

Penalty Function: Step vs Slope

A sloped penalty function implies:

- A non-trivial (model-dependent) banking decision each year
- A resulting threshold analogous to Am. options' 'exercise boundary'

Penalty Function: Step vs Slope

A sloped penalty function implies:

- A non-trivial (model-dependent) banking decision each year
- A resulting threshold analogous to Am. options' 'exercise boundary'

Price of SRECs of vintage y at time t now calculated via

$$p_{t,y} = \max\left(f_t(x_t), e^{-r\Delta t}\mathbb{E}_t[p^y_{t+\Delta t}]\right),$$

for $t \leq y + \tau$ (i.e. before expiry) where for $t \in \mathbb{N}$,

$$f_t(x_t) = \max\left(0, \min\left(\pi_t, \left(\pi_t - \frac{\pi_t}{2\lambda R_t}(x_t - (1-\lambda)R_t)\right)\right)\right)$$

Here x_t is the optimal number of SRECs submitted at t. But optimal how?

Penalty Function: Step vs Slope

A sloped penalty function implies:

- A non-trivial (model-dependent) banking decision each year
- A resulting threshold analogous to Am. options' 'exercise boundary'

Price of SRECs of vintage y at time t now calculated via

$$p_{t,y} = \max\left(f_t(x_t), e^{-r\Delta t}\mathbb{E}_t[p^y_{t+\Delta t}]\right),$$

for $t \leq y + \tau$ (i.e. before expiry) where for $t \in \mathbb{N}$,

$$f_t(x_t) = \max\left(0, \min\left(\pi_t, \left(\pi_t - \frac{\pi_t}{2\lambda R_t}(x_t - (1-\lambda)R_t)\right)\right)\right)$$

Here x_t is the optimal number of SRECs submitted at t. But optimal how?

$$V_t = \min_{x_t} \mathbb{E}_t \sum_u e^{-r(u-t)} \int_{x_t}^{(1+\lambda)R_u} f_u(x')dx',$$

(Can write x_t as the solution of an overall cost minimization problem)

Penalty Function: Step vs Slope

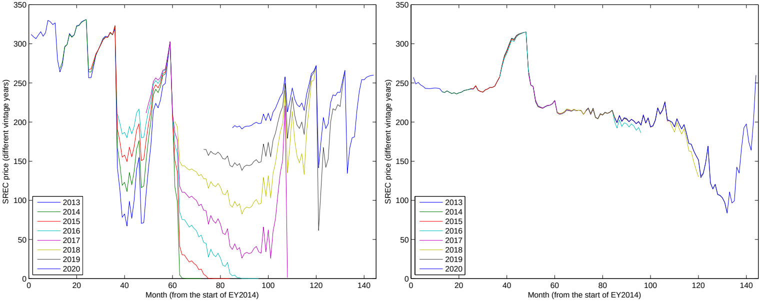
Simulations of different vintages reveal that with a sloped penalty:

- Lower volatility, more stable prices, fewer sudden price drops
- Much smaller price gaps between different vintage years

Penalty Function: Step vs Slope

Simulations of different vintages reveal that with a sloped penalty:

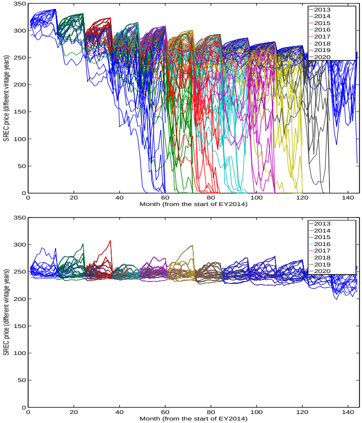
- Lower volatility, more stable prices, fewer sudden price drops
- Much smaller price gaps between different vintage years



Simulations above use the same set of random numbers but for the step case ($\Delta = 0$) on the left and slope case ($\Delta = 500$ GWh) on the right.

Penalty Function: Varying Slopes

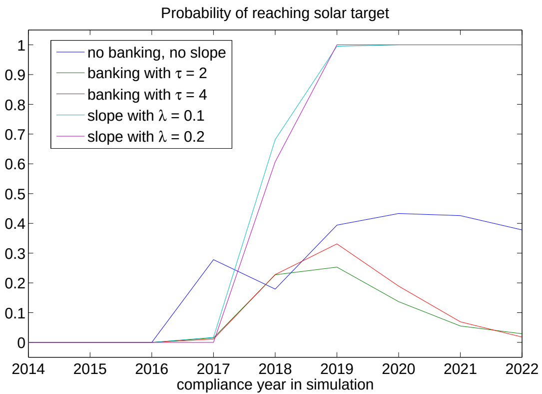
20 simulations of 8yrs, with increasing values of λ (flattening slope):



Similar vol decrease achievable via longer banking, but some tradeoffs...

