Designing Dynamic Subsidies to Spur Adoption of New Technologies

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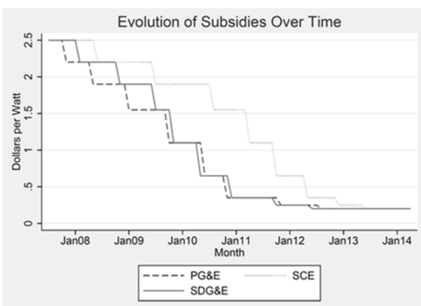
(Working paper very soon!)

Policymakers commonly subsidize adoption of new durable good technologies.

(If have other good examples, please do mention them now or later.)

Policymakers must decide how these subsidies will evolve over time, which in turn affects how adoption and subsidy spending evolve over time.



Yet the design of an efficient subsidy schedule has thus far remained an open policy question.

We formally analyze the dynamically efficient subsidy schedule.

The regulator commits to a subsidy policy designed to achieve a target level of adoption by a certain date.

The regulator values cumulative adoption and dislikes spending money.

Consumers have heterogeneous, private values for the technology.

We show that the efficient subsidy schedule depends on:

1) The anticipated pace at which technical change will reduce the private cost of adopting the technology

2) Whether consumers consider future changes in the cost of the technology and the level of the subsidy when they decide whether to adopt the technology.

We combine our theoretical analysis with a dynamic discrete choice estimation of households' preferences for residential solar systems in California in order to understand the relative magnitude of these forces in practice.

We show that consumer foresight can increase public spending substantially.

First, consumers' rational expectations of future subsidies limit the regulator's ability to intertemporally price discriminate by offering a low subsidy in early periods and a high subsidy in later periods.

- In a world without technological progress, this effect increases total spending by 9% and slows the rate at which the efficient subsidy increases over time.

Second, the regulator must offer forward-looking consumers a high subsidy in order to compensate them for forsaking the option to adopt solar at some later time.

- In a world with technological progress, the regulator's total spending is 50% greater when households have rational expectations.

Our primary contribution is to ground the design of dynamic subsidy instruments in economic principles.

Despite the prevalence of subsidies for durable investments, there has been little formal analysis of these instruments.

Kalish and Lillien (1983) study the efficient subsidy trajectory in the presence of learning and of word-of-mouth diffusion.

- In their conclusion, they mention that a desire to avoid subsidizing high-value consumers could argue for an increasing subsidy schedule.

Meyer et al. (1993) discuss how to design investment tax credits in order to obtain the “biggest bang for the buck.” Policymakers should aim to combine a high marginal credit with a low average credit.

These papers' informal observations illustrate the logic underpinning our intertemporal price discrimination channel. We formally demonstrate this channel, show how it depends on private actors' expectations, and introduce new channels.

A larger literature has analyzed how monopolists should set prices for durable goods over time.

Several papers have explored the conditions under which a monopolist finds intertemporal price discrimination to be optimal (Stokey, 1979; Landsberger and Meilijson, 1985; Salant, 1989).

- Our setting follows these in assuming that the regulator can commit to a subsidy schedule and in analyzing the implications of rational expectations.

Many authors have also explored how a monopolist should price durable goods when it cannot commit to later periods' prices.

- For instance, Coase, 1972; Stokey, 1981; Conlisk et al., 1984; Gul et al., 1986; Kahn, 1986; Besanko and Whinston, 1990; and Sobel, 1991.
- Waldman (2003) criticizes the assumption that commitments are not possible.
- He notes that firms often do appear to commit to policies in practice. Similarly, it is easy to provide examples in which policymakers appear to successfully commit to a subsidy schedule.
- Our theoretical analysis focuses on this environment with commitment. It therefore relates more closely to the optimal capital taxation literature (e..g, Judd, 1985; Chamley, 1986; Chari and Kehoe, 1999).

Outline

- Setting
- Theoretical Analysis
- Dynamic Structural Model of Preferences for Solar
- Results

Setting

Households choose when to adopt a durable technology.

