Renewable energy certificates: market design, investment decisions and price dynamics

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based mainly on: Coulon, M., Khazaei, J. and Powell, W. (2015) SMART-SREC: a stochastic model of the New Jersey solar renewable energy certificate market. *Journal of Environmental Economics and Management*, **73**, 13-31.

2015 Energy Finance Christmas Workshop,
IHP, Paris

Dec 17th, 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.)*
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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.
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Strong links between these markets, their design and price behaviour!

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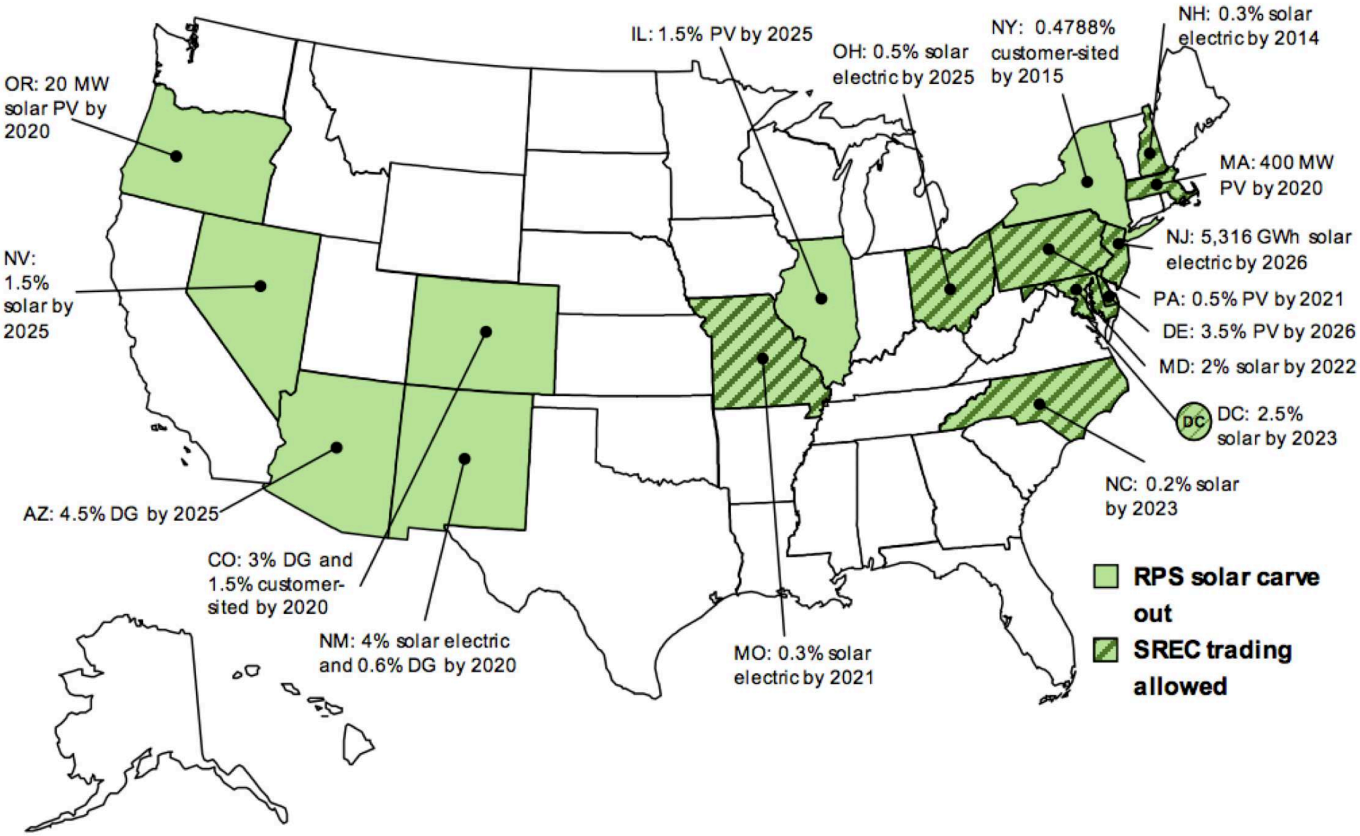
Hence many interesting research questions emerge, with little literature:

- 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?

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.

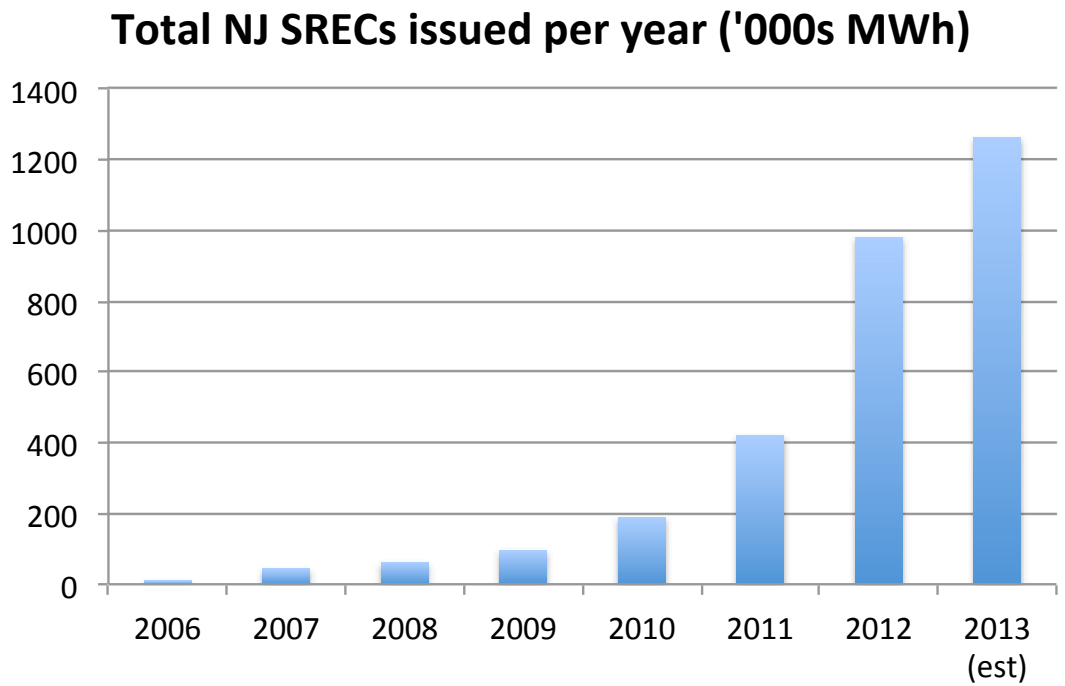


(map taken from: US DoE-NREL report by Bird, Heeter, Kreycik, 2011)

The New Jersey SREC market

The New Jersey SREC market is the biggest among the American 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.



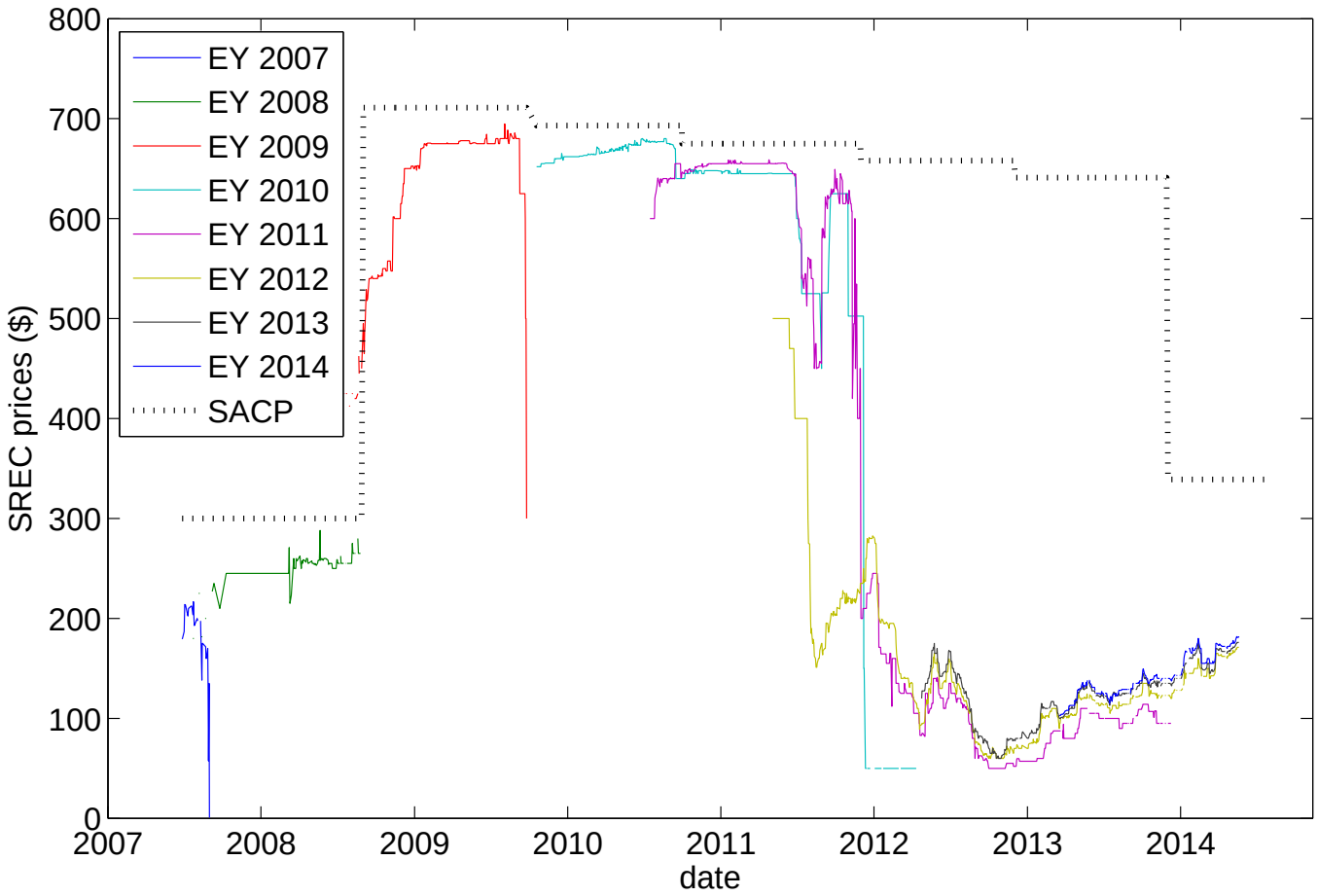
The New Jersey SREC market

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)*		2008 change *(3-year life)*		2012 change *(5-year life)*	
		R	π	R	π	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