Extra Banking vs Sloped Penalty

Using the approx current NJ conditions (huge oversupply, but high R), we simulate the probability of reaching targets on **installed** solar: $\mathbb{P}\{\hat{g}_t > R_t\}$



Increased banking can lead to years of being stuck in oversupply!

Other Policy Options

While useful for smoothing dynamics (as an alternative to banking with some advantages), a sloped penalty may not address long-term imbalances which often trigger new legislation. Any other ideas?

Other Policy Options

While useful for smoothing dynamics (as an alternative to banking with some advantages), a sloped penalty may not address long-term imbalances which often trigger new legislation. Any other ideas?

- A dynamically adaptive requirement level each year. For example, set

$$R_y = \tilde{R}_y + \alpha\,(b_{y-1} - \tilde{R}_{y-1}), \qquad 0 \le \alpha \le 1, y \in \mathbb{N}.$$

Other Policy Options

While useful for smoothing dynamics (as an alternative to banking with some advantages), a sloped penalty may not address long-term imbalances which often trigger new legislation. Any other ideas?

- A dynamically adaptive requirement level each year. For example, set

$$R_y = \tilde{R}_y + \alpha \ (b_{y-1} - \tilde{R}_{y-1}), \qquad 0 \leq \alpha \leq 1, y \in \mathbb{N}.$$

- Policy could work in conjunction with a function $\pi(R)$ for adaptive penalties which gradually reduce as long-term solar targets approach.
- Unrealistically complicated?

Other Policy Options

While useful for smoothing dynamics (as an alternative to banking with some advantages), a sloped penalty may not address long-term imbalances which often trigger new legislation. Any other ideas?

- A dynamically adaptive requirement level each year. For example, set

$$R_y = \tilde{R}_y + \alpha \, (b_{y-1} - \tilde{R}_{y-1}), \qquad 0 \leq \alpha \leq 1, y \in \mathbb{N}.$$

- Policy could work in conjunction with a function $\pi(R)$ for adaptive penalties which gradually reduce as long-term solar targets approach.
- Unrealistically complicated? Currently in Massachusetts, they use:

Total Compliance Obligation 2015 = Total Compliance Obligation 2014
+1.3 [Total SRECs Generated (projected) 2014 - SRECs Generated (actual) 2013]
+ Banked Volume 2013 + Auction Volume 2013 - ACP Volume 2013

Other Policy Options

While useful for smoothing dynamics (as an alternative to banking with some advantages), a sloped penalty may not address long-term imbalances which often trigger new legislation. Any other ideas?

- A dynamically adaptive requirement level each year. For example, set

$$R_y = \tilde{R}_y + \alpha\ (b_{y-1} - \tilde{R}_{y-1}), \qquad 0 \le \alpha \le 1, y \in \mathbb{N}.$$

- Policy could work in conjunction with a function $\pi(R)$ for adaptive penalties which gradually reduce as long-term solar targets approach.
- Unrealistically complicated? Currently in Massachusetts, they use:

  Total Compliance Obligation 2015 = Total Compliance Obligation 2014 +1.3 [Total SRECs Generated (projected) 2014 - SRECs Generated (actual) 2013] + Banked Volume 2013 + Auction Volume 2013 - ACP Volume 2013

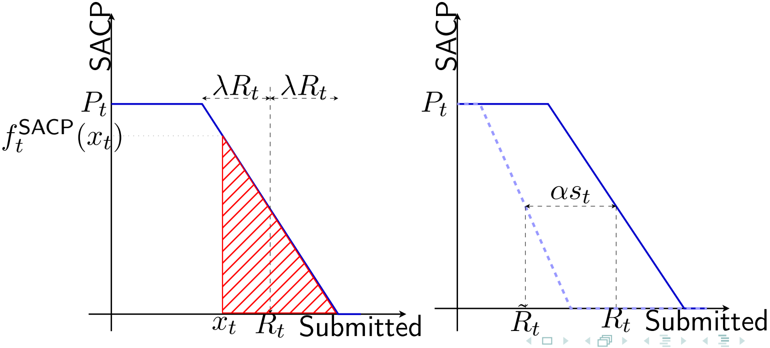
- Finally, in addition to this formula for R, Mass implements a $300 fixed-price auction each year, as a form of 'price floor mechanism'.

ADAPT policy proposal

We hence suggest an approach called 'ADAPT' (Adjustable Dynamic Assignment of Penalties and Targets) which provides regulators with two parameters (λ, α) as tools to control price volatility in the market.