Households value the technology at $v_{it} = h_{it} + \epsilon_{i1t}$.

All households that adopt at time *t* receive subsidy s_t.

But they also pay the tech's cost: $C(t, Q_t, \mu_t) \geq 0$.

- This cost may decline exogenously: $C_1(t, Q_t, \mu_t) \leq 0$.
- It may also decline as a result of induced tech change: $C_2(t, Q_t, \mu_t) \leq 0$.

A household who chooses not to adopt the technology at time t receives $v_{i0t} = \epsilon_{i0t}$.

Myopic households who have not yet adopted the technology will adopt at time *t* iff $v_{it} + s_t - C(t, Q_t, \mu_t) \geq v_{i0t}$.

Forward-looking households form rational expectations over the evolution of the tech's cost, the subsidy, and their own characteristics. Their value of making the choice at time *t* is:

$$V(\Omega_t, \vec{\varepsilon}_t) = \max\{h_{it} - C(t, Q_t, \mu_t) + s_t + \varepsilon_{i1t},\ \beta\mathbb{E}[V(\Omega_{t+1}, \vec{\varepsilon}_{t+1})|\Omega_t] + \varepsilon_{i0t}\}$$

The regulator commits at time 0 to offer a subsidy s_t to all $Q_{t+1} - Q_t$ households who adopt the technology at time *t*.

The regulator aims to achieve total adoption $\hat{Q}$ after some given time $T > 0$.

She knows the distribution of potential adopters' values but does not know any particular household's value.

The regulator dislikes spending money. Her distaste for spending money is $G(s_t[Q_{t+1} - Q_t]) > 0$, with $G(\cdot)$ strictly increasing and strictly convex.

The regulator receives instantaneous benefit $B(Q_t) > 0$ from cumulative adoption, with $B(\cdot)$ strictly increasing and strictly concave.

The regulator chooses the subsidy schedule at time 0 to maximize:

$$\sum_{t=0}^{T}(1+r)^{-t}\mathbb{E}_0\left[B(Q_t) - G\left(s_t\left[Q_{t+1} - Q_t\right]\right)\right] \quad \text{s.t. } Q_{T+1} = \hat{Q}$$

Theoretical Analysis

We specialize the full setting in two ways:

1) Technological progress is deterministic (drop μ_t from cost fn).
2) Households' preferences are fixed over time (v_i instead of v_{it}).

Together, these two assumptions mean that we now have a deterministic model.

We conduct the theoretical analysis in continuous time, with households discounting at rate δ and the regulator discounting at rate *r*.

Begin by considering myopic households.

When potential adopters are myopic, they adopt the technology as soon as their net benefit of adoption is positive.

Therefore, at time t, all actors with $v_i \geq C\big(t, Q(t)\big) - s(t)$ should adopt (or should already have adopted) the technology.

Define the value at which actors are just indifferent to adopting as $V(t) \stackrel{\text{def}}{=} C\big(t, Q(t)\big) - s(t)$.

Normalize the measure of potential adopters to 1:
The number of households who are willing to pay no more than v_i for the technology is the twice-differentiable cumulative distribution function $F(v_i) \in [0,1]$.

Cumulative adoption by t is $Q(t) = 1 - F(V(t))$. Current adoption is $\dot{Q}(t) = -f\big(V(t)\big)\,\dot{V}(t)$, with $f(v_i) \geq 0$ the density function.

We transform the regulator's problem into a more tractable form.

Rather than imagining the regulator selecting the subsidy at each instant, imagine the regulator selecting the quantity of adoption via $V(t)$, with the subsidy determined by this choice and by actors' equilibrium conditions. The regulator's problem becomes:

$$\max_{y(t)} \int_0^T e^{-rt}\left[B\Big(1 - F(V(t))\Big) - G\Big(-[C(t, 1-F(V(t))) - V(t)]\, f(V(t))\, y(t)\Big)\right] \mathrm{d}t$$
$$\text{s.t. } \dot{V}(t) = y(t)$$
$$V(0) = F^{-1}(1 - Q_0),\ V(T) = F^{-1}(1 - \hat{Q}).$$

A quick sketch of how to solve the model.

