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Authors
Torani, Kiran
Rausser, Gordon
Zilberman, David

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Innovation Subsidies versus Consumer Subsidies: A Real Options Analysis of Solar Energy

Kiran Torani, Gordon Rausser, and David Zilberman*

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Abstract

Given the interest in the commercialization of affordable, clean energy technologies, we examine the prospects of solar photovoltaics (PV). We consider the question of how to transition to a meaningful percentage of solar energy in a sustainable manner and which policies are most effective in accelerating adoption. This paper develops a stochastic dynamic model of the adoption of solar PV in the residential and commercial sector under two sources of uncertainty. The analytic results suggest that a high rate of innovation may delay adoption of a new technology if the consumer has rational price expectations. We simulate the model across alternative rates technological change, electricity prices, subsidies and carbon taxes. It is shown that there will be a displacement of incumbent technologies and a widespread shift towards solar PV in under 30 years - and that this can occur without consumer incentives and carbon pricing. We show that these policies have a modest impact in accelerating adoption, and that they may not be an effective part of climate policy. Instead, results demonstrate that further technological change is the crucial determinant and main driver of adoption. Further, results indicate that subsidies and taxes become increasingly ineffective with higher rates of technological change.

JEL codes: C61, O33, O38, Q42, Q47, Q54, Q58
Keywords: Renewable energy; Climate change; Government policy; Technological change

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* Department of Agricultural and Resource Economics, University of California at Berkeley. Email: kirantorani@berkeley.edu. This work was supported by the Energy Biosciences Institute at the University of California, Berkeley.

I. Introduction

The installed capacity of solar PV systems has increased dramatically over the past five years, increasing by 53% per year in the US and by 60% per year globally. While this rapid growth has partly been driven by declining costs in solar, it has primarily been driven by state and federal incentives and policy support.

Current adoption of solar PV systems without incentives remains unlikely. Notwithstanding recent declines, the high cost of solar PV renders it unable to compete with incumbent electricity technologies, even when incorporating benefits of the technology which might not have been previously accounted for (Goodrich et al., 2012; Borenstein, 2008).

Incentives to the residential and commercial sectors (which historically account for approximately 70% of installed capacity in the US) have ranged from up-front cash rebates to renewable portfolio standards, and federal and state tax benefits. Incentives have covered an estimated 3% to 50% of total system cost, and have amounted up to $22,000 per installation (Peterson, 2011).

Yet in 2012 solar energy amounted to little over 1% of generated electricity in the US (EIA, March 2013), and contributed the smallest share amongst all renewable-generated electricity.[2]

If our aim is to speed the commercialization and deployment of affordable, clean energy technologies and transition to market driven industries, then the central question remains - how do we get to a meaningful percentage of solar PV generation in a sustainable way? Will there be a widespread shift towards solar PV, and which policies are effective and which aren't? The question is pertinent, and Chakravorty et al. (1997) suggest that the transition to backstop technologies may be the only viable solution to global warming.

In this paper, we examine the prospects for future adoption of solar PV in the residential and commercial sector, recognizing that what drives the process on a sustainable basis is the consumer's adoption decision. We examine which policies will have an impact in accelerating adoption and what role solar energy will ultimately play in our future energy mix.

We use a stochastic dynamic framework, and develop a theoretic real options model to evaluate the threshold and timing of the consumer's optimal investment decision, given two sources of uncertainty – uncertainty in both the price of electricity and the cost of solar. We derive analytic results regarding the threshold of adoption under alternative regimes of R&D funding and technological change, subsidies and carbon taxes. And we develop an algorithm and simulation

[2] Which is ironic, since solar is by far the most abundant of all the renewable resources.

technique based on a bivariate kernel density estimation to derive projections of the cumulative likelihood and timing of substitution amongst energy resources and towards solar. In this paper, we apply the methodology to solar PV as an illustration of the technique given multiple sources of uncertainty, and provide a general framework to evaluate investments in competing alternative renewable energy technologies.

We use a real options approach (ROA) which is an application of option valuation techniques originally developed in the finance literature (Black and Scholes, 1973), but which has found important applications in natural resource economics (Arrow and Fisher, 1974; Conrad, 1980; Brennan and Schwartz, 1985), environmental economics (Pindyck, 2000), water economics (Carey and Zilberman, 2002), and most recently in renewable energy economics.

ROA is fundamentally a stochastic dynamic framework analyzing investment decisions in the presence of three factors: uncertainty of the economic environment, irreversibility, and the ability to postpone the investment decision (Dixit and Pindyck, 1994). Traditional static "now or never" net present value (NPV) breakeven models of investment have resulted in predictions that have been observed to overestimate investment and adoption. However, a key result of the real options framework is that the investor will require a significant excess return above the expected present value before making the investment in light of these factors.