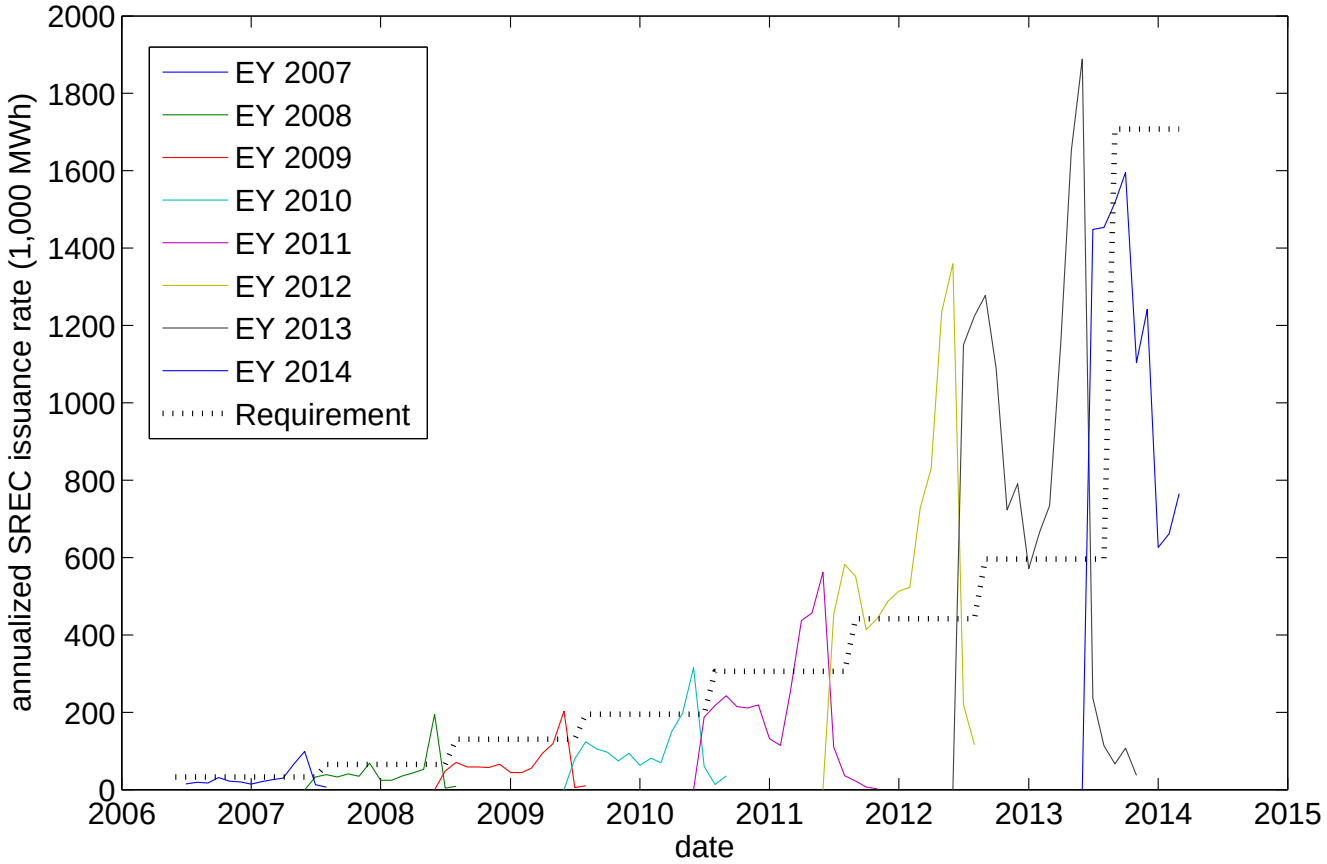
The New Jersey SREC market

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).



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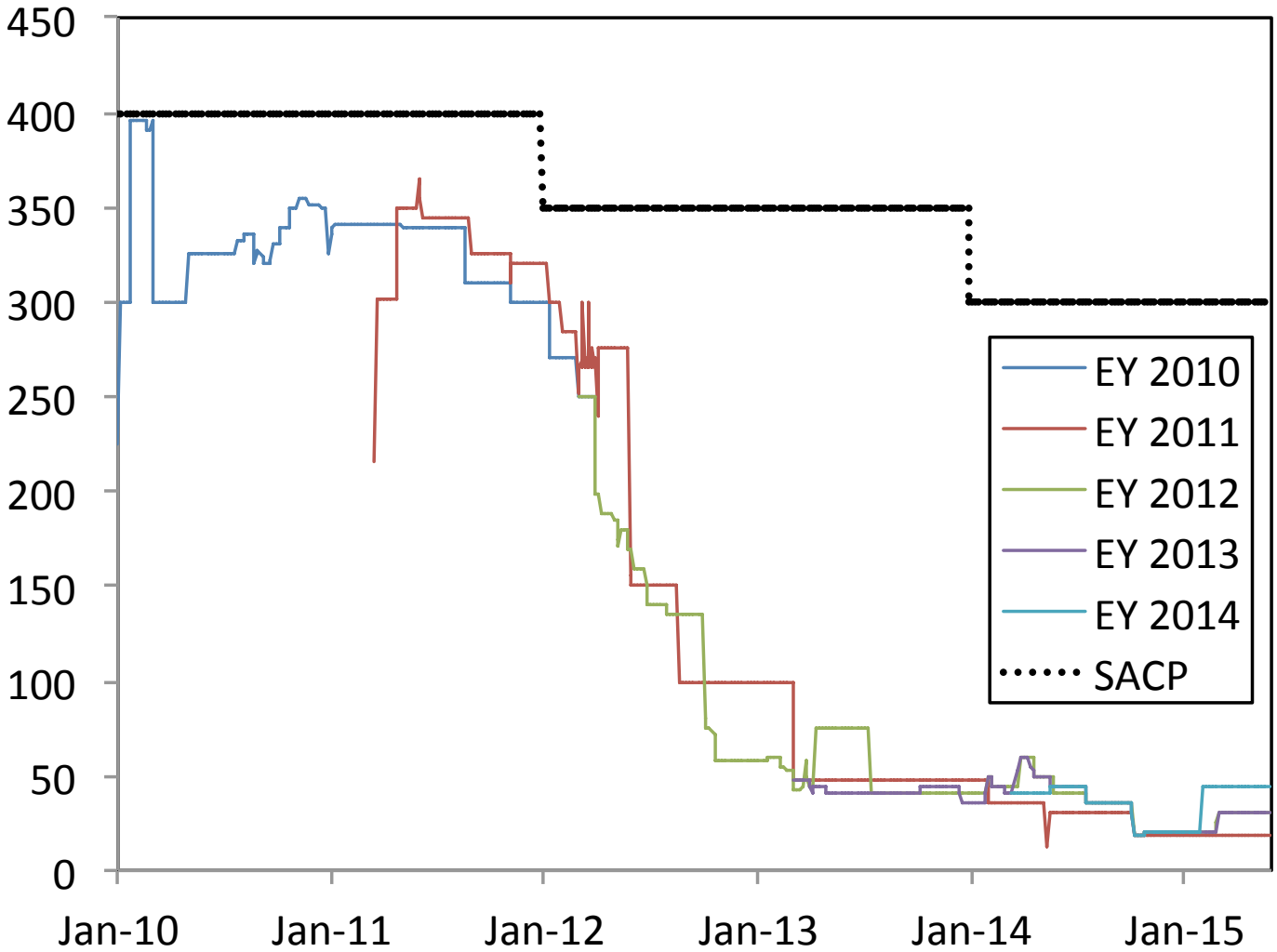
Ohio SREC prices 2010-15:



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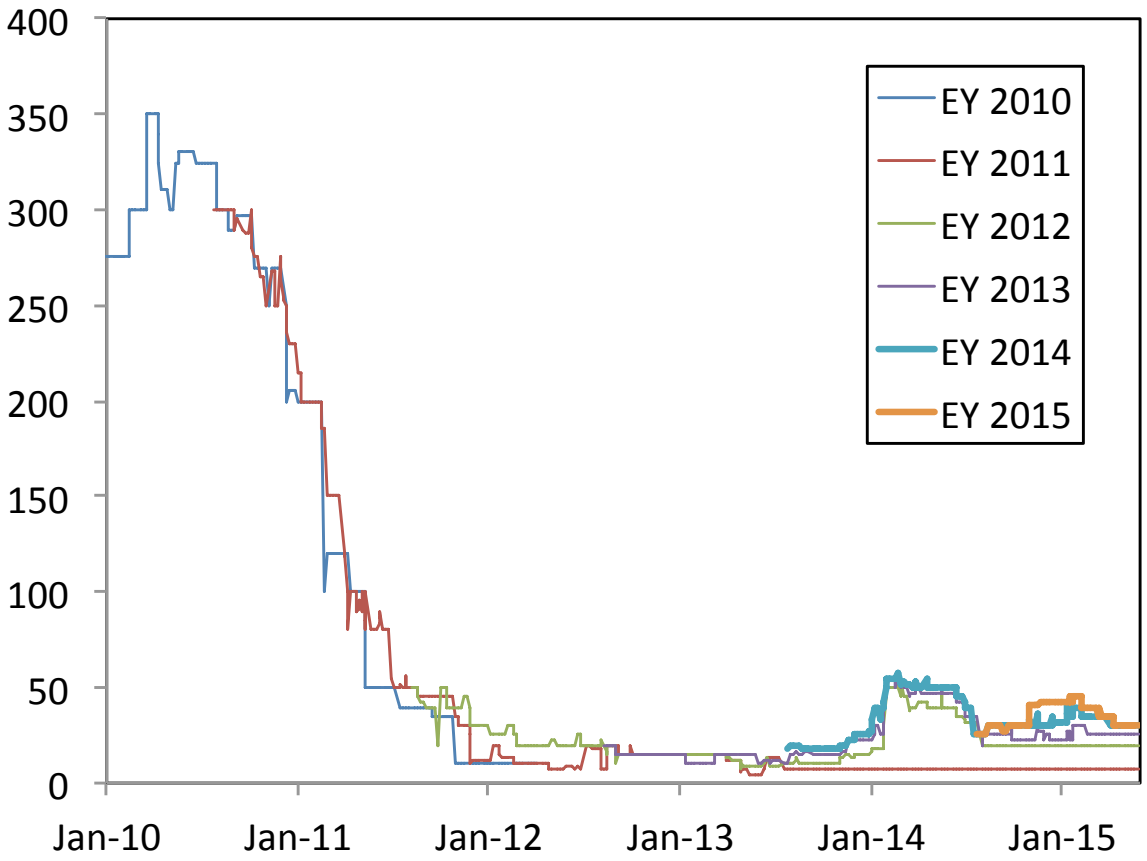
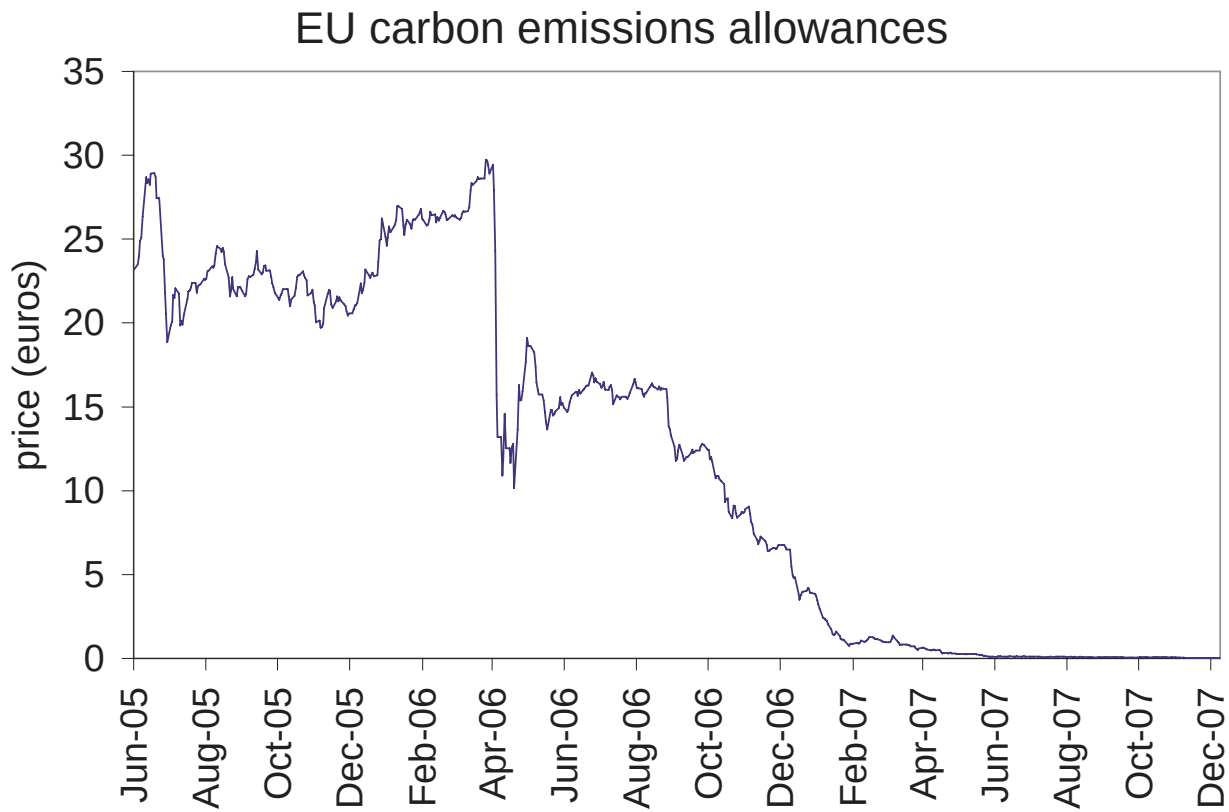
Pennsylvania SREC prices 2010-15:



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

Memories of early carbon markets...

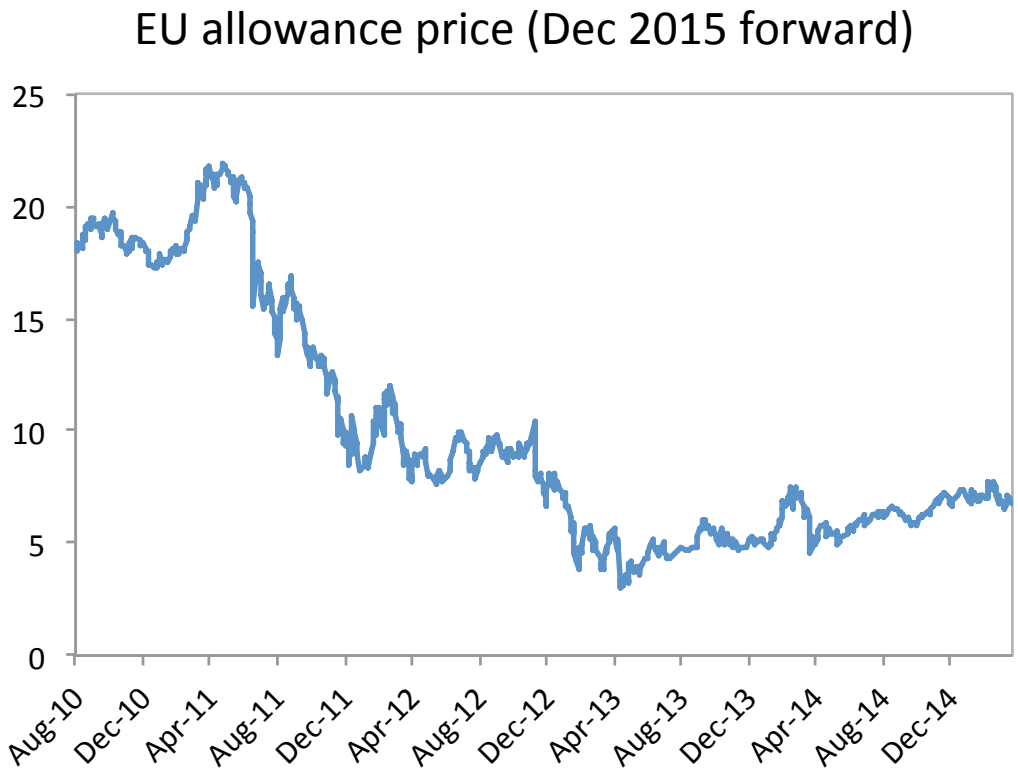
Recall, from the first EU-ETS trading period (Phase I, 2005-07):



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

Any better now?

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



Low prices led to some attempts to claw back oversupply, and to recent rule changes: the Market Stability Reserve (MSR). see Taschini *et al* 2014.

What about other carbon markets?

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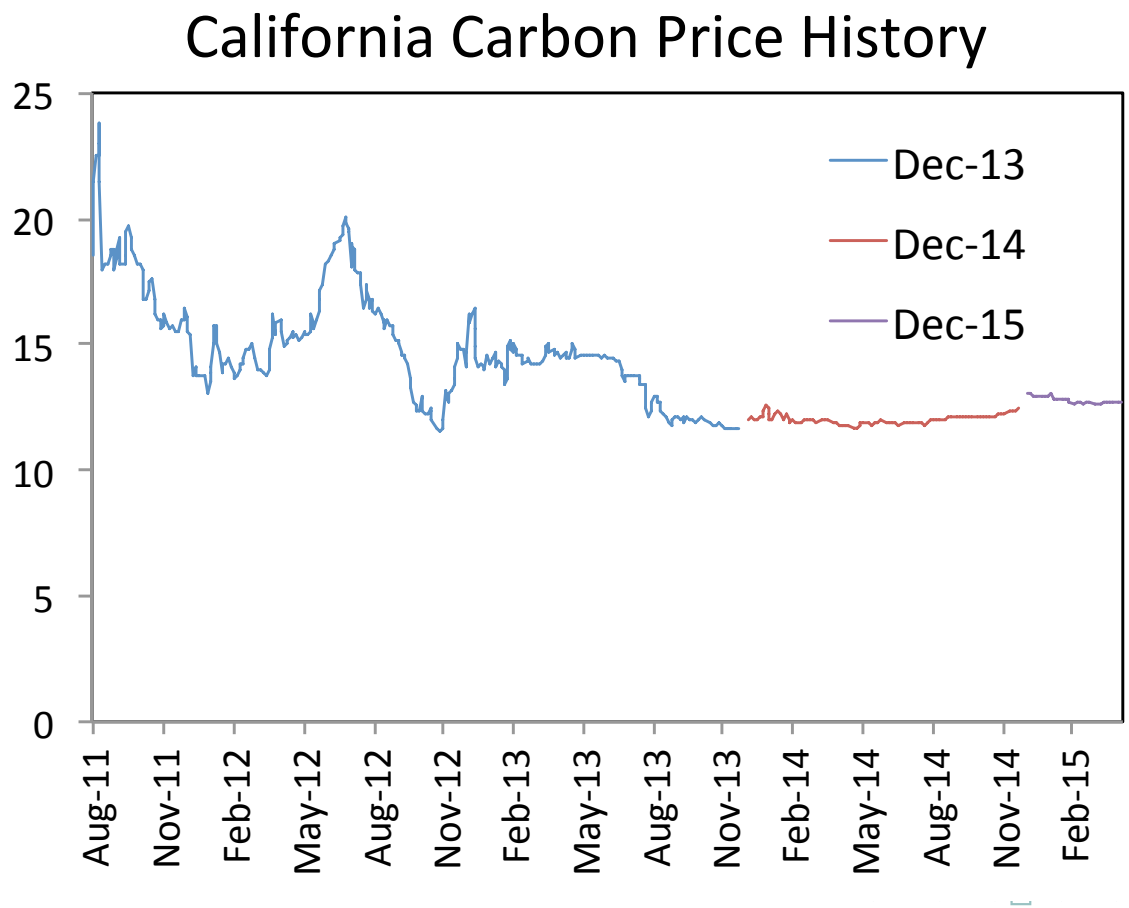
The recently formed California (plus Quebec!) market as similarly slipped into a period of oversupply recently, with prices near 'auction reserve' price of about \$10-\$11 dollars (grows with inflation).