Define the Hamiltonian:

$$H(t, y(t), V(t), \lambda(t)) = e^{-rt}\left[B\Big(1 - F(V(t))\Big) - G\Big(-[C(t, 1-F(V(t))) - V(t)]\, f(V(t))\, y(t)\Big)\right] + e^{-rt}\lambda(t) y(t).$$

The Maximum Principle gives us a first necessary condition:

$$\lambda(t) = -[C(t, 1-F(V(t))) - V(t)]\, f(V(t))\, G'\Big(-[C(t, 1-F(V(t))) - V(t)]\, f(V(t))\, y(t)\Big)$$

Note that $\lambda(t) \leq 0$. Because smaller $V(t)$ corresponds to greater $Q(t)$, this is (sensibly) saying that the shadow value of adoption is positive.

The costate equation gives a second necessary condition (messy: see text), along with the transition equation, the initial condition, and the terminal condition.

We then time-differentiate the necessary condition given above and substitute for $\dot{\lambda}(t)$ from the costate equation. Recall that households' behavior implies $V(t) = C\big(t, Q(t)\big) - s(t)$, which in turn implies $\dot{V}(t) = \dot{C}\big(t, Q(t)\big) - \dot{s}(t)$. Substituting this and solving for $\dot{s}(t)$ then gives us the main result (on the next slide).

We see five channels determining the efficient subsidy.

We find that, along an efficient trajectory, $\dot{s}(t)$ equals:

$$\frac{-r\,\lambda(t) - B' f(V(t)) - G' y(t)\, f(V(t)) - [s(t)]^2\, G''\, f(V(t))\ddot{Q}(t) - G'\,[f(V(t))]^2\, y(t)\, C_2(t, Q(t))}{G'\, f(V(t)) - s(t)\, f(V(t))\, G''\, y(t)\, f(V(t))}$$

1) <u>Hotelling</u> (≥ 0): The social cost of spending must grow at the discount rate *r*, since the regulator prefers to defer spending.

2) <u>Adoption benefit</u> (<0): High earlier subsidies provide benefits by increasing the technology's penetration tomorrow.

3) <u>Price discrimination</u> (≥ 0): Raising the subsidy over time avoids overpaying high-value actors who would adopt for a small subsidy.

4) <u>Smooth spending</u> (<0 iff $\ddot{Q}(t) > 0$): If adoption is increasing at an increasing rate, this channel favors a decreasing subsidy (because the cost of funds is convex). Tech change amplifies this channel.

5) <u>Endogenous technology</u> (≤ 0): When induced technical change is possible, a higher subsidy in earlier instants carries the additional benefit of reducing technology costs in later periods.

Now consider forward-looking households.

Forward-looking household *i* chooses the optimal time Ψ_i to adopt the technology, for given subsidy and cost trajectories:
$\max_{\Psi_i} e^{-\delta \Psi_i}[v_i - C\big(\Psi_i, Q(\Psi_i)\big) + s(\Psi_i)]$.

The first-order necessary condition is
$$\delta\big[v_i - C\big(\Psi_i, Q(\Psi_i)\big) + s(\Psi_i)\big] = \dot{s}(\Psi_i) - \dot{C}(\Psi_i, Q(\Psi_i)).$$
It equates the cost of waiting (LHS) to the benefit of waiting (RHS).

Rearranging, the subsidy must evolve as:
$$\dot{s}(t) = \delta\big[v_i - C\big(\Psi_i, Q(\Psi_i)\big) + s(\Psi_i)\big] + \dot{C}(\Psi_i, Q(\Psi_i)).$$
In the myopic setting, equilibrium adoption constrained only the level of the subsidy, but now it also constrains the change in the subsidy.

