A Model for Solar Renewable Energy Certificates:

Shining some light on price dynamics and optimal market design

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January 15th, 2014

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Carbon Market Outlook

Outlook for EU market bleak recently... *(Apr 2013 Economist article)*

ETS, RIP?

The failure to reform Europe’s carbon market will reverberate round the world

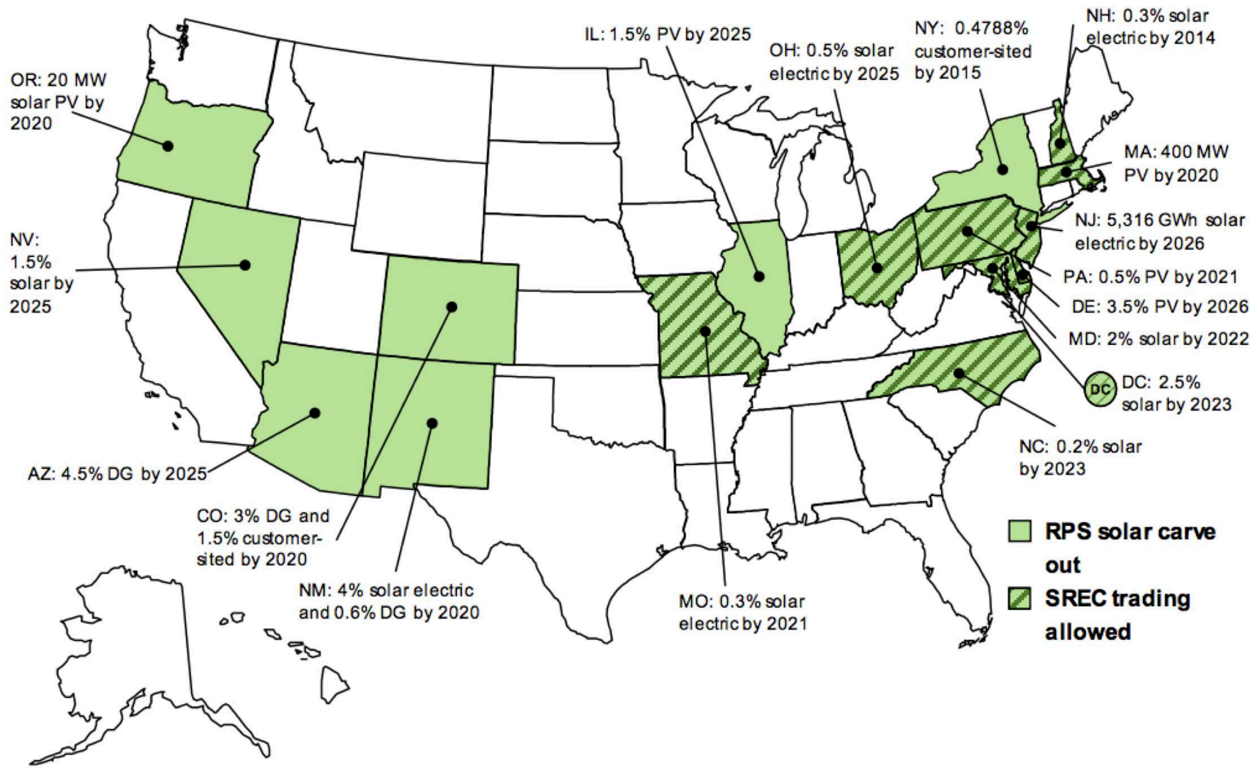
Apr 20th 2013 |From the print edition

On the other hand, other regions are developing (eg, California, China).

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)



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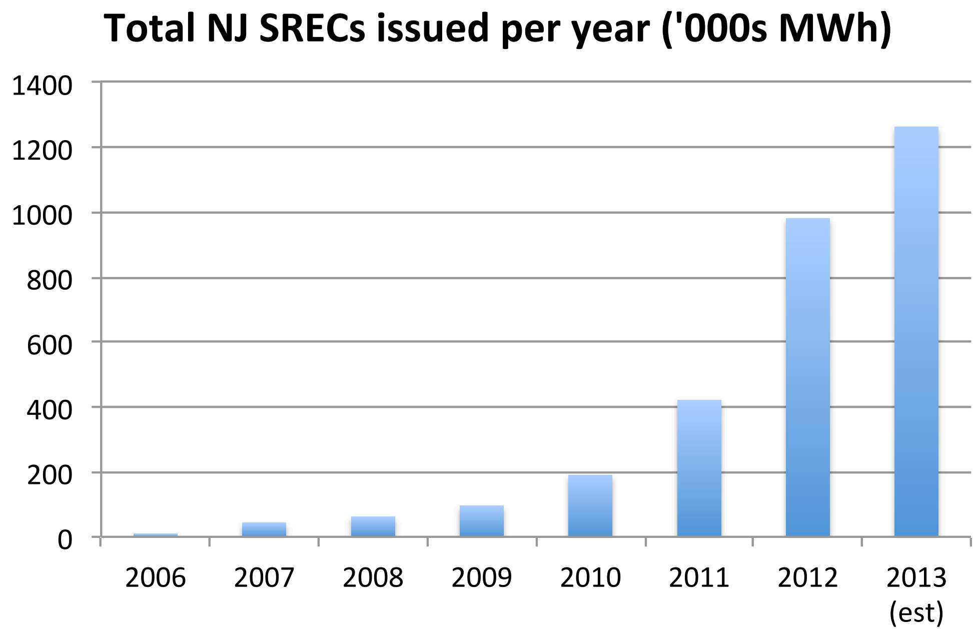
But... if prices are too volatile, it can be very risky for solar investors relying on revenues from selling SRECs, counteracting the goal of the market

$\Longrightarrow$ Market design very important!

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.



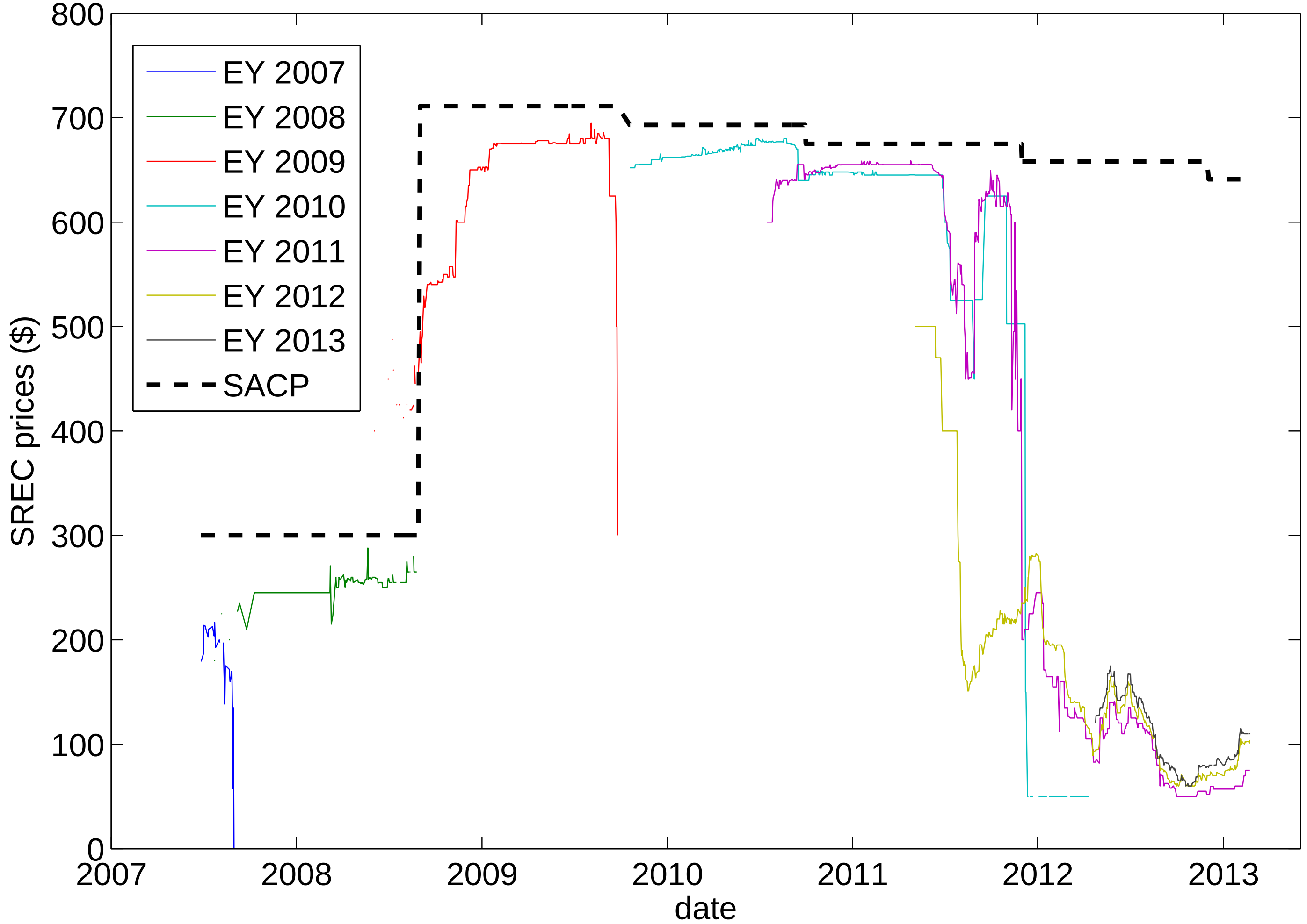
The New Jersey SREC market

The rules of the NJ market have been changed many times. Just a summary:

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			1,150,000	594	2,360,376	323
2017	6 mon					2,613,580	315
2018	6 mon					2,829,636	308