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Key features:

- Financial contract, unlike other commodities $\Longrightarrow$ $\mathrm{e}^{-rt}P_t$ martingale
- Derivative on total generation $b_t = \int_0^t g_u du$ ('generation rate' $g_t \geq 0$)
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Key Extensions:

- Banking rules imply multi-period model needed for prices
- g_t (and hence b_t) should be dependent on P_t, due to the feedback

Multi-period SREC model

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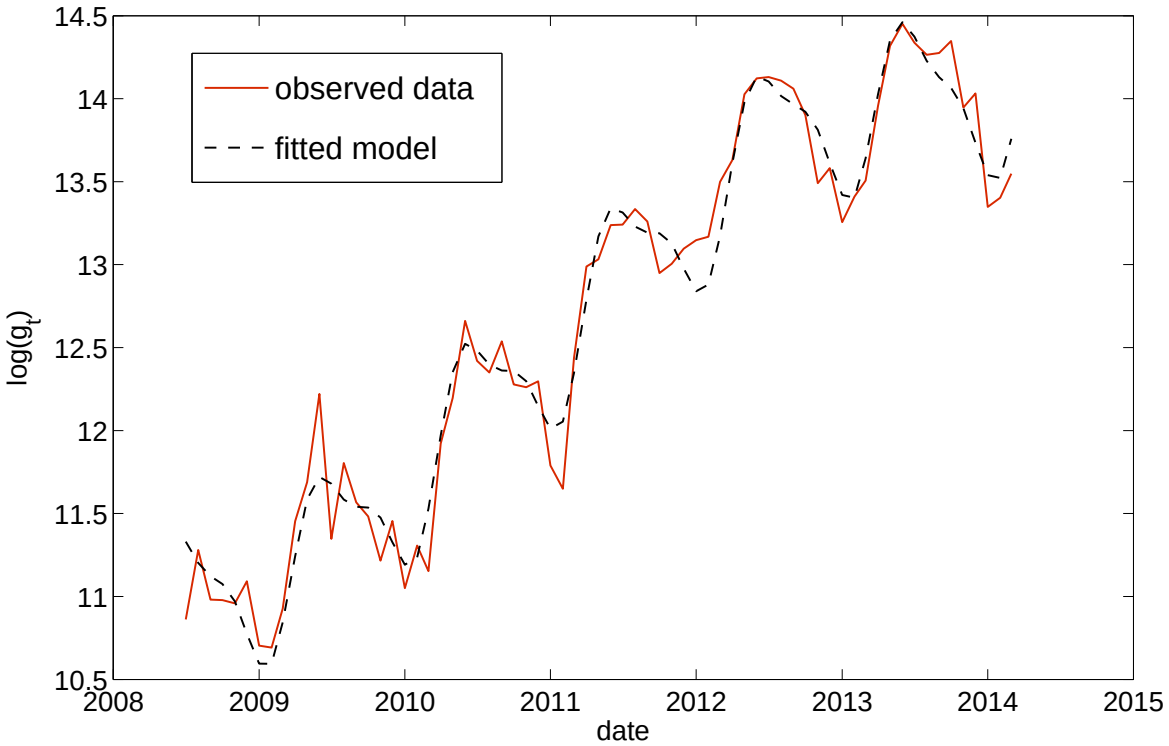
Note: Extending to multi-period in carbon similar but 'withdrawal' rule $\implies$ price is a sum, not a max! (e.g., Hitzemann Uhrig-Homburg 2014)

NJ SREC issuance data

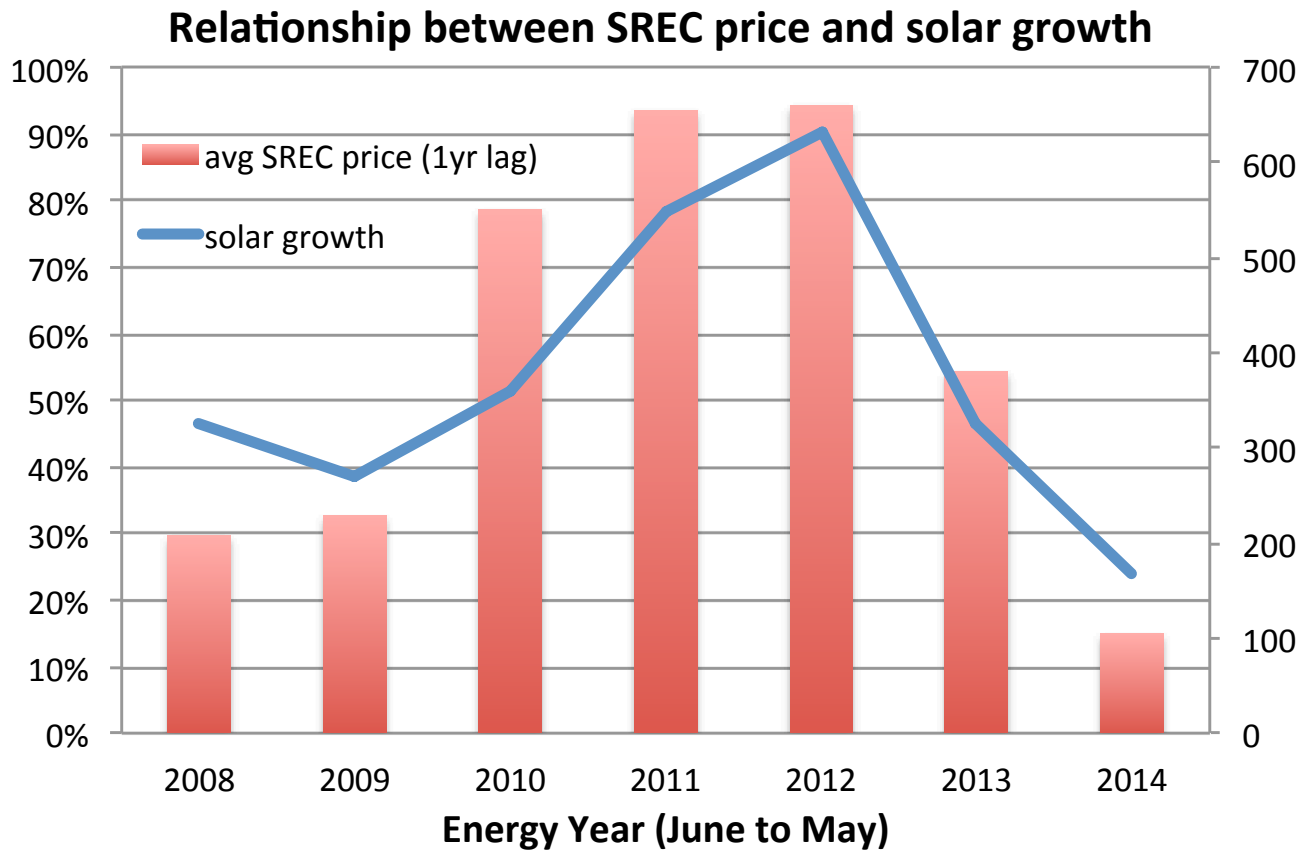
Lastly, a stochastic model for solar generation rate g_t. Log of monthly SREC issuance shows some noise, seasonality and a clear upwards trend:



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!

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

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

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

$$\bar{p}_t^y = \delta p_{t-\gamma}^y + (1-\delta)\bar{p}_{t-\Delta t}^y \qquad (\text{where} \quad \bar{p}_{t_0}^y = p_{t_0-\gamma}^y).$$

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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:

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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).

Carbon Price Modelling - FBSDE framework

Analogous carbon setup: processes for demand D_t, fuels ($\mathbf{S}_t = (C_t, G_t)$), cumulative emissions E_t and allowance price A_t:

$$\begin{cases} \mathrm{d}D_t = \mu_d(t, D_t)\mathrm{d}t + \sigma_d(D_t)\mathrm{d}\tilde{W}_t^0, & D_0 = d_0 \in (0, \bar{\xi}), \\ \mathrm{d}\mathbf{S}_t = \mu_s(\mathbf{S}_t)\mathrm{d}t + \sigma_s(\mathbf{S}_t)\mathrm{d}\tilde{\mathbf{W}}_t, & S_0 = s_0 \in \mathbb{R}_{++}, \\ \mathrm{d}E_t = \mu_e(D_t, A_t, \mathbf{S}_t)\mathrm{d}t, & E_0 = 0, \\ \mathrm{d}A_t = rA_t\mathrm{d}t + Z_t^0\mathrm{d}\tilde{W}_t^0 + Z_t \cdot \mathrm{d}\tilde{\mathbf{W}}_t, & A_T = \pi 1_{\{E_T > K\}}. \end{cases}$$

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

Summarizing the model, (details in *Carmona Coulon Schwarz (2012)*)

- Electricity demand D_t exogenous (Jacobi Diffusion in $[0, \bar{\xi}]$)
- Fuel prices C_t and G_t exogenous (exponential OU processes)
- Power price S_t, emissions E_t, allowance price A_t all endogenous