The regulator solves:

$$\max_{y(t), s(0)} \int_0^T e^{-rt}\left[B\Big(1 - F(V(t))\Big) - G\Big(-s(t)\, f(V(t))\, y(t)\Big)\right] \mathrm{d}t$$
$$\text{s.t. } \dot{V}(t) = y(t)$$
$$\dot{s}(t) = \delta\,[V(t) - C(t, 1-F(V(t))) + s(t)] + \dot{C}(t, 1 - F(V(t)))$$
$$V(0) = F^{-1}(1 - Q_0),\ V(T) = F^{-1}(1 - \hat{Q})$$
$$s(T) = C(T, \hat{Q}) - V(T) + J(V(T), C(T, \hat{Q})).$$

We show that consumer foresight flattens the efficient subsidy.

We get the same five channels plus a new channel that favors a decreasing subsidy when promises are accumulating: the regulator promises low future subsidies to spur earlier adoption.

We show that the new term partially cancels the price discrimination term and leaves a promise-keeping channel.

- This is a price discrimination channel constrained by actors' willingness to wait for higher future subsidies (determined by their discount rate δ).
- At time 0, the promise-keeping channel is zero, and it is very small for times near 0.
- Consumer foresight therefore favors a flatter/declining subsidy early on, because it replaces the positive price discrimination channel with the smaller promise-keeping channel.

Empirical Setting and Model

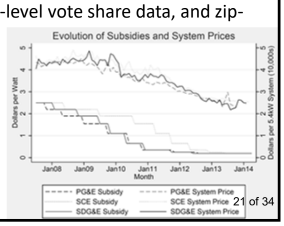
We quantitatively evaluate the efficient subsidy and its drivers in the context of the California Solar Initiative (CSI).

The CSI subsidized residential solar from 2007-2016.

It started at $2.50 per W and declined to $0. It spent $2.2 billion to obtain 1,940 MW of new solar generation.

The CSI maintains data on all applications, including date, zip code, utility, subsidy received, and characteristics of the installed system.

We combine these with block-group-level demographic data from the American Community Survey, precinct-level vote share data, and zip-code-level median solar radiation.



We estimate a dynamic model of residential solar system demand, which we will pair with a calibrated version of our regulator's optimization problem.

Our dynamic demand estimation is consistent with previous literature (Burr, 2014; Reddix II, 2014; De Groote and Verboven, 2016).

We specialize our general model in four ways (beyond EV1 errors).

1) Recalling that we had $v_{it} = h_{it} + \epsilon_{i1t}$, we now assume that $h_{it} = X_{it}'\gamma$, where X_{it} is known characteristics of the household and the tech.

2) We allow the disutility of spending money to vary by household and we model the federal subsidy for installing solar.

3) We assume that each state evolves according to its own first-order Markov process. (Except: households know future subsidies with certainty.)

4) To account for households that are not in a position to choose solar (e.g., because they live in an apartment complex), we include a random variable Φ_i that indicates whether a household considers solar.

We estimate the model by maximum likelihood, where each step of the likelihood maximization requires solving for the value function recursively from the period when all subsidies equal zero.

$$\Pr\{\text{i adopts in t}\} = \Phi_i \frac{\exp(X_{it}'\gamma + \alpha_i \tilde{C}_t)}{\exp(X_{it}'\gamma + \alpha_i \tilde{C}_t) + \exp(\beta E[V(\Omega_{t+1}|\Omega_t)])}$$

Our estimation timeframe begins in January 2009, when the federal solar subsidy became stable. It ends 41 months later, when PG&E's subsidy expired.

We only have demographic data at the zip code level. We therefore assume that households that install solar are randomly drawn from households in their zip code (e.g., Nevo (2001)).

- Identification of demographic coefficients therefore comes from variation in the demographics of zip codes where installations occur.

Once a household installs solar, it exits the data.

7.5% of households consider installing solar at all during the timeframe.

Identification: We need the causal effect of changes in system costs on adoption.

Utility-level cost changes come from changes in subsidies and from changes in panel costs (via tech change, input costs, and exchange rates).