Most recently, ROA has found applications in evaluating investments in renewable energy technologies, two notable examples being Lemoine (2010) and Schmit, Luo and Conrad (2011). Lemoine (2010) uses option valuation to compute a more complete market valuation of a plug-in hybrid electric vehicle (PHEV) by incorporating the additional benefit derived from the driver's ability to respond to fuel and electricity prices on a daily basis. Schmit et al. (2011) use the real options framework to evaluate combined entry and exit investment decisions in an ethanol plant.

We extend the current literature both methodologically and empirically. Methodologically, based on Dixit & Pindyck (1994), we incorporate two sources of uncertainty as an extension of the traditional single variable model and provide new analytic insights and comparative static results. While both Lemoine (2010) and Schmit et al. (2011) incorporate two stochastic processes in their analysis, both papers do so in a different framework, and Lemoine examines the valuation but not the threshold of adoption, while Schmit et al. use a numerical approximation procedure to solve the optimal switching problem.

Empirically, to our knowledge, this is the first real options paper to examine the question of solar energy. Further, we develop an algorithm and simulation technique based on a bivariate kernel density estimation, which is essential due to the extension of ROA to incorporate two stochastic processes, and which has general applicability and can be used to evaluate investments in alternative renewable energy technologies.

The results of the model show that if assumptions are maintained, there will be a displacement of incumbent technologies and a widespread shift towards solar PV in the residential and commercial sector in under 30 years, across plausible rates of technological change. Projections consistently indicate that this can occur independent of downstream incentives and carbon pricing policies (at \$21/ton CO2, \$65/ton CO2 and \$150/ton CO2) which generally have a modest impact – and may not be an effective part of climate policy in this regard. Further, both consumer subsidies and carbon taxes become more ineffective with higher rates of technological change, making virtually no difference in certain cases. Results demonstrate that further technological change alone is the crucial determinant and main driver of adoption, outweighing the effect of subsidies and taxes. Suggesting that subsidies and taxes don't make a substantial difference in a technology that's not viable – instead that research does. These results are robust across varying levels of interest rates, technological change, electricity price growth, and incentives.

The results suggest several significant policy conclusions: (i) Concerns regarding recently decreasing consumer subsidies dampening the consumer economics of solar adoption are overstated. (ii) Carbon taxes of \$21/ton CO2 and \$65/ton CO2 have a minor impact in accelerating widespread adoption of solar PV as compared to baseline projections. Carbon pricing at \$21/ton CO2 accelerates adoption by an average of 0-3 years, and pricing at \$65/ton CO2 accelerates adoption by an average of 2-5 years, depending on tech advancement scenario. (iii) A carbon tax of \$150/ton CO2 will have a modest impact on accelerating adoption by an average of 6 - 8 years if the recent higher rates of technological advancement in solar PV are maintained. The impact will be more significant in the scenario with historical lower rates of technological advancement, accelerating adoption by an average of 10.5 to 15.5 years. However projections still indicate a widespread shift towards solar within 26-31 years in this scenario.

Results show that R&D support and technological advancement in solar PV is the crucial determinant in accelerating widespread adoption of solar PV and should play a key role in climate policy. Projections indicate that if recent rates of technological change in solar are maintained, there could be a widespread shift towards solar in 25-28 years *without* any subsidies or carbon pricing.

The paper is organized as follows. Section II presents the model of the consumer's adoption decision within a stochastic dynamic framework and two sources of uncertainty. Section III outlines the empirical model, and section IV presents the simulation results and policy implications. Lastly, section V concludes with a discussion of the main results and limitations of the model.

II. The Model

We examine the solar PV adoption decision in the residential/commercial sector, driven by the consumer's objective to minimize costs. The consumer weighs the tradeoff between the cost of the solar PV unit versus the long term price of electricity and the potential cost savings that the investment in the solar unit may provide through the value of the displaced electricity.

We abstract from other factors that may motivate the decision to invest in renewable technologies, including energy security concerns, climate change objectives and a general higher willingness to pay for such. Instead we focus on the basic objective of cost minimization, since it is crucial to consider the situation where the solar PV unit pays for itself as that would have a substantial impact on adoption by individual households/enterprises.

We extend ROA to model the investment decision under uncertainty given two stochastic processes – the price of electricity, and the cost of the solar PV unit. Based on this methodology, a threshold decision rule influenced by the individual drift and volatilities of these two processes is developed.