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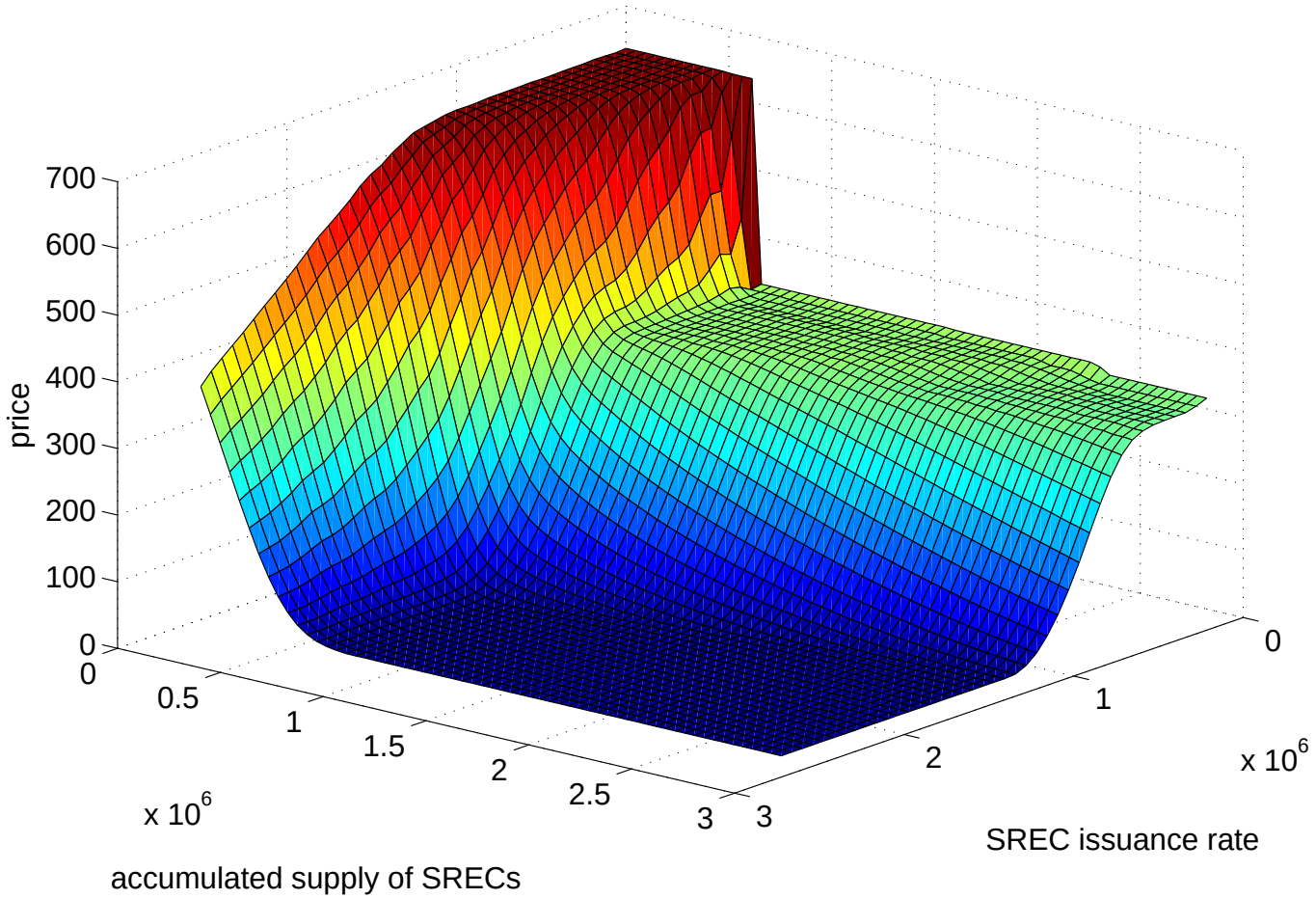
However, many other rule variations. For example, in Scandinavia:

- 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')

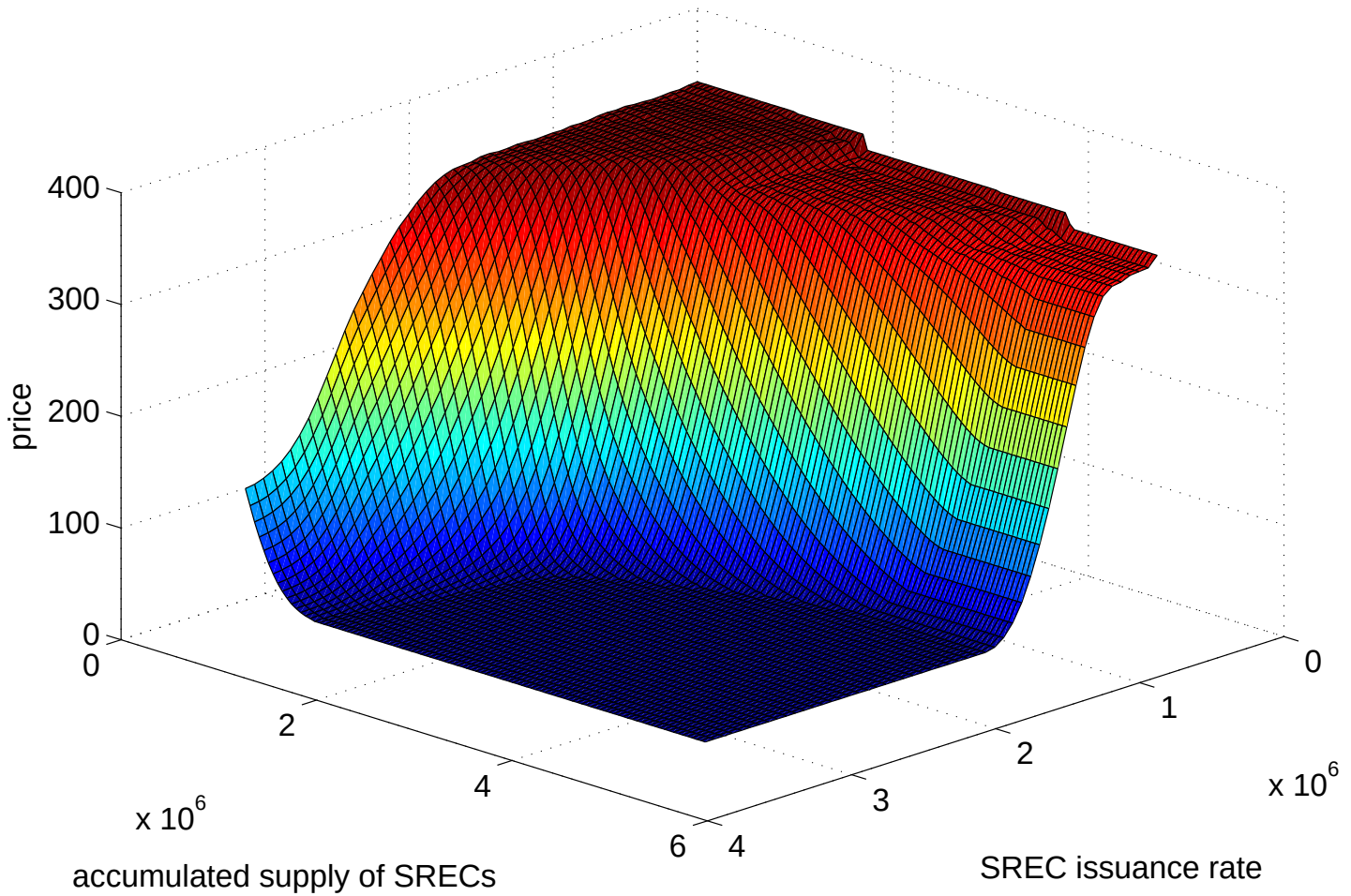
Back to NJ SRECs - Results of structural model

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:



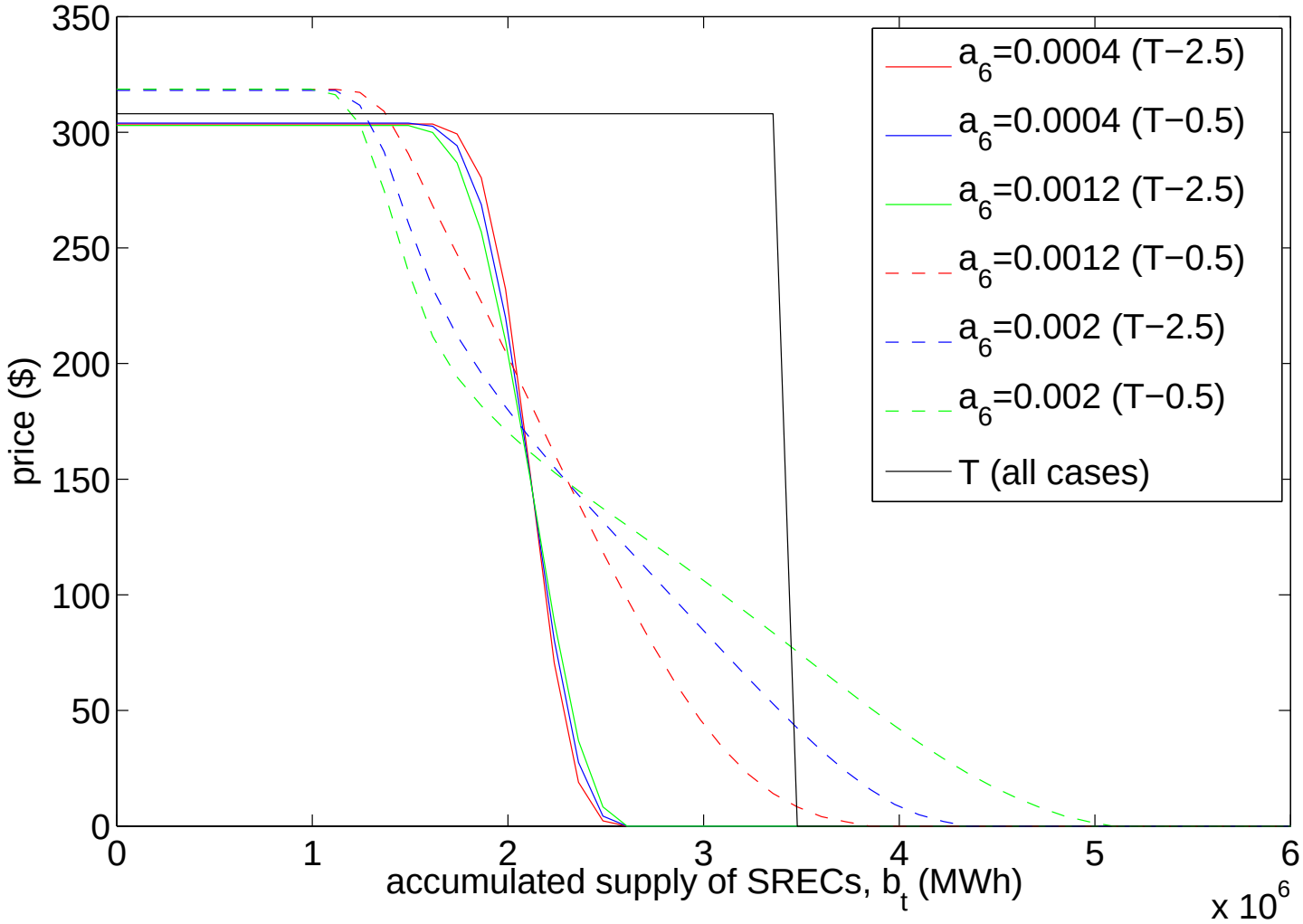
Results of structural model

Same price surface but six months later:



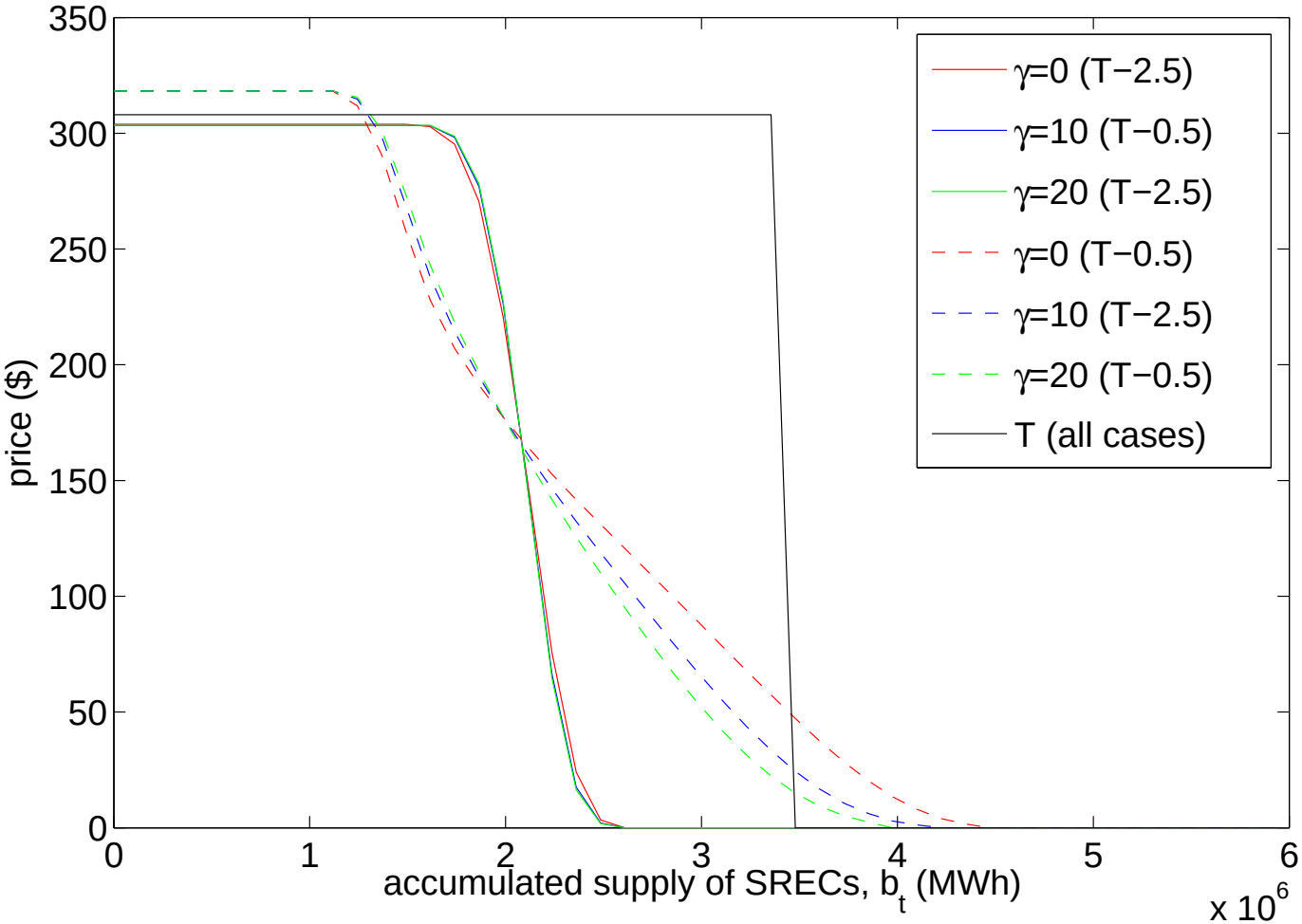
Results of structural model

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

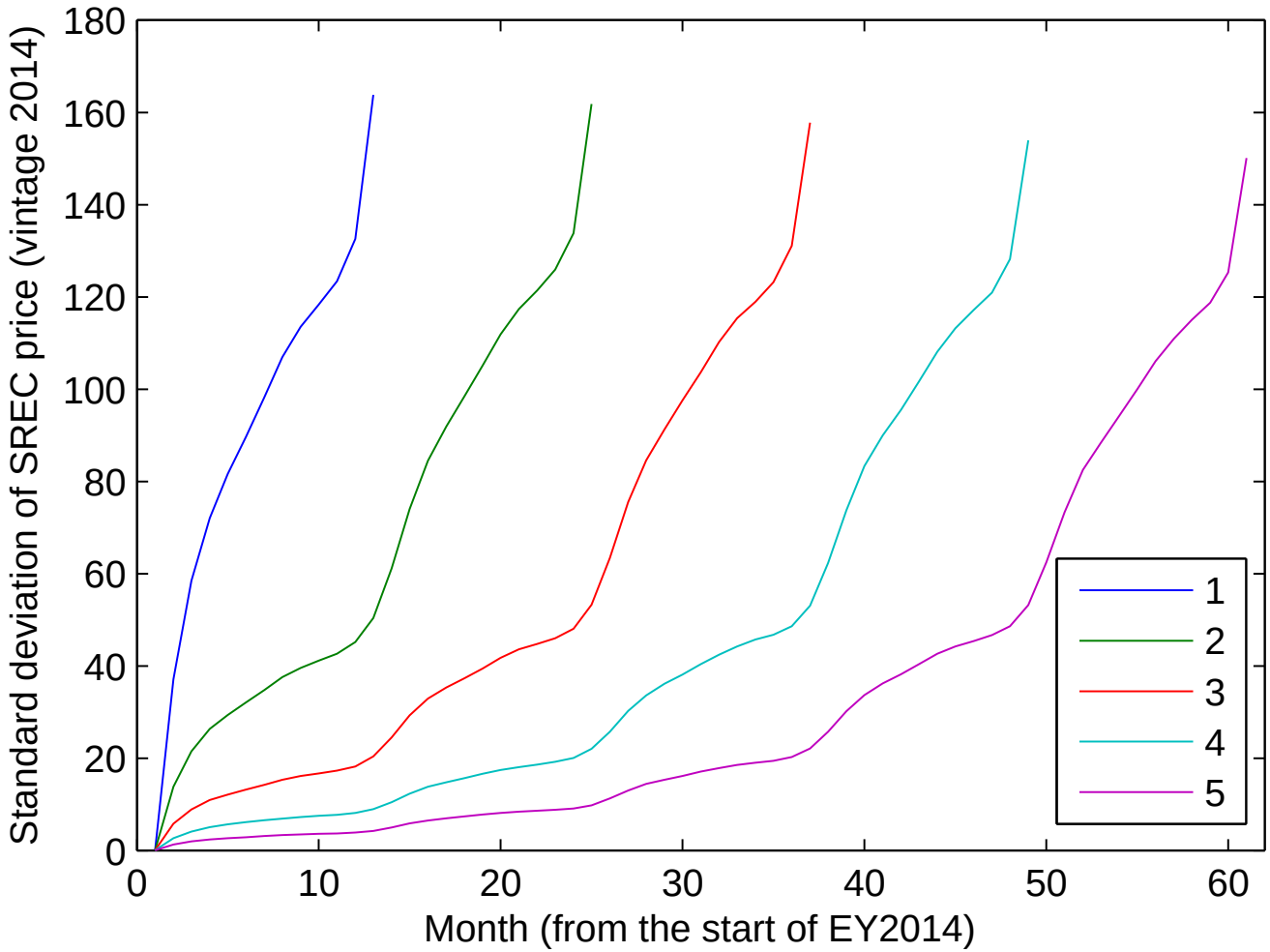
Feedback parameter found to be $a_6 = 1.3 \times 10^{-3}$. With lag $\gamma = 5/12$:

Comparison to history

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

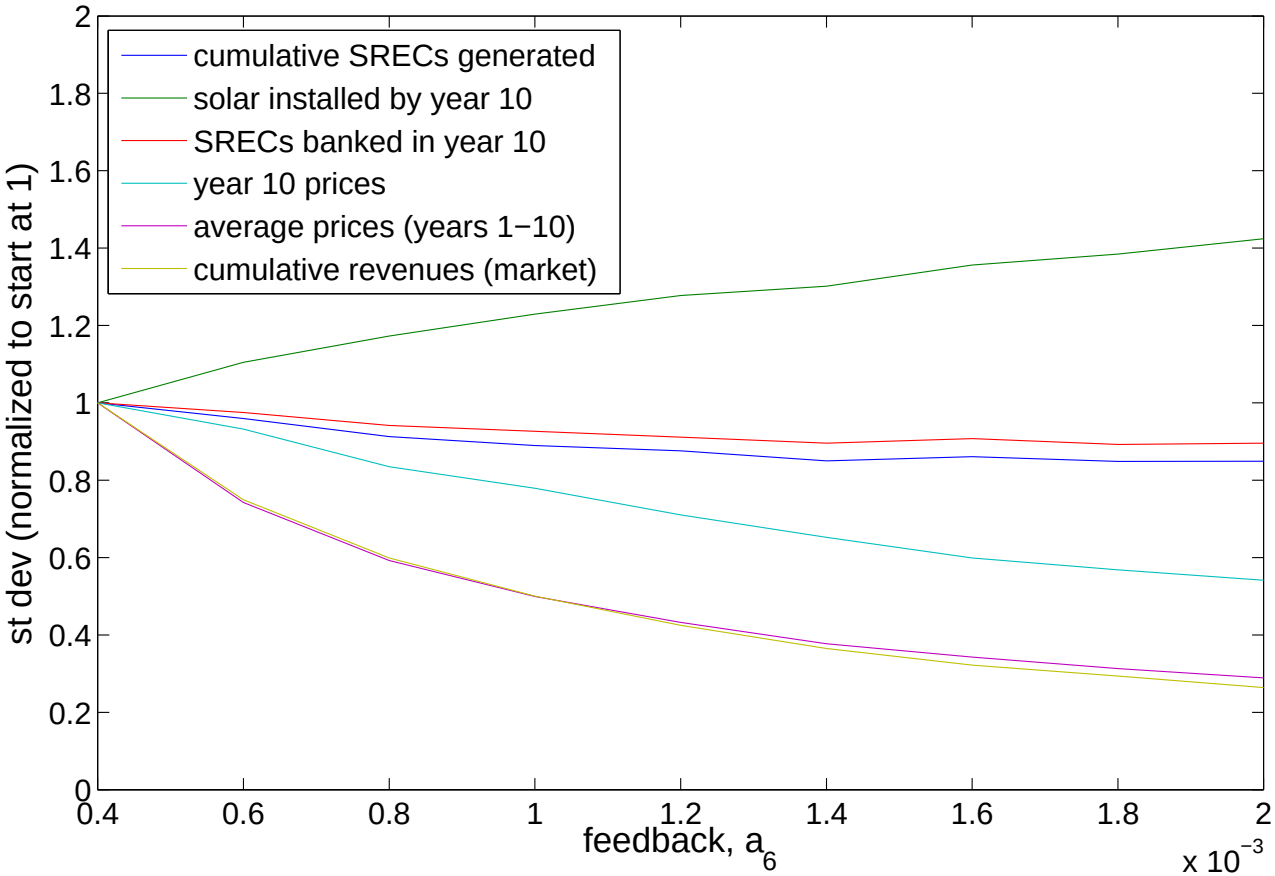
Impact of Banking

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



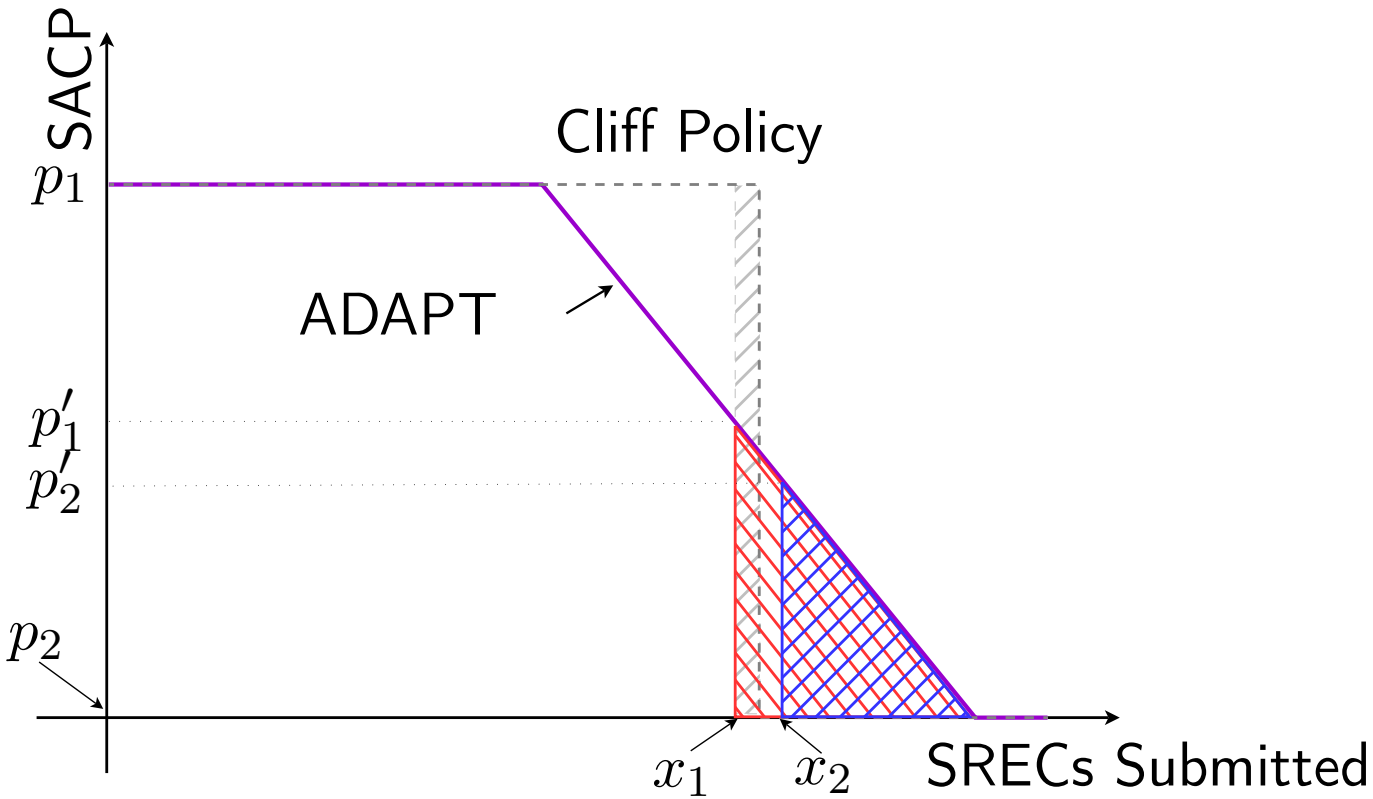
Impact of Feedback

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)



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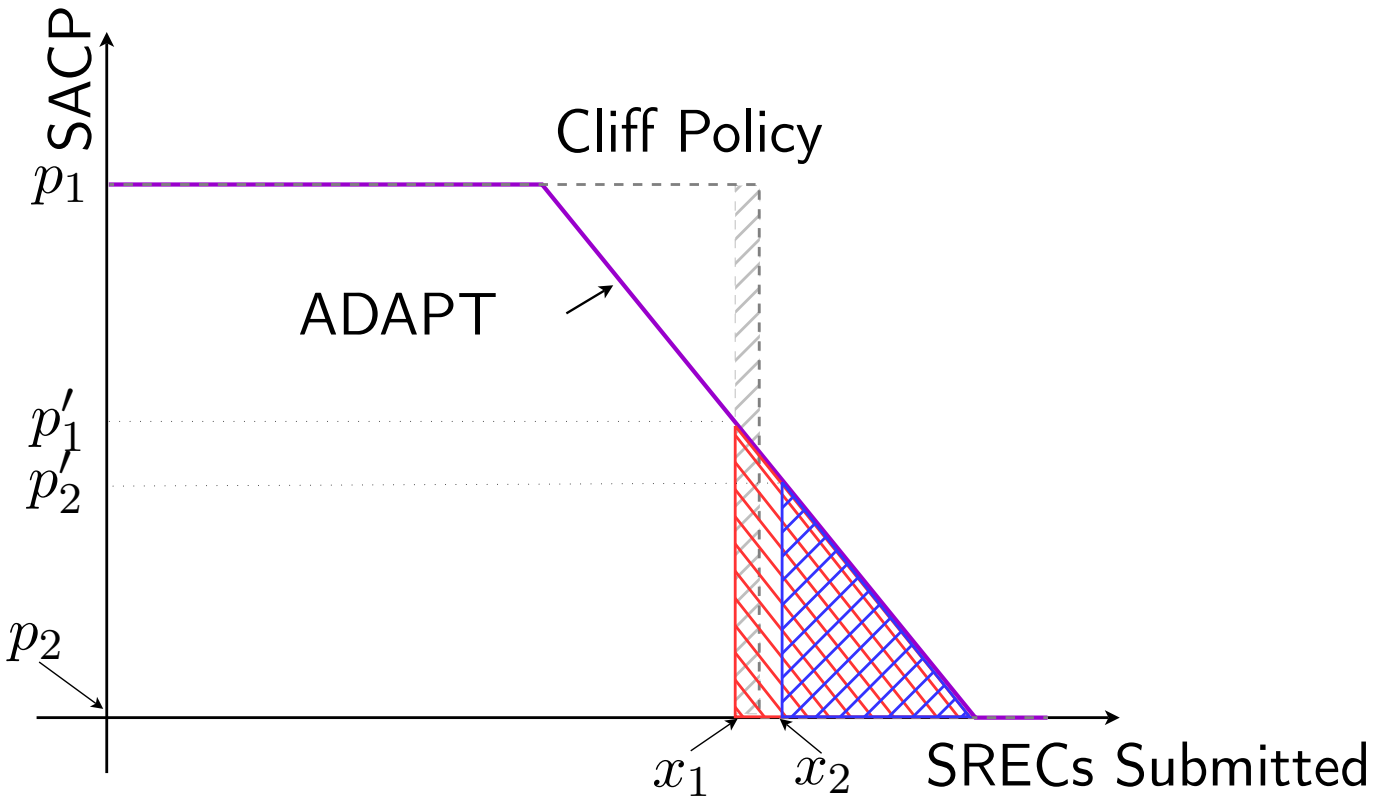
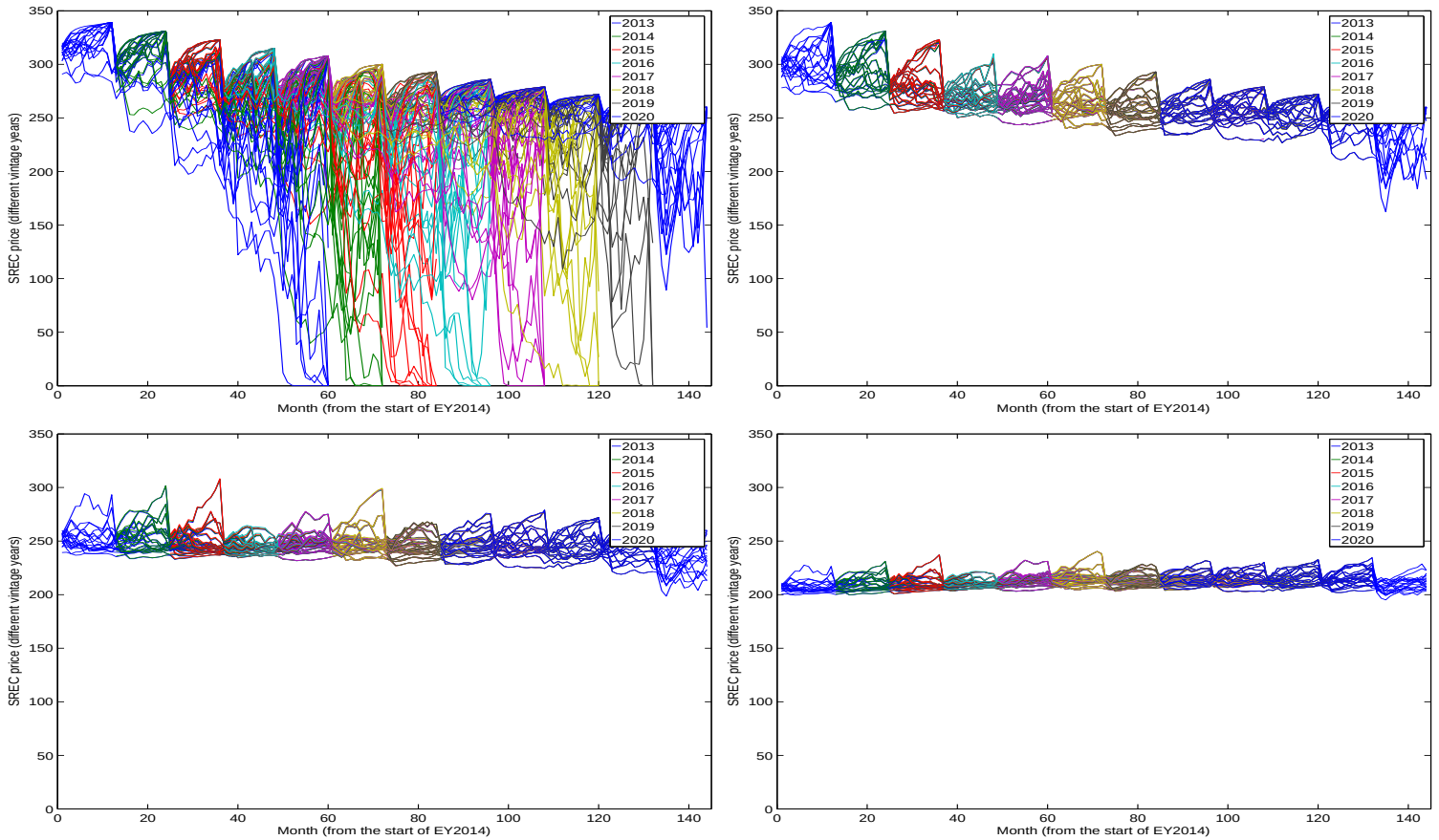