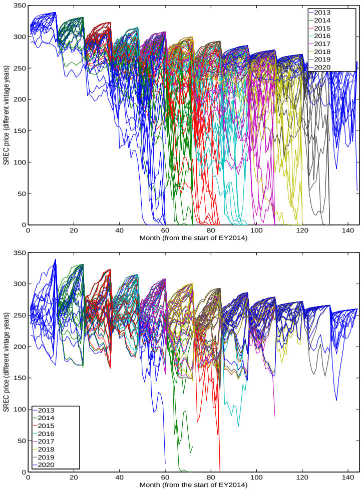
- λ controlling the slope of the penalty function.
- α for controlling the responsiveness of the requirement.

Ultimately different hybrid schemes between fixed price and fixed quantity!



ADAPT policy: Varying λ and α

20 simulations, with (λ, α) given by $(0,0), (0.3,0), (0,0.5)$, and $(0.3,0.5)$:



Market Design Ideas

Many market design options to stabilize prices (encourage investment):

- ie, banking, slope, dynamic targets, price floors, stability reserve,...

Market Design Ideas

Many market design options to stabilize prices (encourage investment):

- ie, banking, slope, dynamic targets, price floors, stability reserve,...

But how to determine an appropriate objective for market design? e.g.

Market Design Ideas

Many market design options to stabilize prices (encourage investment):

- ie, banking, slope, dynamic targets, price floors, stability reserve,...

But how to determine an appropriate objective for market design? e.g.

- Quantity based: reaching a target with a high probability

Market Design Ideas

Many market design options to stabilize prices (encourage investment):

- ie, banking, slope, dynamic targets, price floors, stability reserve,...

But how to determine an appropriate objective for market design? e.g.

- Quantity based: reaching a target with a high probability
- Price based: ensuring relatively stable prices (at least avoiding price collapses / prices stuck at penalty)

Market Design Ideas

Many market design options to stabilize prices (encourage investment):

- ie, banking, slope, dynamic targets, price floors, stability reserve,...

But how to determine an appropriate objective for market design? e.g.

- Quantity based: reaching a target with a high probability
- Price based: ensuring relatively stable prices (at least avoiding price collapses / prices stuck at penalty)
- Perhaps a clever combination, or a model in which more stable prices help meet quantity targets!

Market Design Ideas

Many market design options to stabilize prices (encourage investment):

- ie, banking, slope, dynamic targets, price floors, stability reserve,...

But how to determine an appropriate objective for market design? e.g.

- Quantity based: reaching a target with a high probability
- Price based: ensuring relatively stable prices (at least avoiding price collapses / prices stuck at penalty)
- Perhaps a clever combination, or a model in which more stable prices help meet quantity targets!
- Other measures: profits to power generators, cost to society, etc. (eg, Carmona, Fehr, Hinz, Porchet *et al.* 2010 on market design)

Market Design Ideas

Many market design options to stabilize prices (encourage investment):

- ie, banking, slope, dynamic targets, price floors, stability reserve,...

But how to determine an appropriate objective for market design? e.g.

- Quantity based: reaching a target with a high probability
- Price based: ensuring relatively stable prices (at least avoiding price collapses / prices stuck at penalty)
- Perhaps a clever combination, or a model in which more stable prices help meet quantity targets!
- Other measures: profits to power generators, cost to society, etc. (eg, Carmona, Fehr, Hinz, Porchet *et al.* 2010 on market design)

Related challenge: designing a global carbon market. One more objective:

Market Design Ideas

Many market design options to stabilize prices (encourage investment):

- ie, banking, slope, dynamic targets, price floors, stability reserve,...

But how to determine an appropriate objective for market design? e.g.

- Quantity based: reaching a target with a high probability
- Price based: ensuring relatively stable prices (at least avoiding price collapses / prices stuck at penalty)
- Perhaps a clever combination, or a model in which more stable prices help meet quantity targets!
- Other measures: profits to power generators, cost to society, etc. (eg, Carmona, Fehr, Hinz, Porchet *et al.* 2010 on market design)

Related challenge: designing a global carbon market. One more objective:

climate equity/fairness!

Global Carbon Market Design

Lima COP20 climate change conference in Dec 2014 led to typical frustration and obstacles, but also some important progress:

- Abandoning of the traditional Annex I - non-Annex I split of nations
- Instead, 'Common but differentiated rights and respective capabilities'
- Nationally determined targets (INDCs) due to be submitted, but effective no means to link these to global temperature targets.

Global Carbon Market Design

Lima COP20 climate change conference in Dec 2014 led to typical frustration and obstacles, but also some important progress:

- Abandoning of the traditional Annex I - non-Annex I split of nations
- Instead, 'Common but differentiated rights and respective capabilities'
- Nationally determined targets (INDCs) due to be submitted, but effective no means to link these to global temperature targets.