Unobserved shocks to local adoption are unlikely to be correlated with average utility-level solar system costs.

Thus, we should get the causal effect that we need in order to optimize over counterfactuals with different cost trajectories (i.e., with different subsidy policies).

Note that we are not claiming to have the causal effect of demographics, nor do we need this. We need the distribution of willingness-to-pay for solar, so if home value is actually capturing home value and income that is fine.

The estimated coefficients show that the average household that considers installing solar has a negative valuation of solar. This reflects the substantial nonmonetary costs of going through the process.

Benefit increases in solar radiation received.

Benefit is increasing over time, at a decreasing rate (system quality improves).

Households dislike higher prices, but less so when in zip codes with high home values.

Benefit of Solar		-9.0078***
		(2.6959)
	* Median Radiation (kWh/m²/day)	5.9447**
		(2.6776)
	* Time Trend	0.1315***
		(0.0121)
	* Time Trend Squared	-0.0023***
		(0.0005)
	* Years of Schooling	0.0458
		(0.0609)
	* SCE	-0.5508
		(0.4743)
	* SDG&E	0.7817
		(0.5197)
Price ($10,000s)		-1.3008
		(0.9327)
	* Home Value ($1,000,000s)	0.5731**
		(0.2601)
Log-likelihood		194,286
Months		41

Standard errors in parentheses.

Results:
The Efficient Subsidy for Rooftop Solar

We take these preference estimates into the regulator's optimization problem.

We calibrate the regulator's benefit to the social value of solar energy (including emission displacement) from Baker, Fowlie, Lemoine, and Reynolds (2013).

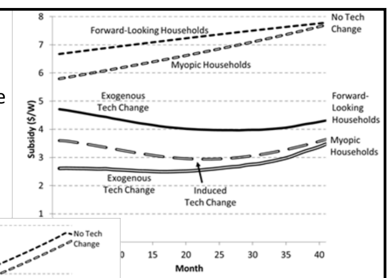
The concavity of the regulator's benefit reflects the intermittent nature of solar energy reducing its value once there is a lot of solar on the grid, calibrated to Gowrisankaran, Reynolds, and Samano (2016).

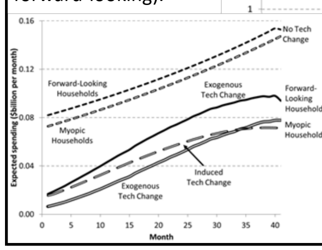
We calibrate the marginal cost of public funds to literature reviewed in Barrage (2016), and we assume that this marginal cost doubles if the regulator's per-period spending were to ever match its actual cumulative spending.

We require the regulator to achieve a target of 3% adoption in 41 months.

– The actual regulator's target was too low to require subsidizing myopic households. We use a higher adoption target because our aim is to understand the drivers of the efficient policy.

The efficient subsidy increases over time if technology is fixed but can decrease over time if technology is improving (especially when households are forward-looking).





Total spending is greater when technology is fixed rather than improving over time.

It is more expensive to obtain adoption from forward-looking households than from myopic households.

	No Tech Change	Exogenous Tech Change	Induced Tech Change
Myopic households			
Present value of spending ($billion)	3.5	1.4	1.6
Present value of spending ($/W)	5.4	2.1	2.5
Initial subsidy ($/W)	5.8	2.6	3.6
Terminal subsidy ($/W)	7.7	3.5	3.6
Forward-looking households			
Present value of spending ($billion)	3.8	2.1	TBA
Present value of spending ($/W)	5.8	3.2	TBA
Initial subsidy ($/W)	6.7	4.7	TBA
Terminal subsidy ($/W)	7.8	4.3	TBA

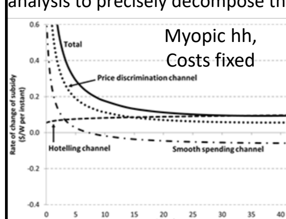
Today's subsidy must compensate forward-looking households not just for losses from installing solar but also for forsaking the option to adopt solar.