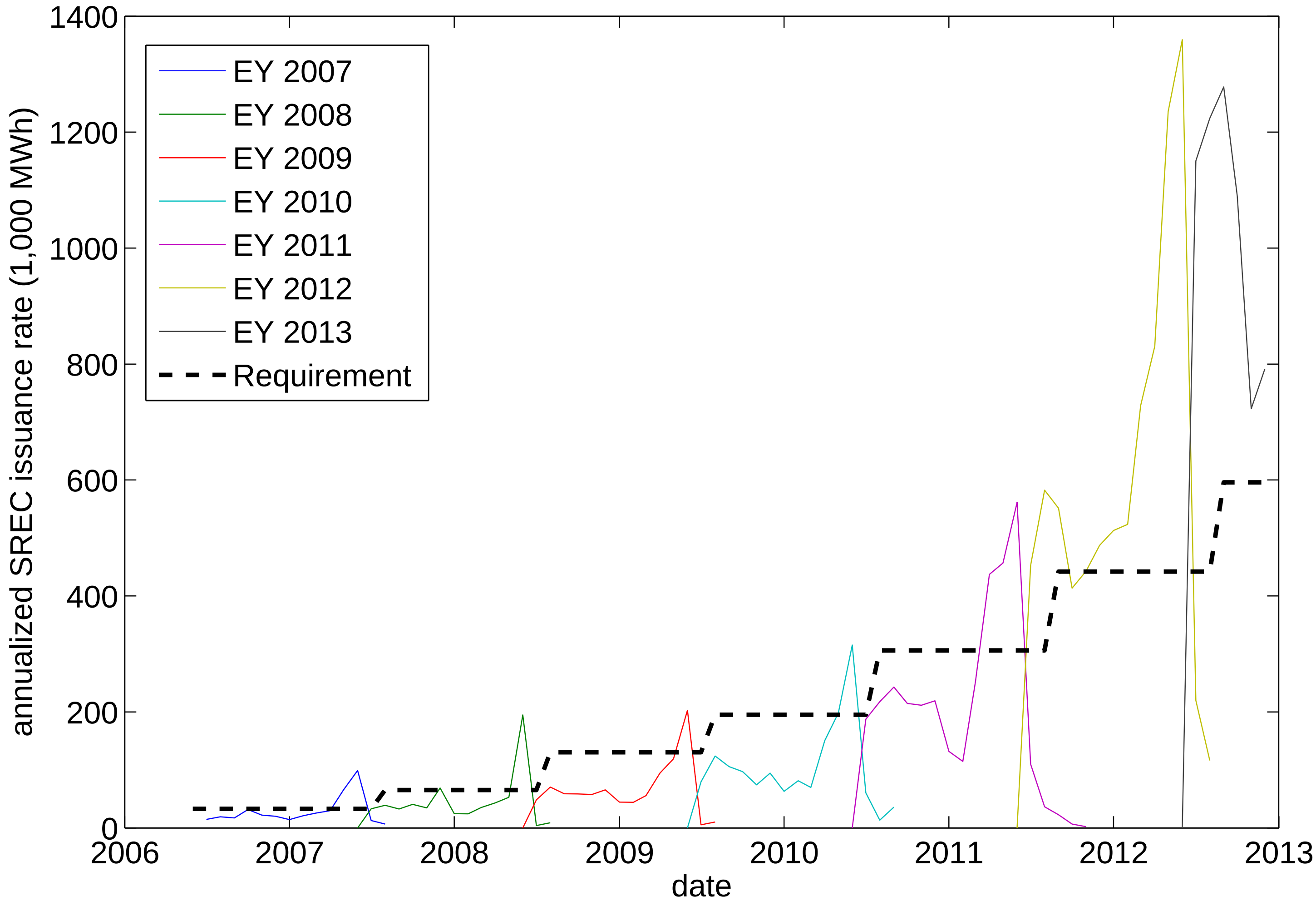
The New Jersey SREC market

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



The New Jersey SREC market

Historical (monthly) issuance data easily available online. Solar generation has grown fast (faster than R), with clear seasonality... will this continue?



Stochastic models for SREC prices

How can we model an SREC price p_t^y (for vintage year $y \in \mathbb{N}$)?

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- Instead we draw on strong parallels with carbon emissions markets (with supply and demand reversed... here government fixes *demand*)

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Consider a single-year case $t \in [y-1, y]$ (no banking). Like carbon,

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- SRECs are traded financial contracts, and thus martingales under $\mathbb{Q}$
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Therefore, for $t \in [y-1, y]$,

$$\begin{aligned} p_t^y &= e^{-r(y-t)} \pi_t^y \mathbb{E}_t \left[1_{\{\int_{y-1}^y g_u \mathrm{d}u < R_t^y\}} \right], \\ &= e^{-r(y-t)} \pi_t^y \mathbb{P} \left\{ \int_t^y g_u \mathrm{d}u < R_t^y - \int_{y-1}^t g_u \mathrm{d}u \right\}, \end{aligned}$$

where g_t is the annualized solar generation rate (ie, SREC issuance rate).

Structural model for SREC prices

Next step: Include τ years of banking, such that a vintage year y SREC is valid for compliance at times

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

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):

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

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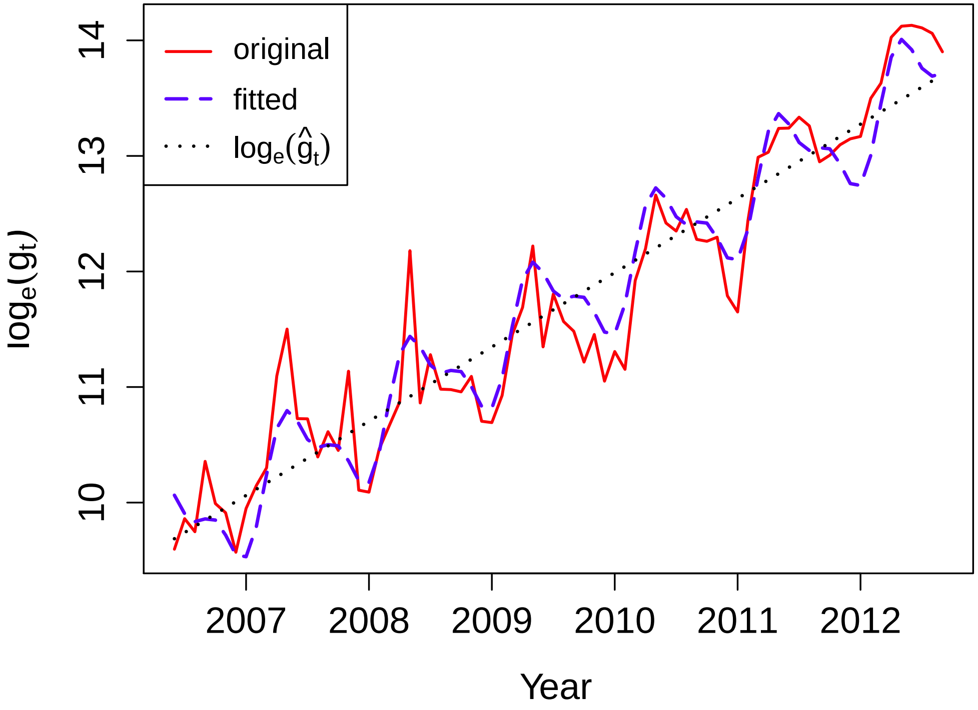
Final step: A stochastic model for solar generation rate g_t?

NJ SREC issuance data

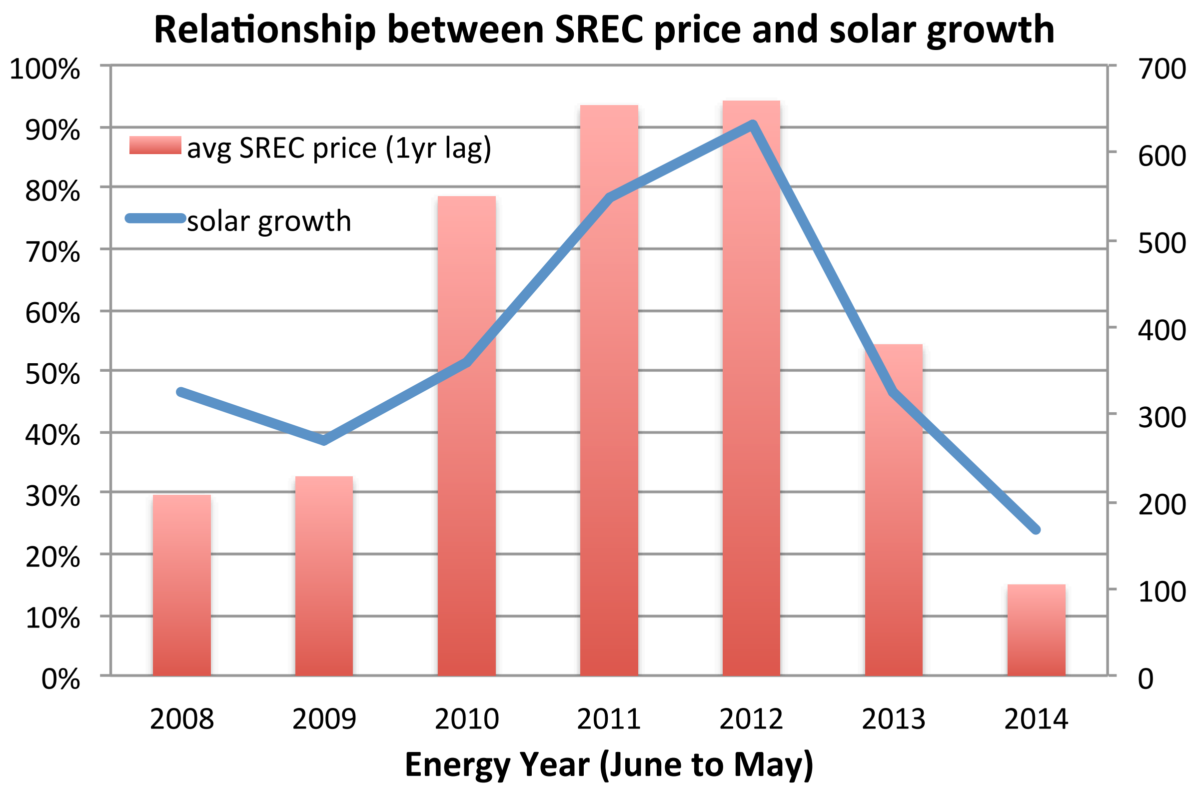
Log plot of total monthly issuance shows some noise but also a clear trend (slope = 0.64) and seasonality:



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

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 first fit seasonality and Gaussian noise term ε_t:

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

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

$$\frac{\ln(\hat{g}_{t+\Delta t}) - \ln(\hat{g}_t)}{\Delta t} = a_5 + a_6 \bar{p}_t, \qquad \text{for } a_5 \in \mathbb{R}, a_6 > 0,$$

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This completes the model. We can 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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Analogously for carbon (emissions E_t, allowance price A_t), the FBSDE:

$$\begin{aligned} dE_t &= \mu_E(A_t, \cdot) dt, \qquad & E_0 &= 0, \\ dA_t &= r A_t dt + Z_t dW_t \qquad & A_T &= \pi 1_{\{E_T \geq \kappa\}}, \end{aligned}$$

where the emissions drift $\mu_E(A_t, \cdot)$ is decreasing in A_t.