The Value of a Live Project

The risk neutral consumer's decision to invest in the modern solar technology depends on the tradeoff between the expected present value of the investment and the fixed cost of the investment, represented by the levelized cost of solar electricity (LCOE). The value of the investment is given by the expected potential cost savings from adopting solar as well as the potential revenue from exporting solar generated electricity back to the grid[3], assuming inelastic demand. This is given by:

$$V(P) = E\int_0^{\infty} \big((P - C)(asu) + FIT\,(asp - asu)\big)\, e^{-rt}\, dt \qquad (1)$$

where P is the price of electricity[4], C is the levelized cost of solar electricity, asp is the average amount of solar electricity produced, asu is the average amount of solar electricity used, FIT is the feed in tariff for the excess solar electricity exported back to the grid, and r is the interest rate.

[3] Given the parameterized values of asp > asu.

[4] Under the assumption of a flat rate tariff structure.

This model captures the potential cost savings of the solar generated portion of the total bill. During the hours when solar is not available, the household incurs no potential cost savings and uses grid supplied electricity as usual, since we are not adding any assumptions of storage.

We assume that once the consumer has invested in the solar PV unit, she will not compare electricity prices and the levelized cost of solar on a daily basis, and decide whether to use grid or solar generated electricity depending on the prices. This would resemble a valuation similar to McDonald and Siegel (1985) and Lemoine (2010), but in the case of solar with no variable costs incurred on a daily basis, the assumption is that the user will choose to use the already paid for system first.

The long term price of electricity and cost of solar are uncertain, and may be represented by Geometric Brownian Motion (GBM) processes[5] such that:

$$dP = \alpha_P P dt + \sigma_P P dz_P \qquad (2)$$

$$dC = \alpha_C C dt + \sigma_C C dz_C \qquad (3)$$

Where α_P and α_C are the drift rates for the price of electricity and cost of solar processes, and σ_P and σ_C are the volatility measures respectively, and dz_P and dz_C are increments of a Wiener processes. $E[P(t)] = P_0 e^{\alpha_P t}$ and $E[C(t)] = C_0 e^{\alpha_C t}$ where $P(0) = P_0$ and $C(0) = C_0$. And $E[dz_P^2] = E[dz_C^2] = dt$ as well as $E[dz_P dz_C] = \gamma dt$, where γ denotes the correlation coefficient between P and C. Notably, technological change and an advancements in solar PV implies that α_C is negative, and an increasing rate of technological change implies α_C will become increasingly negative.

Although the price of electricity and cost of solar are both uncertain, once the investment is made, and the technology is adopted, future evolution of the cost of solar becomes irrelevant. Hence, the value of a live project, once adopted is given by:

$$V(P) = \frac{P * asu}{(r - \propto_p)} - \frac{C * asu}{(r)} + \frac{FIT\ (asp - asu)}{(r)} \qquad (4)$$

[5] A discussion of the GBM assumption is included in section III.

In the traditional NPV investment model, the consumer will invest if $V(P) \geq 0$, i.e. if the expected present value is positive[6]. Hence, the threshold price at which adoption occurs is given by:

$$P^*_{NPV} = \left(\frac{C * asu - \; FIT * s}{r}\right)\left(\frac{r - \propto_p}{asu}\right) \qquad (5)$$

where $s = \; (asp - asu)$, i.e. the difference between the amount of solar electricity produced and used.

Intuitively the consumer is more likely to adopt (i.e. P^*_{NPV} decreases) as the difference between the amount of solar produced and used increases, and as FIT increases due to the revenue potential. She is less likely to adopt the nascent technology as the LCOE and the total life cycle costs of the solar system increase.

However, in practice consumers often require that the investment benefit exceeds the cost by a positive hurdle rate, which is not accounted for in the traditional NPV model, but which will invariably have consequences for the adoption potential of a technology.

The Value of the Option to Invest

When considering the value of the option to invest, the consumer will have to consider both the price of electricity and the cost of solar as random variables, i.e. they have the option to invest if the price of electricity should rise in the future and/or the cost of solar PV should fall.

This yields a dynamic programming problem, and specifically an optimal stopping problem where the option to invest is a function of both these variables, i.e. $F(P, C)$ and where one has to find the region of values of (P, C) where investment will occur, not occur and the critical boundary that separates these two regions.