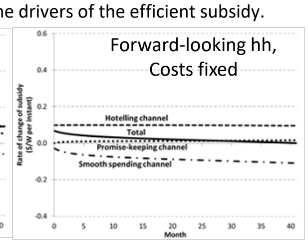
– When technology is fixed, households' foresight increases the regulator's spending by $300 million (9%).

The effect of foresight is stronger in the presence of tech change, because a household's option to adopt in a later period is especially valuable.

– Households' foresight now increases the regulator's spending by $700 million (30%).

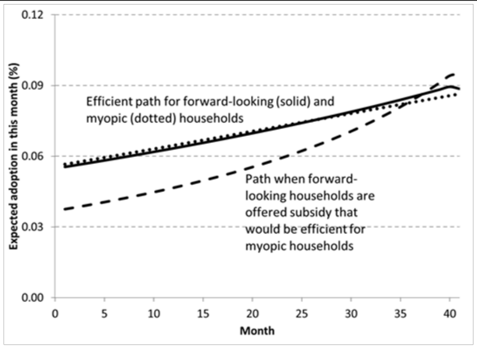
Rather than speculating about why some subsidy trajectories increase strongly, some are flatter, and some decrease, we use the theoretical analysis to precisely decompose the drivers of the efficient subsidy.





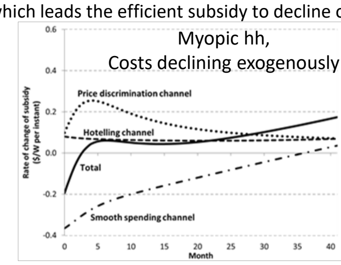
When hh are myopic and tech is fixed, the price discrimination channel drives the subsidy to increase sharply over time.

But when hh are forward-looking, their ability to time adoption constrains the reg's ability to price discriminate. The large, positive price discrimination channel is replaced by a promise-keeping channel that starts at zero and increases only slowly.



If forward-looking households were offered the sharply increasing subsidy designed for myopic households, then many of them would wait for the later, higher subsidies.

Introducing tech change makes the smooth spending channel strongly negative, which leads the efficient subsidy to decline over time.

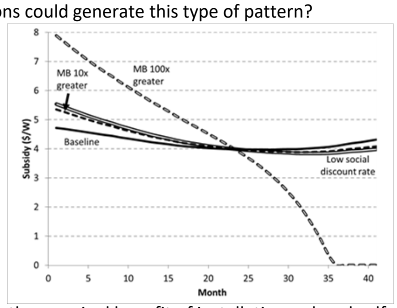


Technological progress increases adoption over time and thus tends to increase the regulator's spending over time for a given subsidy.

A regulator with a convex cost of funds reduces the subsidy over time so as to smooth its spending profile.

Also, note that the price discrimination channel is now weaker because the smaller initial subsidy produces fewer inframarginal households.

But the actual subsidy declined sharply over time. What kinds of assumptions could generate this type of pattern?



Increasing the marginal benefit of installations a hundredfold generates a sharply declining subsidy because the adoption benefit channel becomes large: the regulator values solar so much that she speeds up adoption so as to obtain the benefits sooner, even at the cost of greater spending.

We have demonstrated the forces that determine how to structure a subsidy designed to induce adoption of a new technology over time.

We have shown that if consumers are myopic, then the regulator can reduce its overall spending by using an increasing subsidy schedule as a means of intertemporally price discriminating.

However, if consumers have rational expectations over future subsidies, then their ability to wait for the higher subsidies constrains the regulator's ability to price discriminate.

Quantitatively, these expectations raise the regulator's spending by 9% in the absence of technological change.

Further, rational expectations increase the total cost of the policy program by 50% in a world with technological progress.

Future work should explore the implications of rational expectations and technological dynamics in other policy environments.

Future work should also consider when private decisions to wait are socially inefficient and when regulators may have an incentive to mislead households about future policy or tech change in order to reduce public spending.