Summary Comparison with Carbon

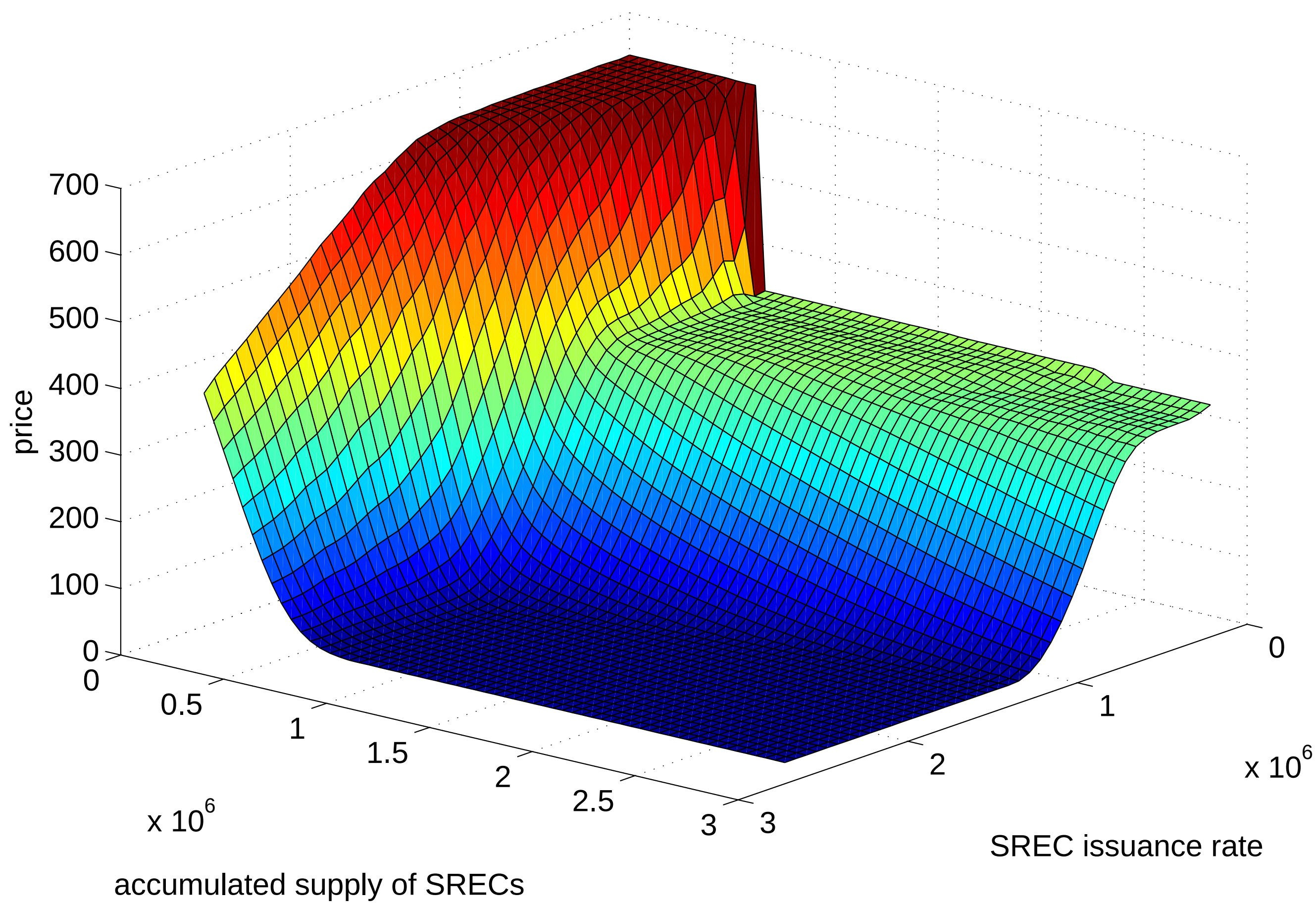
Clearly many similarities with cap-and-trade, but also key differences:

Feature	**Cap-and-trade**	**SREC market**
Banking	(typically) unrestricted	finite number of times (e.g. 4)
Borrowing	within trading periods	none
‘Withdrawal’	Pay penalty plus one allowance debt	Penalty (SACP) only
Periodicities	none	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!*

Results of structural model

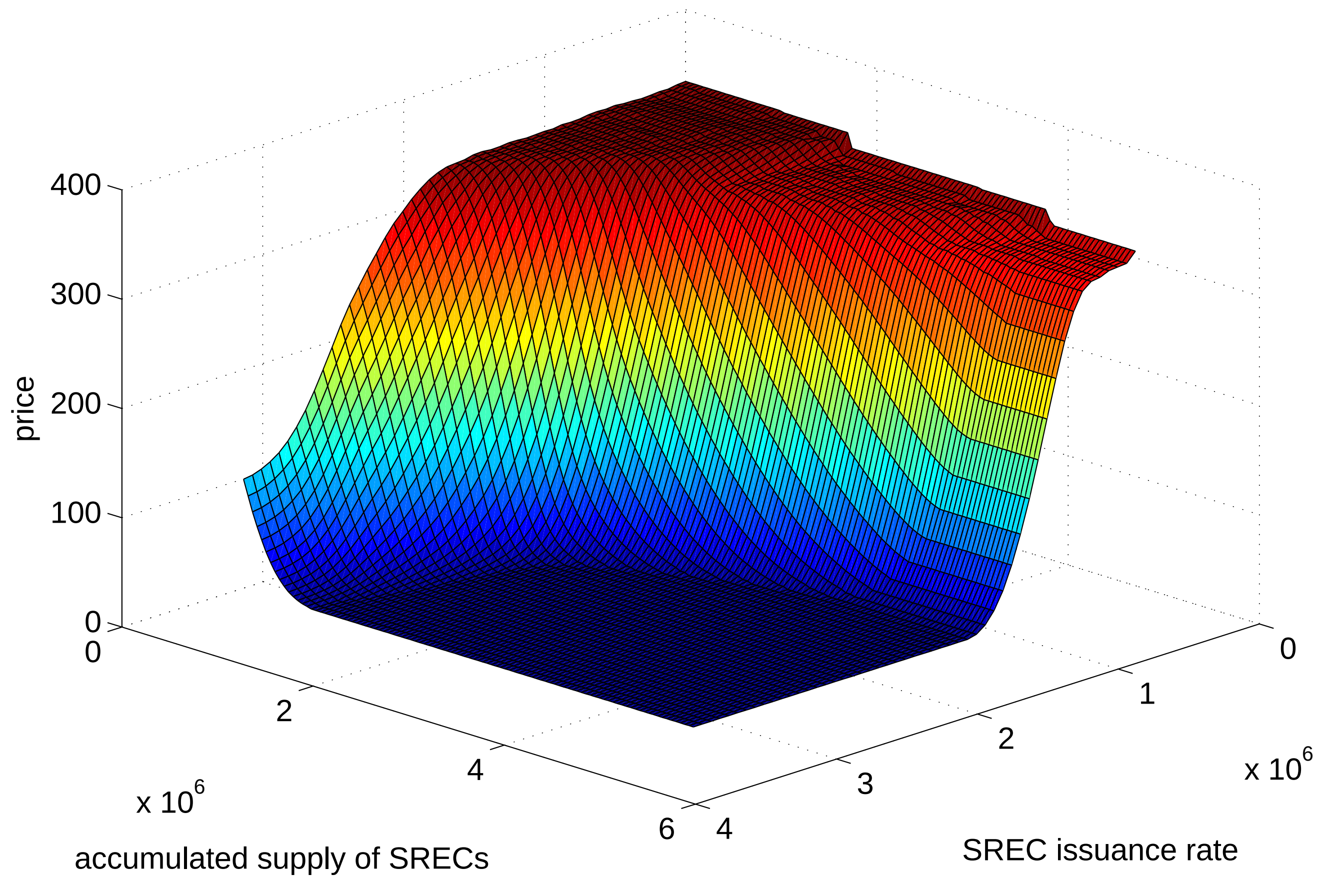
Solving algorithm produces a surface $P_t(b_t, \hat{g}_t)$ for each time.

For 2013 SRECs near the end of the first year:



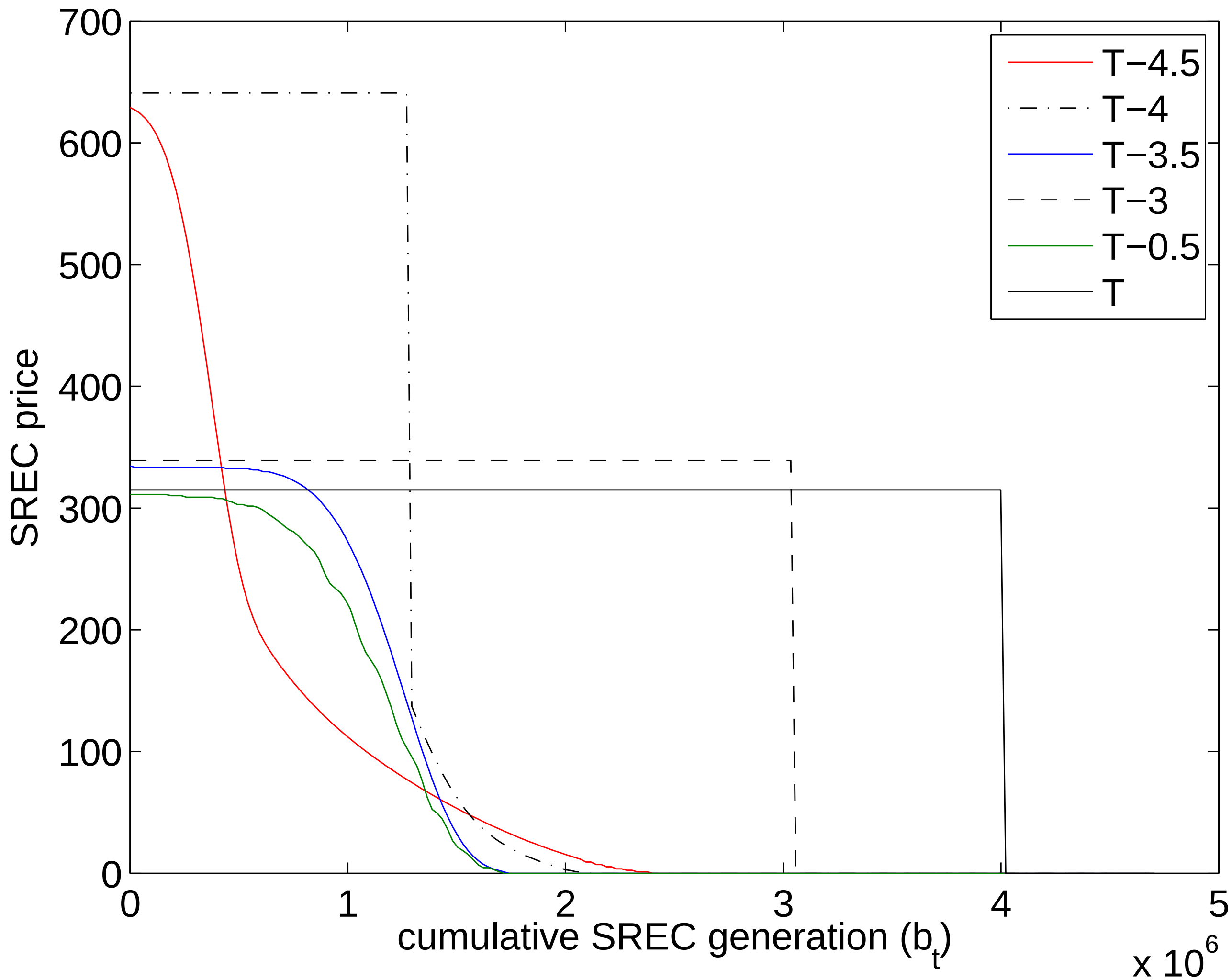
Results of structural model

Same price surface but six months later:



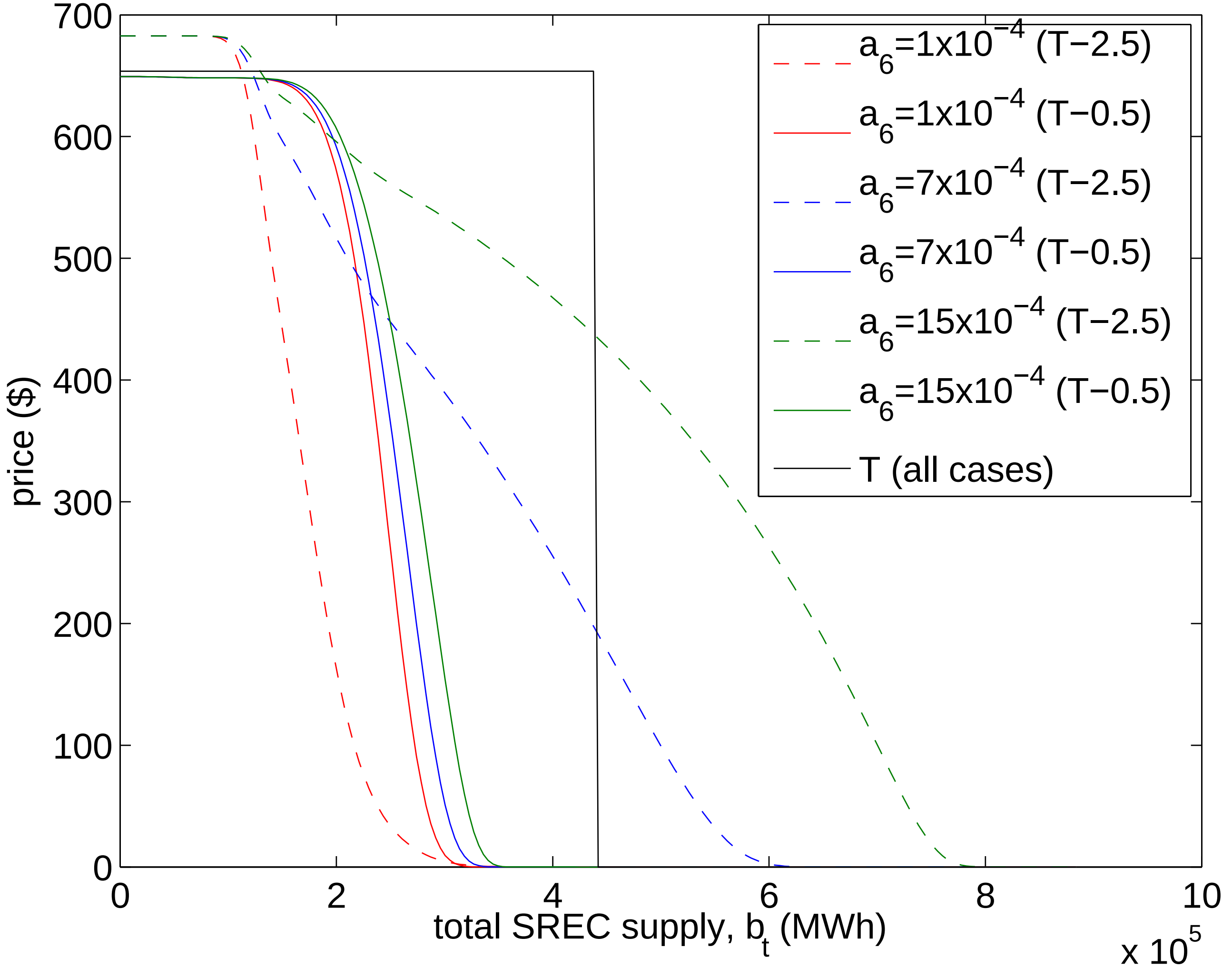
Results of structural model

As with carbon, price surface 'diffuses' from its digital option shape at each compliance date (but not exactly a digital payoff if banking provides value):



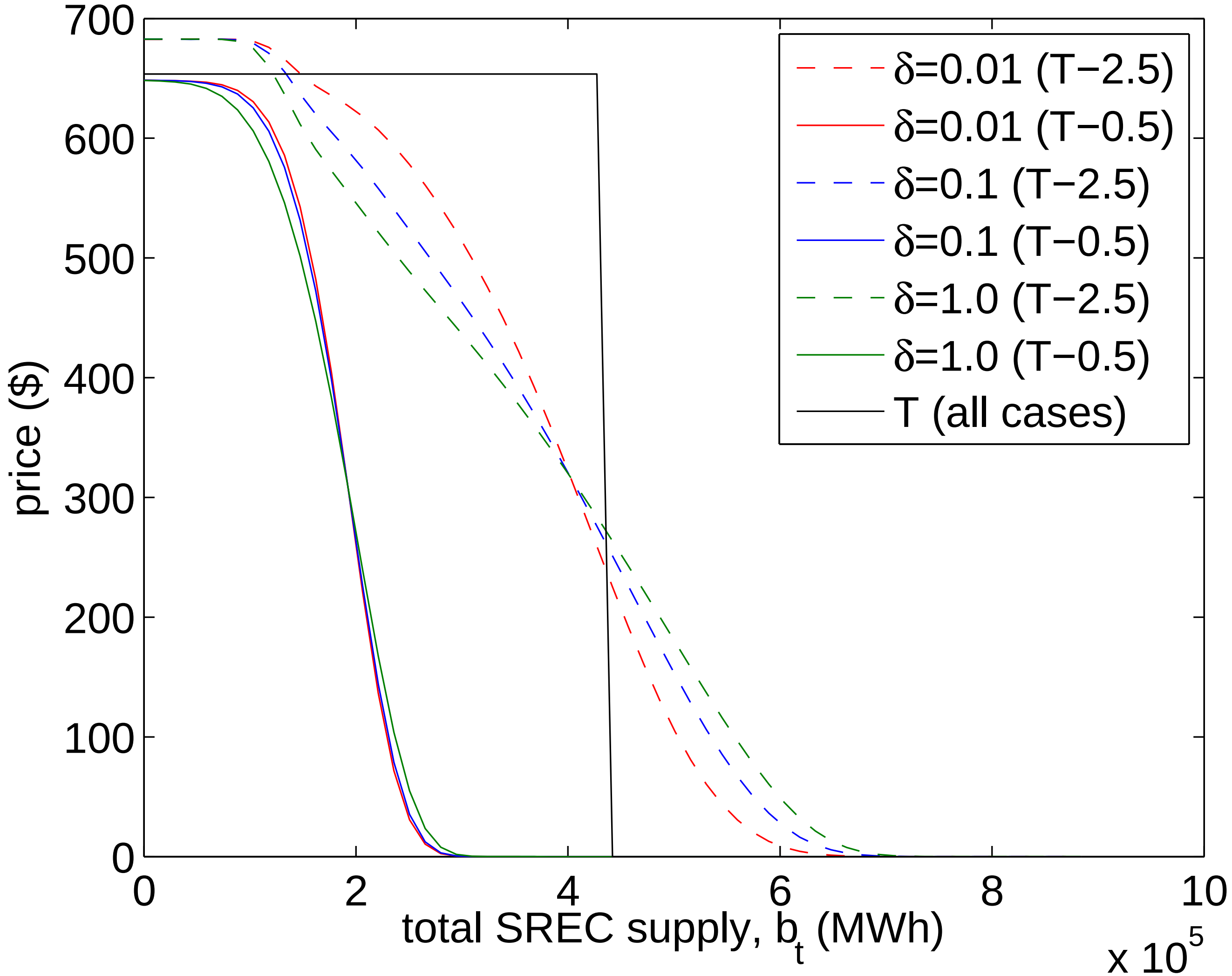
Results of structural model

Sensitivity to feedback parameter a_6:



Results of structural model

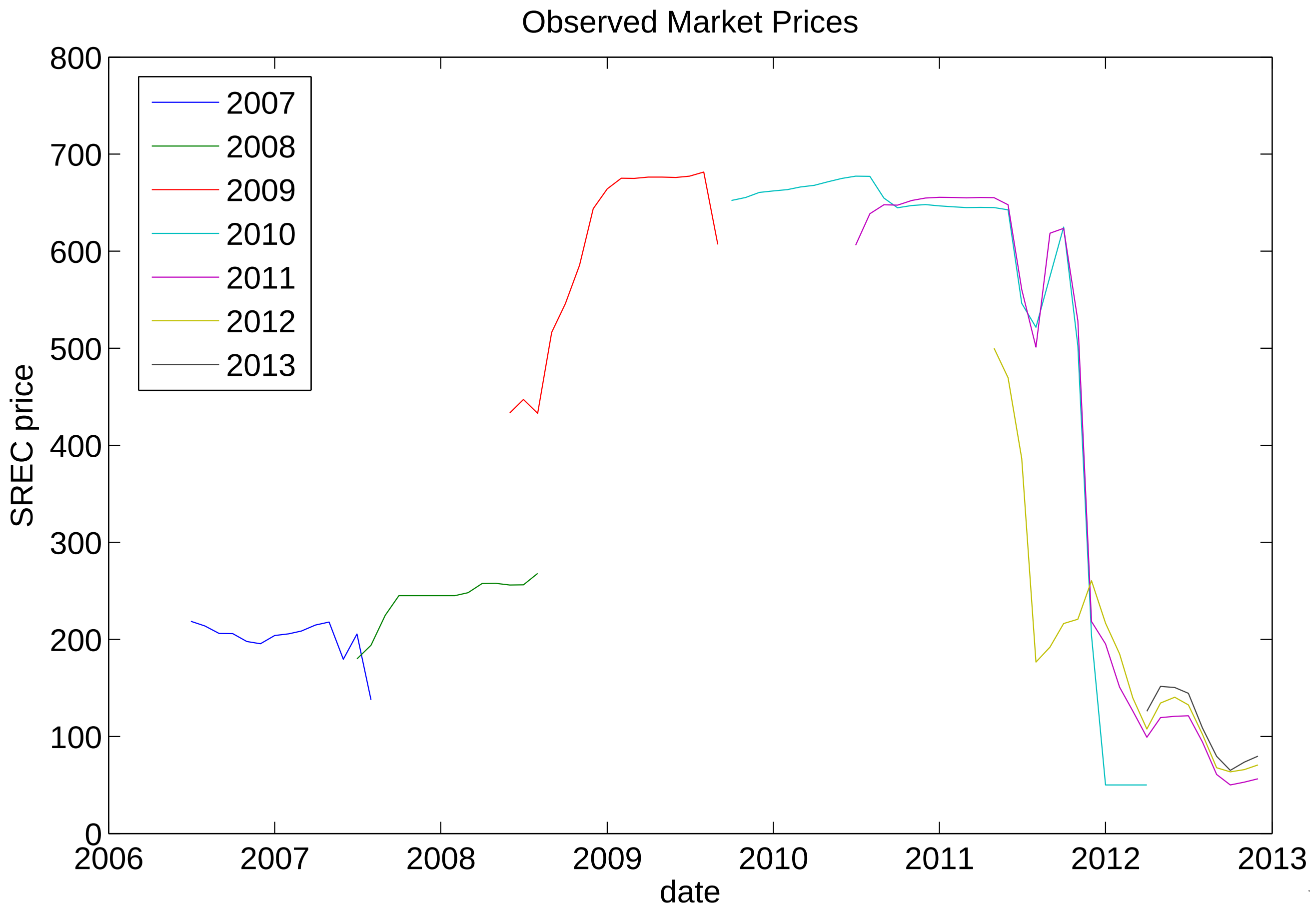
Sensitivity to feedback lag parameter δ:



Comparison to history

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

- Overall price behaviour through history reasonably encouraging
- Also, provides some evidence about the level of feedback in the market



Comparison to history

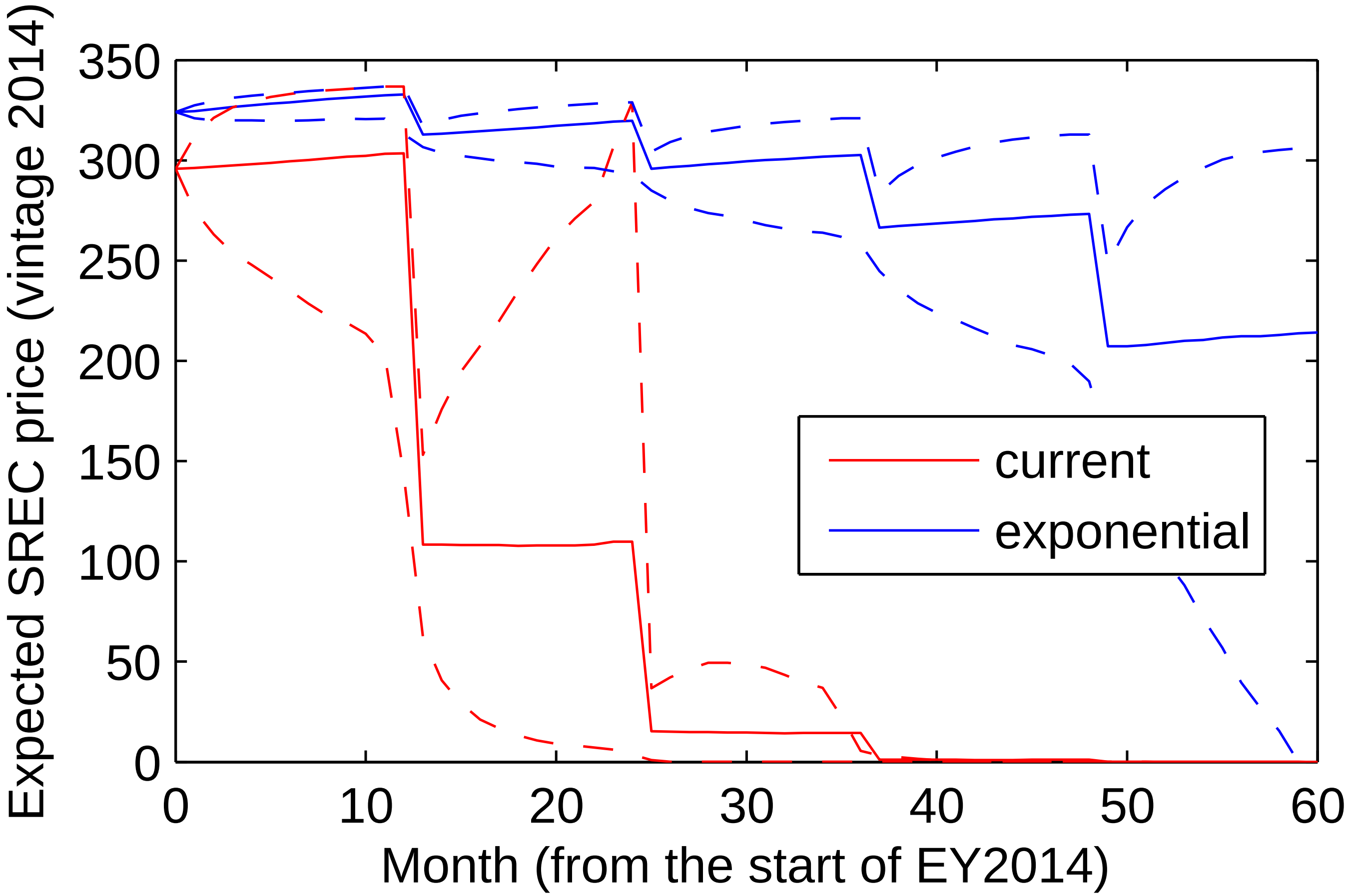
Price elasticity parameter set to $a_6 = 7 \times 10^{-4}$ throughout, except:

- For 2013A line, $a_6 = 5 \times 10^{-4}$ (low feedback)
- For 2013B line, $a_6 = 1 \times 10^{-3}$ (high feedback)

Policy Analysis

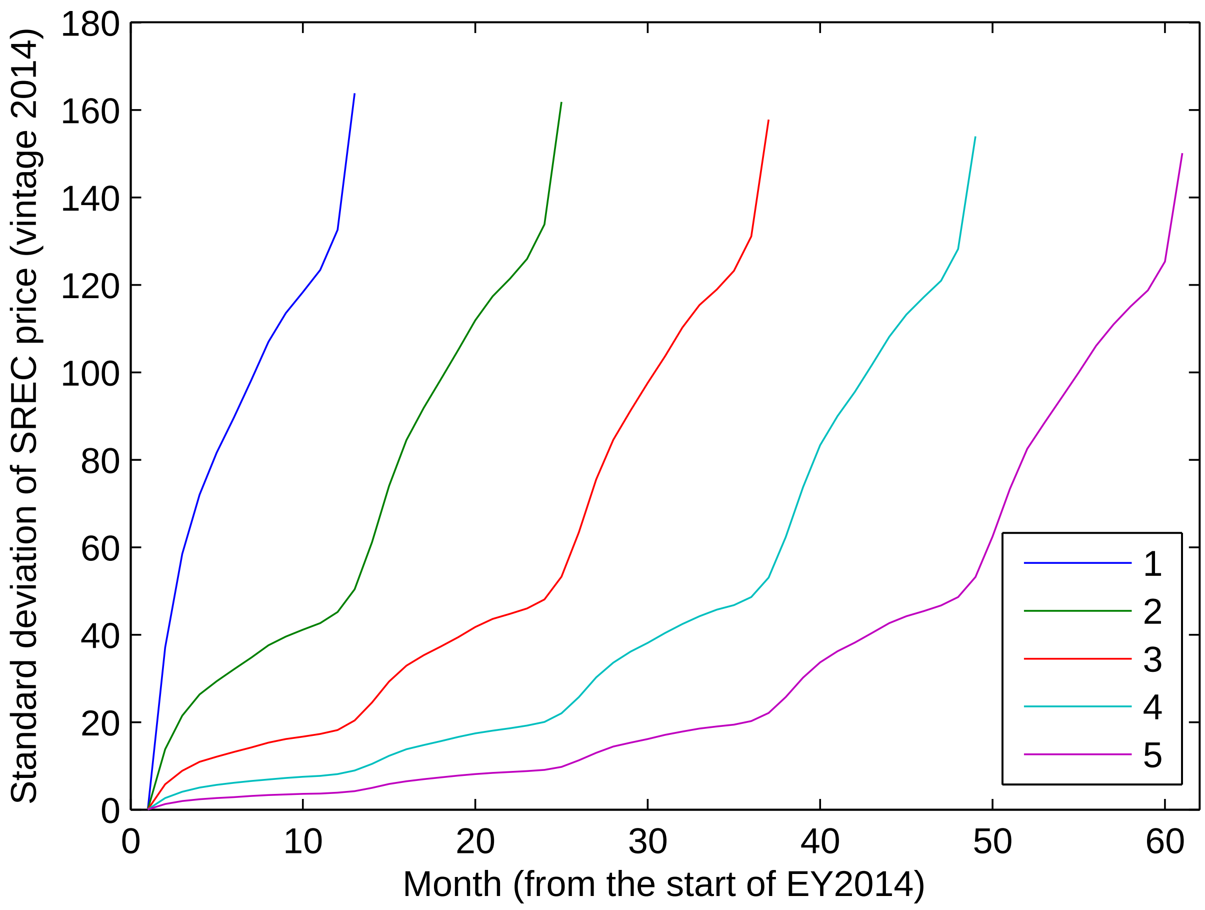
SREC markets (just like cap-and-trade) are very sensitive to market design.