A sloped penalty function implies:

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

Penalty Function: Varying Slopes

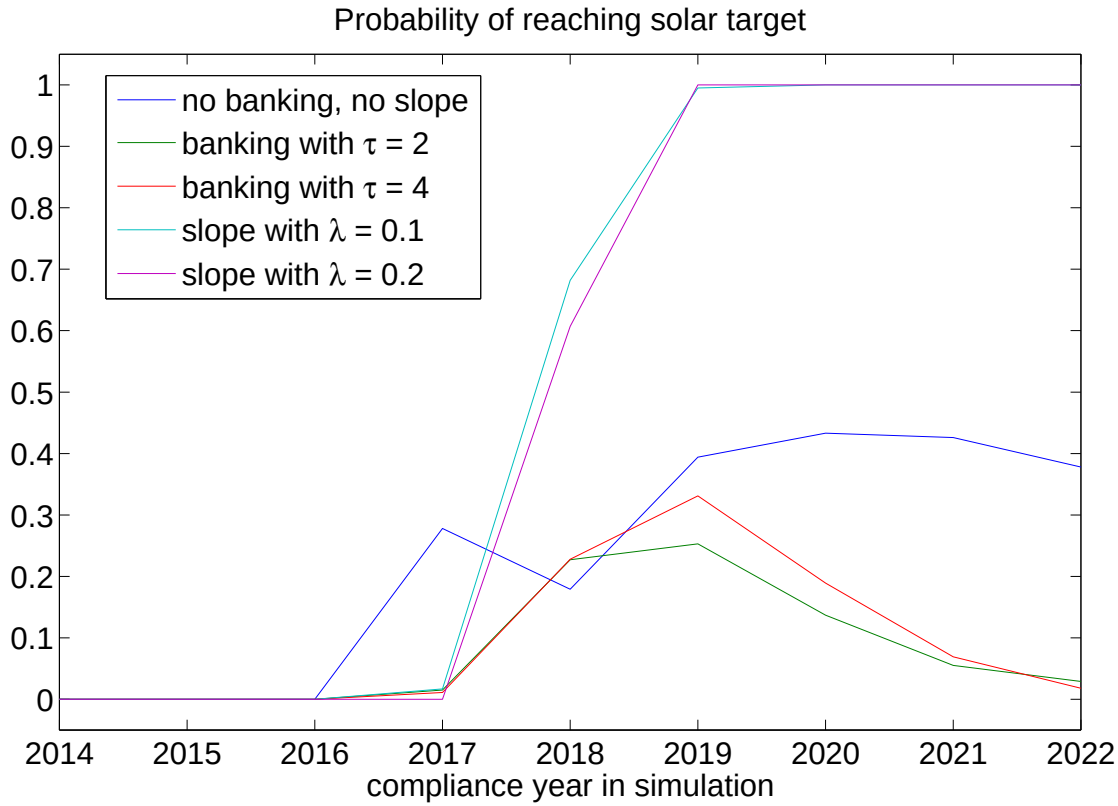
20 simulations of 8yrs, with increasing values of λ (flattening slope):



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?

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

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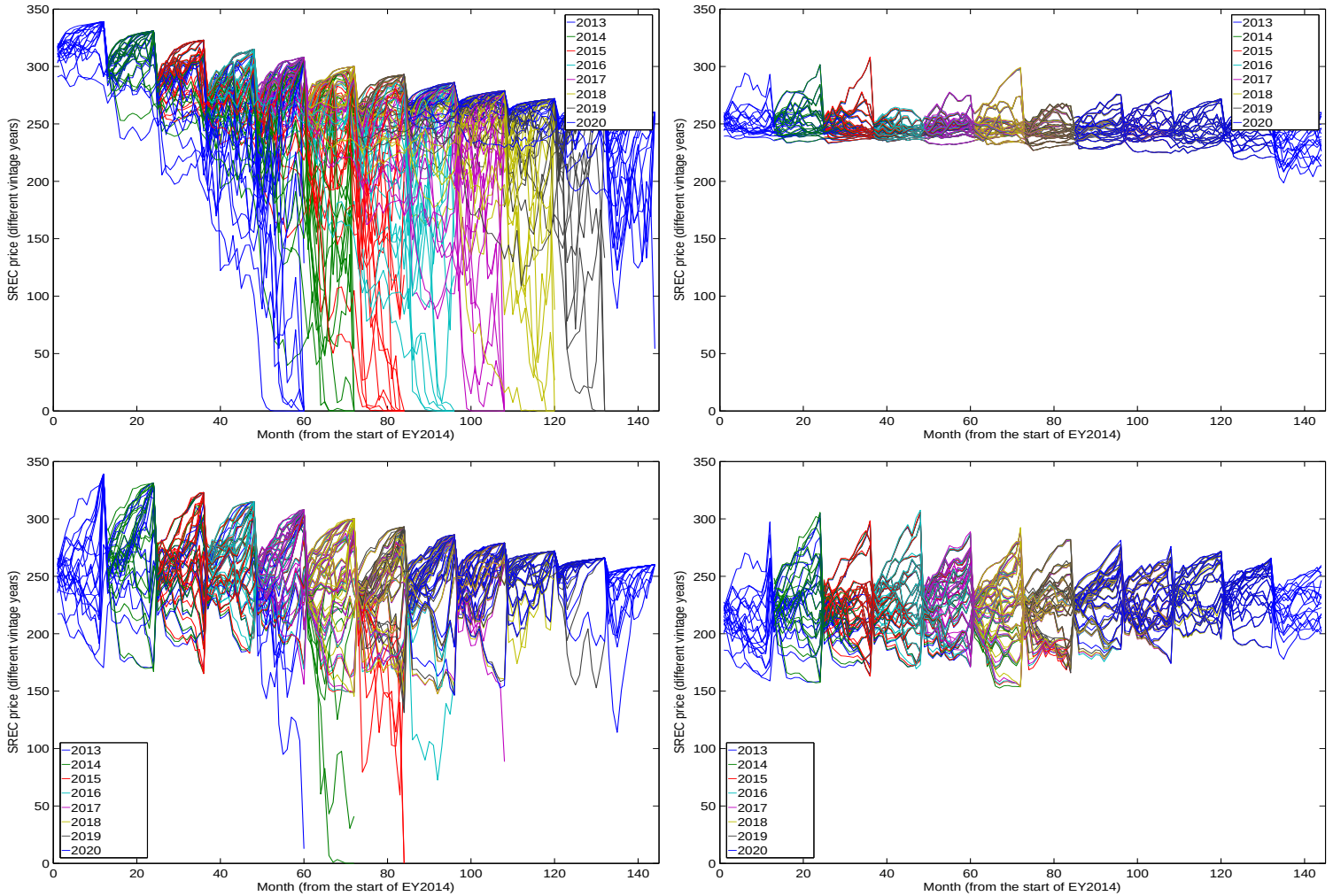
We hence suggest an approach called 'ADAPT' (Adjustable Dynamic Assignment of Penalties and Targets) which provides regulators with two parameters (λ, α) as tools to control price volatility in the market.

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

ADAPT policy: Varying λ and α

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



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Many other interesting questions to be addressed:

- Political risk: how do participants respond to regulatory uncertainty?
- Optimal investment: how does feedback work? when to build solar?
- Lagged effects: how do feedback lags change optimal behaviour?