Hence, crucial to determine how to distribute emissions reductions among countries.Literature considers many concepts, sometimes hard to quantify:

- *Responsibility* - polluter pays for historical responsibilities
- *Equity* - equal long-term per capita emissions rights
- *Sovereignty* - a status quo rights based on current emissions
- *Capability* - more developed / richer countries can do more

Various proposals exist, but new ideas needed on how to identify exempt countries, allocate global reduction duties among others and through time.

A dynamic formula for determining emissions reductions

For country $j = 1, \ldots, N$, we propose a Minimum Reduction Committment (MRC) for period $t+1$ set dynamically as a function of population $P_{j,t}$ and emissions $E_{j,t}$ via

$$MRC_{j,t+1} = \underbrace{(C_{t+1} + V_t)}_{\text{total reductions}} \underbrace{\frac{(PC_{j,t} - PCW_t)P_{j,t}}{\sum_{i:PC_{i,t}>PCW_t} (PC_{i,t} - PCW_t)P_{i,t}}}_{\text{split among parties}}, \quad \underbrace{\text{if } PC_{j,t} > PCW_t}_{\text{reduction criterion}} \tag{1}$$

where $PC_{j,t} = E_{j,t}/P_{j,t}$, $PCW_t = \sum_{i=1}^{N} E_{i,t} / \sum_{i=1}^{N} P_{i,t}$, and C_{t+1} is a predetermined common target, and V_t a dynamic 'variations' term:

$$V_t = \max\left(0, \sum_{i:PC_{i,t-1}<PCW_{t-1}} (E_{i,t} - E_{i,t-1})\right)$$

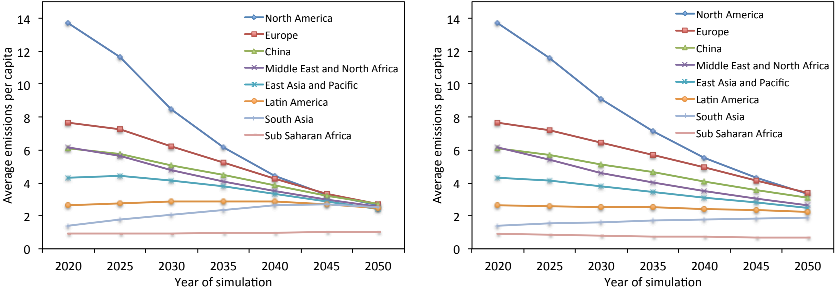
thus allowing countries below average to increase emissions.

Simulation Results from the Dynamic Mechanism

We use UN and World Bank data and the following:

- BAU is simple emissions projections and volatility estimates by country.
- Countries with MRCs assumed to reach these on average, while those below the average grow at scaled versions of business as usual (BAU):

Fast (50-100% of BAU) and slow (0-50% of BAU) growth cases:



Simulation Results from the Dynamic Mechanism

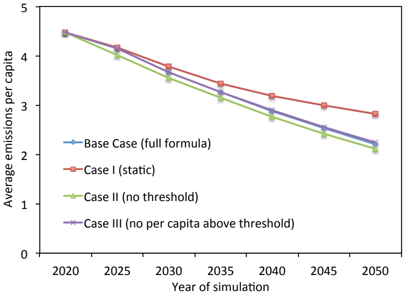
We then the full formula modified versions, removing its key features

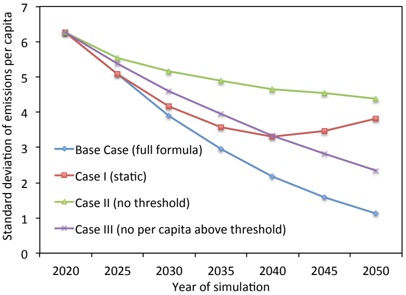
(I) *Static* - equation (1) sets MRCs in advance, by assuming no noise;

(II) *No Threshold* - all countries receive MRCs every period, shifting threshold in equation (1) from PCW_t to zero;

(III) *No Per Capita Differentiation above Threshold* - same threshold, but countries above all receive equal % emissions reduction targets.

Global per capita emission projections (left) and standard devs (right):





Conclusions

Many interesting questions for further research, much work to be done!

- Market design: what should regulator objectives be and how best to achieve these with various regulatory tools?
- Political risk: how do market participants respond to regulatory uncertainty / intervention?
- Optimal investment: how does feedback really work? when should generators build more renewables?
- Lagged effects: how do time lags in feedback change optimal behaviour?
- Global carbon: optimal behaviour of countries once market exists? abating vs buying credits? impact of threshold? game theory?