For example, choosing an appropriate requirement growth schedule:



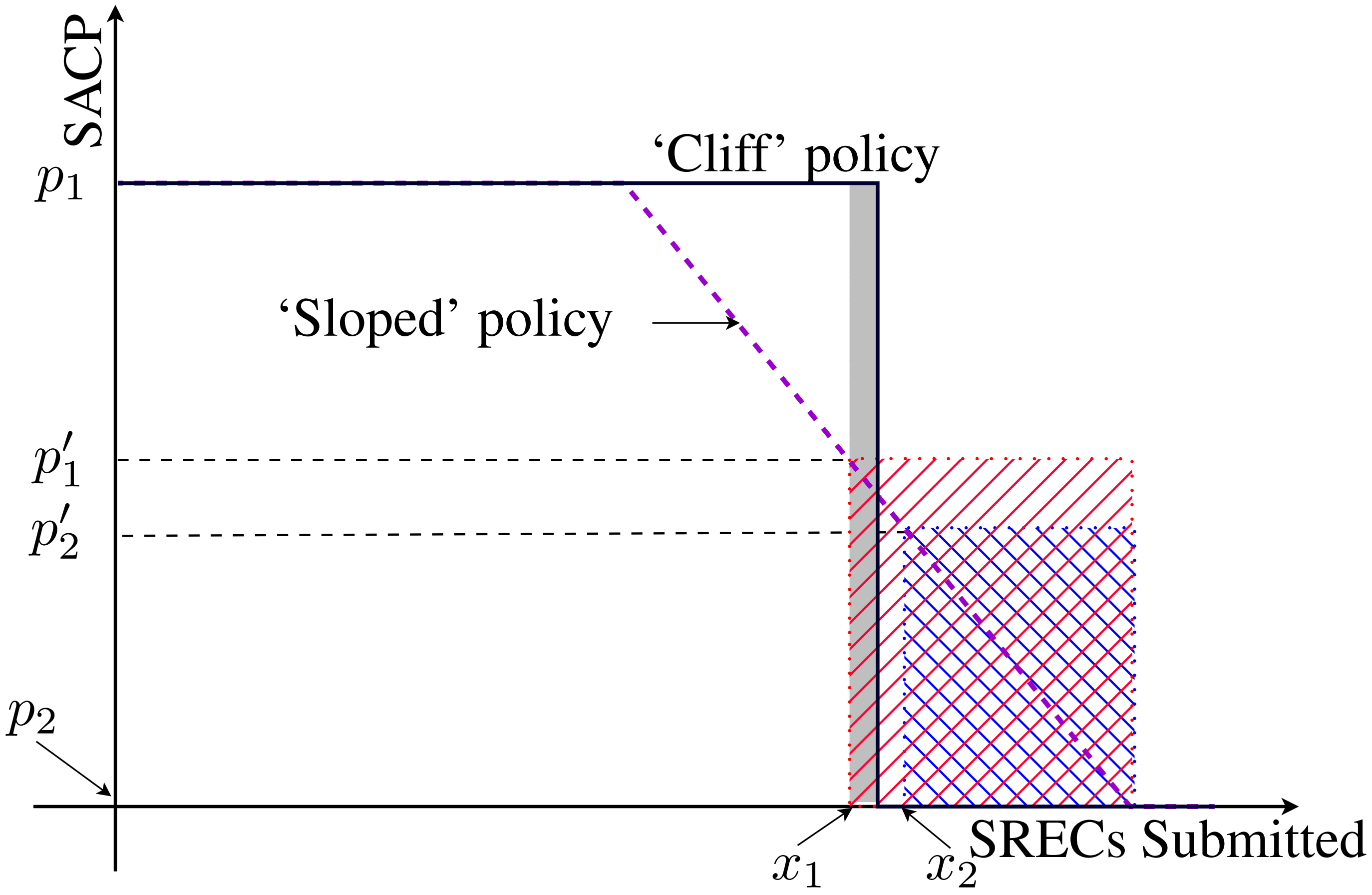
Policy Analysis

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



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, sloped line below)



Example prices shown for submitted SRECs x_1 and x_2. Shaded rectangles = 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'

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

$$f_t(x_t) = \begin{cases} \pi_t, & x_t < (1-\lambda)R_t, \\ \pi_t - \frac{\pi_t}{2\lambda R_t}(x_t - (1-\lambda)R_t), & (1-\lambda)R_t \le x_t < (1+\lambda)R_t, \\ 0 & (1+\lambda)R_t \le x_t. \end{cases}$$

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

Social Welfare Problem

- Formally, we should expand our state variable S_t to track the banked supply of each SREC vintage y, via vector $(b_{t,y})_y$.
- Then $S_t = ((b_{t,y})_y, \hat{g}_t, \bar{p}_t)$, and decision variable $(x_{t,y})_y$.
- Let $b_t = \sum_{y=\max\{1,\lceil t\rceil-\tau\}}^{\lceil t\rceil} b_{t,y}$ and $x_t = \sum_{y=\max\{1,\lceil t\rceil-\tau\}}^{\lceil t\rceil} x_{t,y}$.
- Optimal submission decisions x_t maximize social welfare by solving:

$$V_t(S_t) = \max_{x_t} \mathbb{E}_t \sum_u e^{-r(u-t)} \int_0^{x_t} f_t(u)du,$$

- Maximizing the expected area under the 'inverse demand curve' is equivalent to the minimizing the total expected penalty payments.
- Can show that

$$x_t = \max\left(b_{t,t-\tau}, \min\left(b_t, f^{-1}(e^{-r}\mathbb{E}_t[f_{t+1}(x_{t+1})|x_t])\right)\right).$$

Penalty Function: Step vs Slope

Long-term simulations of different vintages reveal that with a sloped (graduated) penalty policy:

- Lower volatility, more stable prices, fewer sudden price drops
- Much smaller price gaps (often zero!) between different vintages

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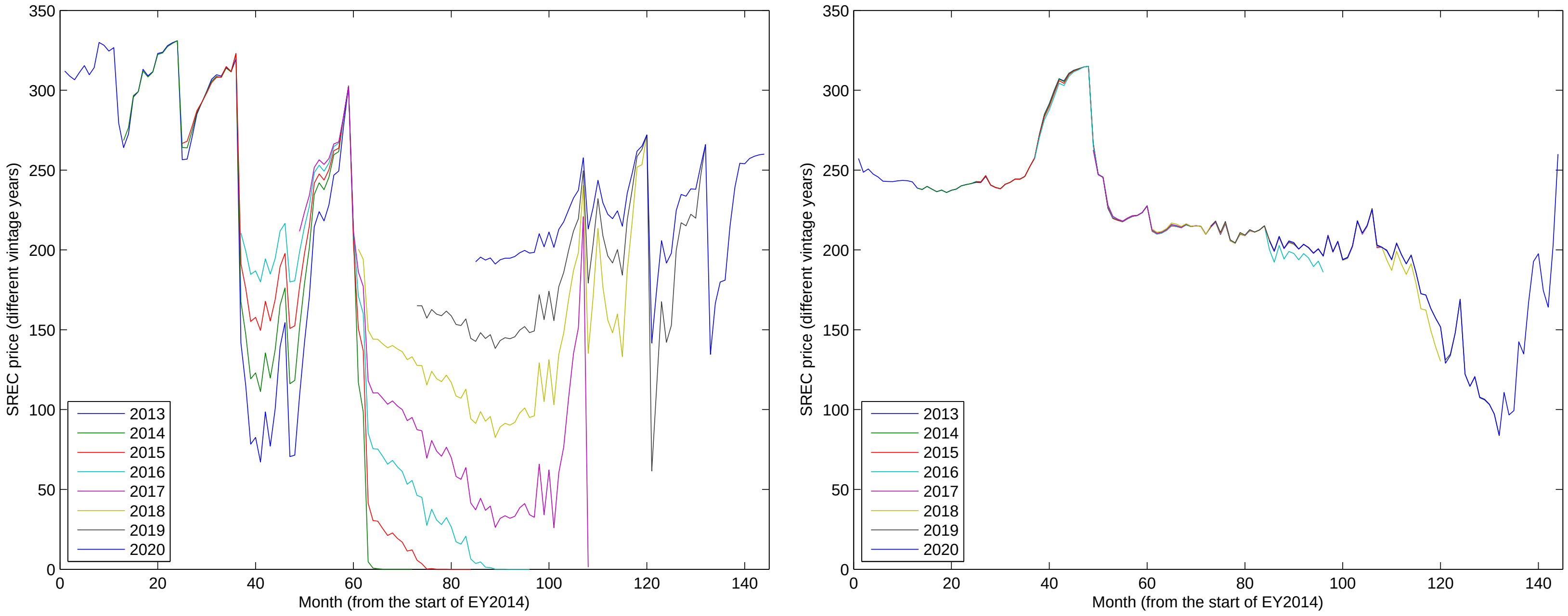
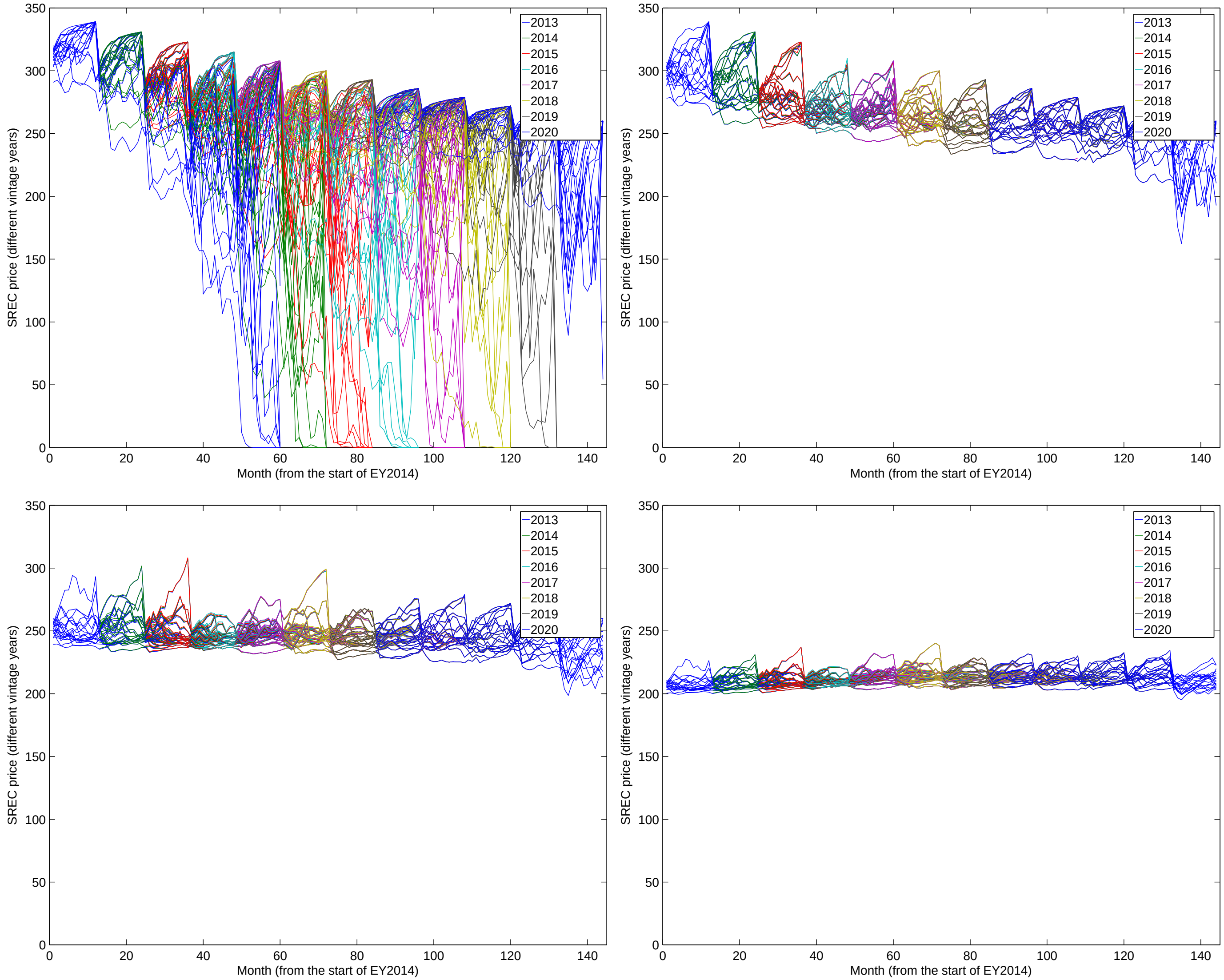


Simulations above use the same set of random numbers but for the step case ($\lambda = 0$) on the left and slope case ($\lambda = 0.3$) on the right.

Penalty Function: Varying Slopes

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



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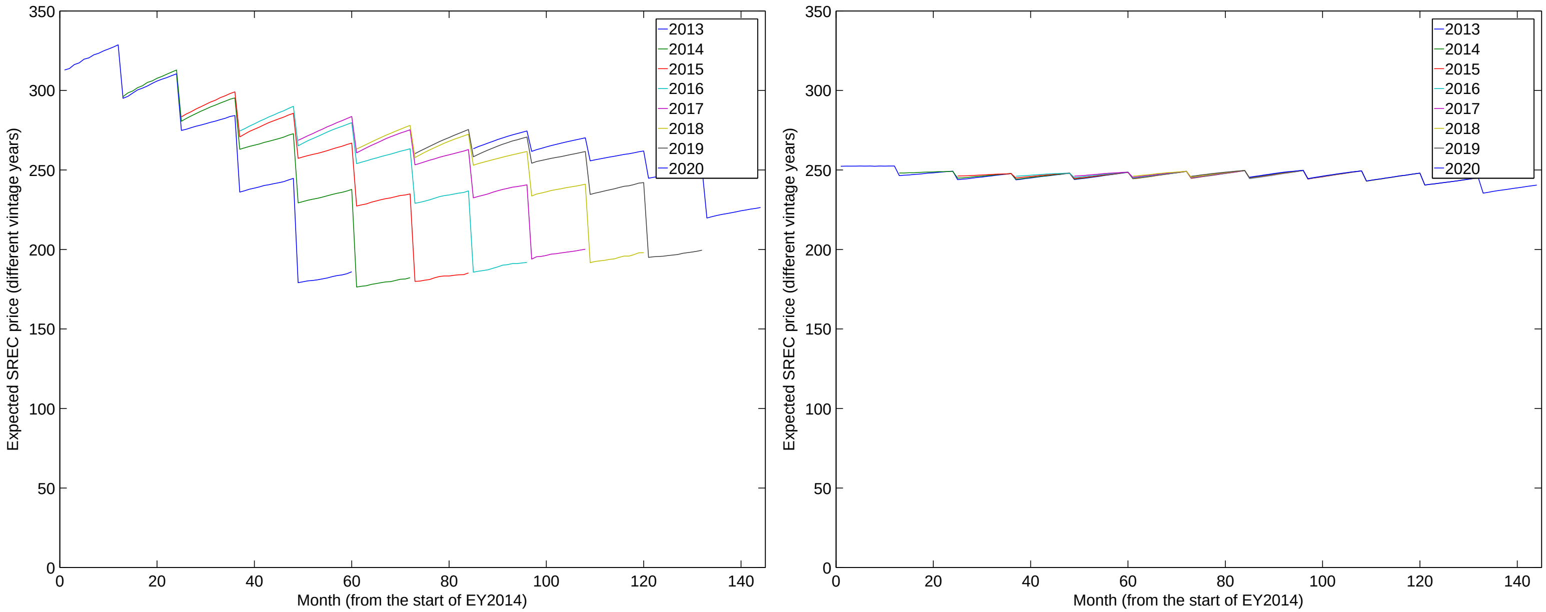

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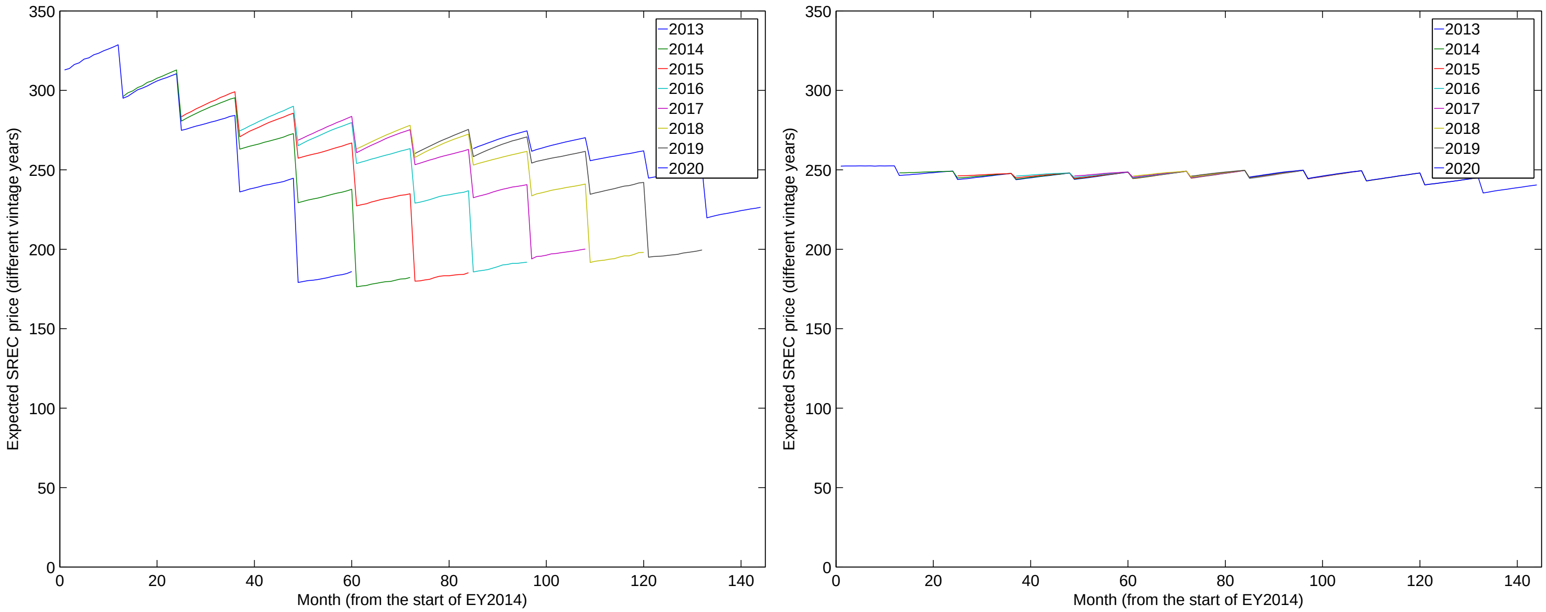

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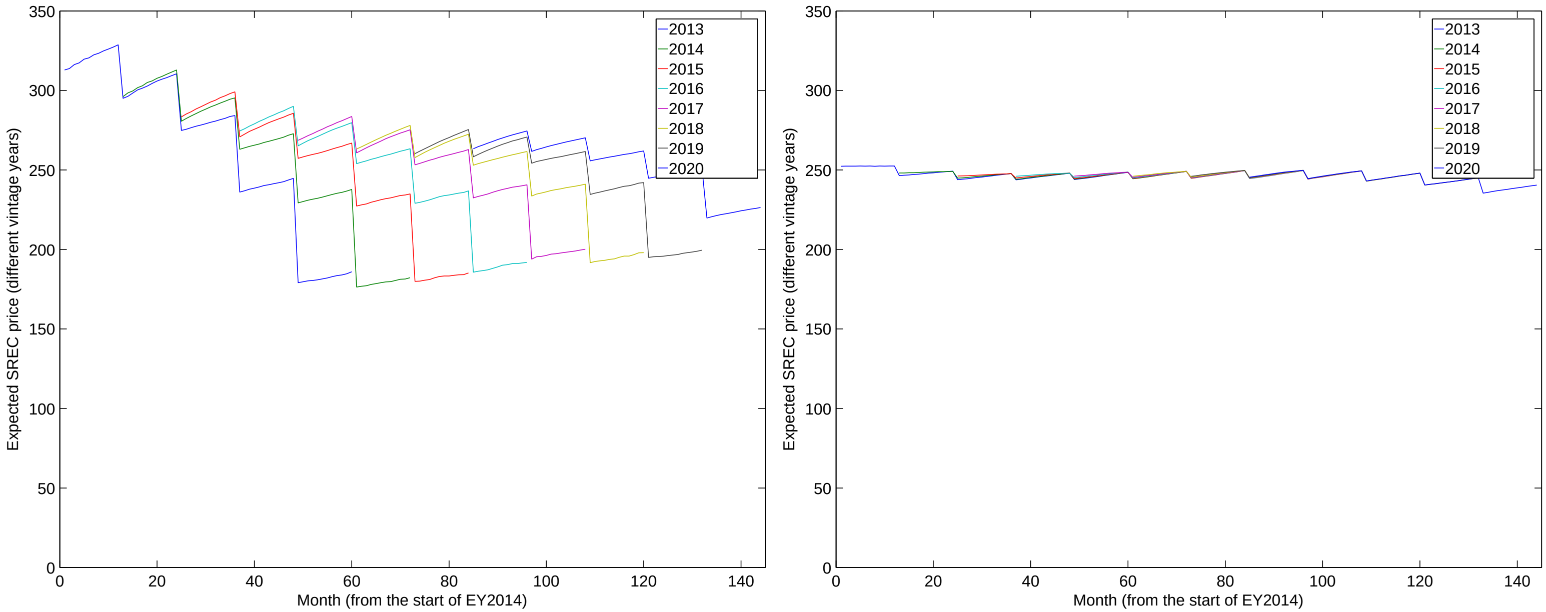

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- Hence utilities choose to pay a penalty even when there is a surplus! (pay a small penalty and bank more, to reduce future penalties)
- Only if the optimal decision x_t falls below $b_{t,t-\tau}$ (an unrealistically high surplus), can a price difference between vintages occur, as it's better to submit $b_{t,t-\tau}$ than let SRECs expire!

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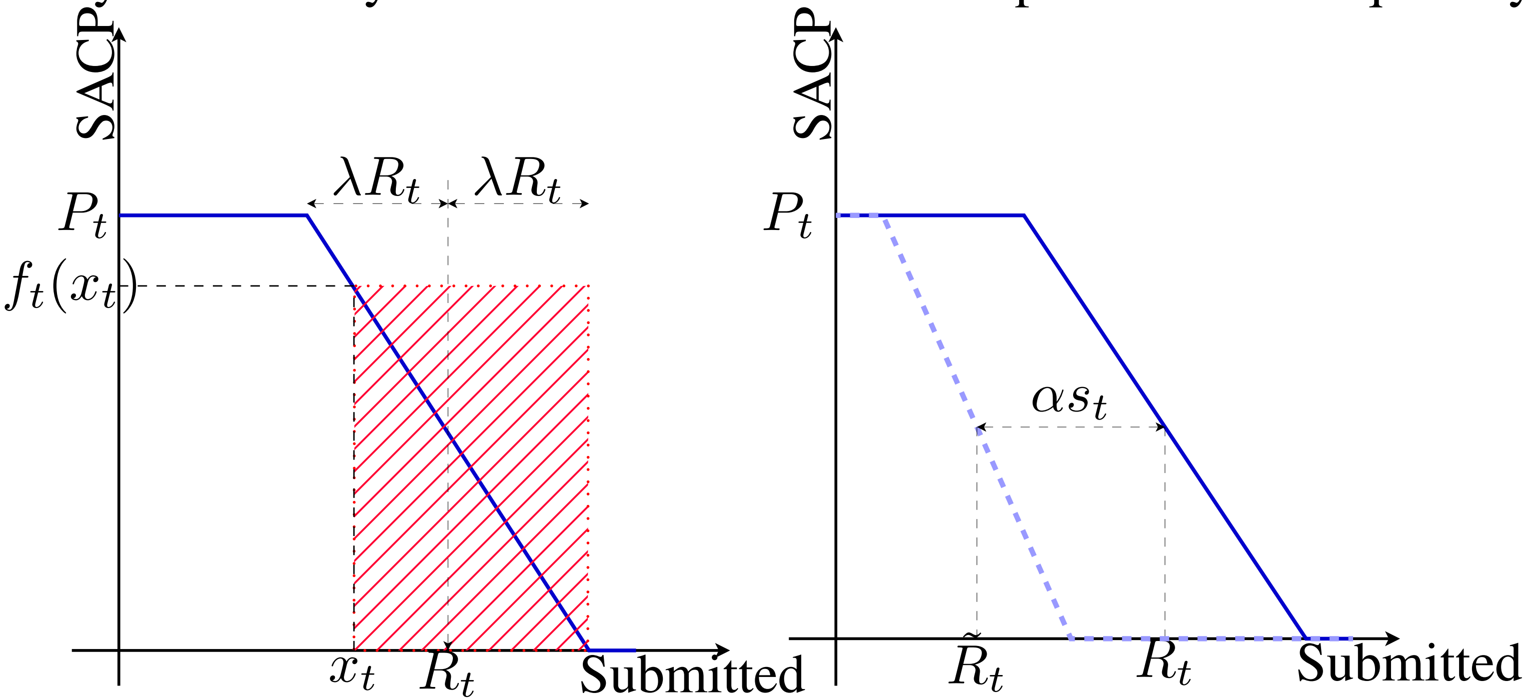
- Finally, in addition to this formula for R, Mass implements a \$300 fixed-price auction each year, as a form of 'price floor mechanism'.

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 the levels of price volatility in the market.

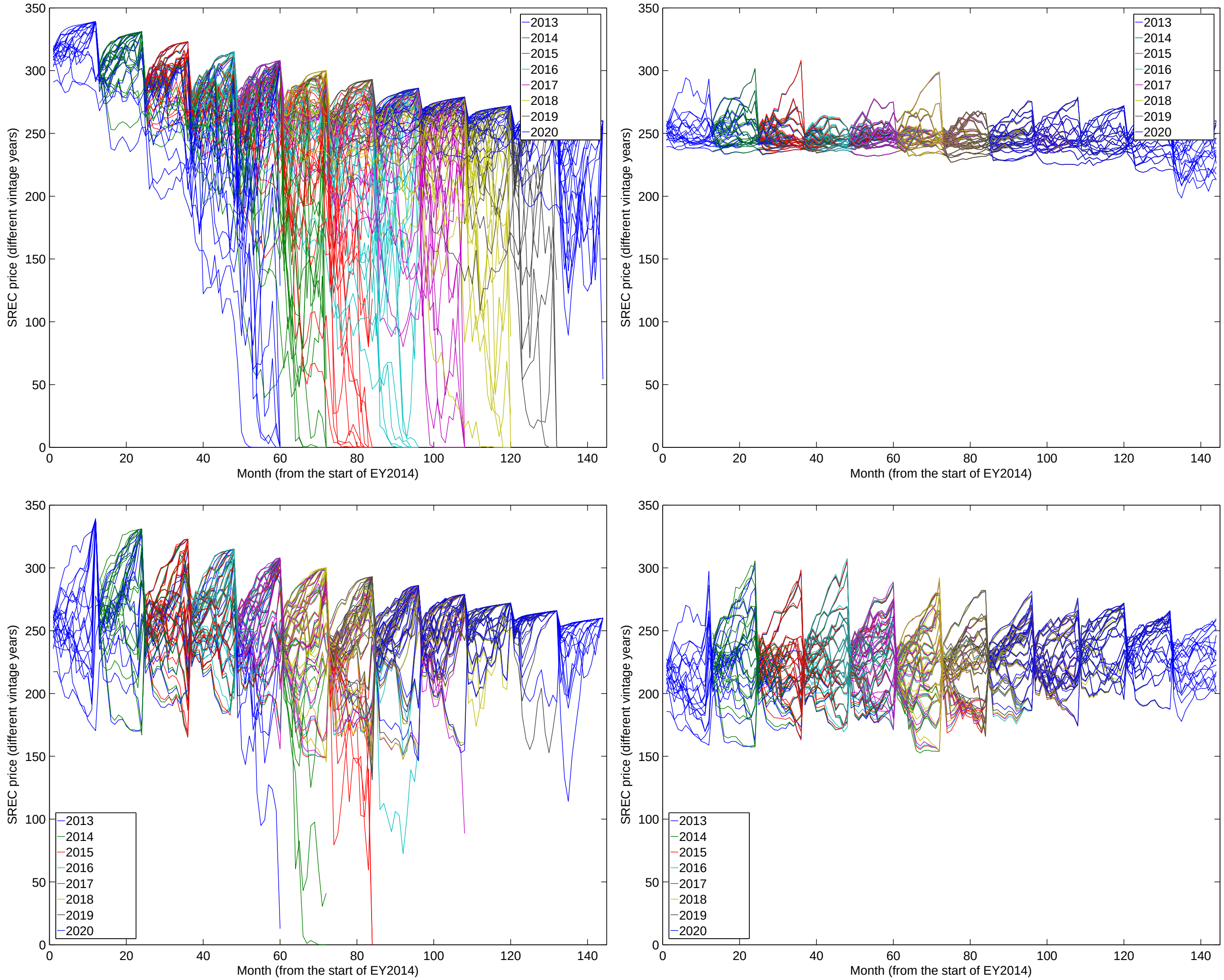
- λ controlling the slope of the penalty function.
- α for controlling the responsiveness of the requirement.

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 $(0.3, 0.5)$:



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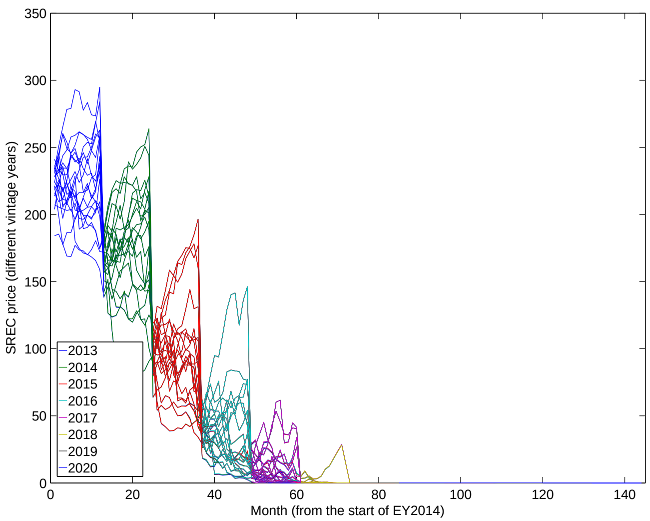
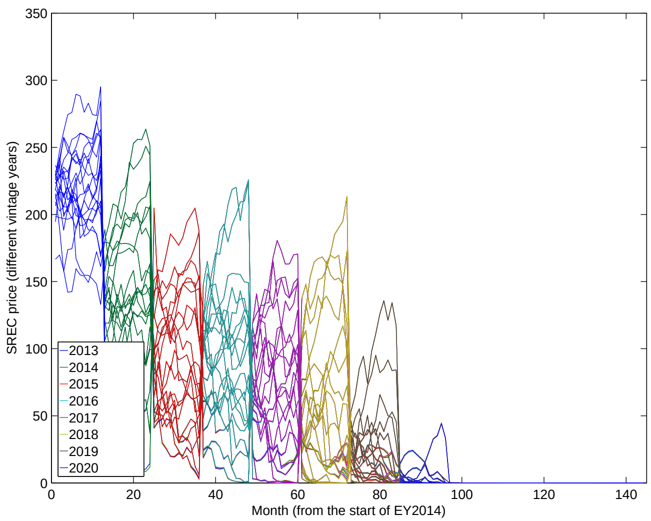
- However, it can also counteract the effect of λ (since it means that banking more today ends up increasing future requirements!).
- e.g. if $\alpha = 1$, the incentive to bank is completely cancelled out.
- But long-term imbalances sometimes more effectively controlled.

Plot below uses current requirement schedule (very low compared to generation in model) with $\alpha = 0$ (left) and $\alpha = 1$ (right).





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Some promising ideas, but details are tricky and more work on understanding and modeling the resulting price dynamics is crucial!

Further Work Needed

Clearly very little research in this area so far, hence many possible topics to explore:

- Further calibration and testing on other US markets and also around the world if possible.
- Further investigation of market design alternatives.
- Incorporating the electricity market into the model: impacts of SREC prices on power and vice versa.
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References

Our recent papers (available soon, or else by request):

- M. Coulon, J. Khazaei, W. Powell (2013) *SMART-SREC: A stochastic model of the New Jersey solar renewable energy certificate market*
- M. Coulon, J. Khazaei, W. Powell (2013) *ADAPT: A Price-stabilizing Compliance Policy for Renewable Energy Certificates: The Case of SREC Markets*

Useful introductions (and market design discussions in the third):

- Bird, L., J. Heeter, and C. Kreycik (2011). *Solar renewable energy certificate (SREC) markets: Status and trends*
- Wiser, R., G. Barbose, and E. Holt (2011). *Supporting solar power in renewables portfolio standards: Experience from the united states*
- Felder, F. A. and C. J. Loxley (2012). *The implications of a vertical demand curve in solar renewable portfolio standards*

Useful websites: www.srectrade.com, www.njcleanenergy.com,