In the continuation region in which it is optimal to hold onto its option to invest, the Bellman equation is given by:

$$rFdt = E[dF] \;\; where \; F(P, C) \qquad (6)$$

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[6] As the levelized cost of electricity from solar includes the total life cycle costs (TLCC) of the system.

since there is no current period payout from holding the option. Equation (6) states that over the interval dt, the return of the investment opportunity is equal to its expected rate of capital appreciation.

Using Ito's lemma to expand dF, yields:

$$dF = F_P dP + F_C dC + \frac{1}{2}(F_{PP}(dP)^2 + 2F_{PC} dP dC + F_{CC}(dC)^2) \qquad (7)$$

Which, substituting for $dP$and dC and rearranging, yields:

$$E[dF] = \alpha_P \mathrm{P} F_P dt + \alpha_C \mathrm{C} F_C dt + \frac{1}{2}(F_{PP}\sigma_{\mathrm{P}}^2 P^2 + 2F_{PC}\gamma\sigma_P\sigma_C PC + F_{CC}\sigma_{\mathrm{C}}^2 C^2)dt \qquad (8)$$

Where $E[dz_P] = E[dz_C] = 0$ and where γ is the correlation coefficient between P and C.

Given (8) the Bellman equation now becomes:

$$\alpha_P \mathrm{P} F_P + \alpha_C \mathrm{C} F_C + \frac{1}{2}(F_{PP}\sigma_{\mathrm{P}}^2 P^2 + 2F_{PC}\gamma\sigma_P\sigma_C PC + F_{CC}\sigma_{\mathrm{C}}^2 C^2) - rF = 0 \qquad (9)$$

Which applies over the region of (P, C) space where it is optimal to leave the option unexercised.

Over the region where the option is immediately exercised, we have the relevant value matching and smooth pasting conditions. However the boundary is itself unknown, and must be determined together with the solution for the function satisfying (9).

Consistent with Dixit & Pindyck (1994), since the option function is homogeneous of degree 1 in P and C, the optimal decision should therefore depend only on the ratio k≡P/C, enabling us to write:

$$F(P, C) = Cf\left({}^{P}/_{C}\right) = Cf(k) \qquad (10)$$

Where $f(k)$is now the function to be determined. The corresponding partials are given by:

$$F_P(P,C) = f'(k)$$

$$F_C(P,C) = f(k) - kf'(k)$$

$$F_{PP}(P,C) = f''(k)/C$$

$$F_{PC}(P,C) = -kf''(k)/C$$

$$F_{CC}(P,C) = k^2 f''(k)/C$$

And substituting these in the Bellman equation (9) yields:

$$\frac{1}{2}(\sigma_{\mathrm{P}}^2 - 2\gamma\sigma_P\sigma_C + \sigma_{\mathrm{C}}^2)k^2 f''(k) + (\delta_C - \delta_P)kf'(k) - \delta_C f(k) = 0 \qquad (11)$$

where $\delta_P = (r - \alpha_{\mathrm{P}})$ and $\delta_C = (r - \alpha_{\mathrm{C}})$

The solution for $f(k)$ subject to the relevant boundary conditions:

$$f(0) = 0 \qquad (12a)$$

$$f(k) = \frac{k * asu}{(r - \alpha_{\mathrm{P}})} - \frac{asu}{r} + \frac{FIT * s}{C * r} \qquad \text{(12b)}^{7}$$

$$f'(k) = \frac{asu}{(r - \alpha_{\mathrm{P}})} \qquad \text{(12c)}^{8}$$

has the following form analogous to the one variable case:

$$f(k) = A_1 k^{\beta_1} \qquad (13)$$

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[7]The value matching condition.
[8]The relevant smooth pasting condition.

$$\text{where } \beta_1 = \tfrac{1}{2} - (\delta_C - \delta_P)/\sigma^2 + \{ [\tfrac{(\delta_C - \delta_P)}{\sigma^2} - \tfrac{1}{2}]^2 + [(2\delta_C)/\sigma^2]\}^{1/2}$$

$$\text{and } \sigma^2 = (\sigma_{\mathrm{P}}^2 - 2\gamma\sigma_P\sigma_C + \sigma_{\mathrm{C}}^2) .$$

Solving these equations yields the optimal investment threshold value k^* and P_{ROA}^*:

$$k^* \equiv P/C = \left(\frac{\beta_1}{\beta_1 - 1}\right)\left(\frac{asu}{r} - \frac{FIT * s}{Cr}\right)\left(\frac{r - \propto_p}{asu}\right) \qquad (14)$$

$$P_{ROA}^* = \left(\frac{\beta_1}{\beta_1 - 1}\right)\left(\frac{C * asu - FIT * s}{r}\right)\left(\frac{r - \propto_p}{asu}\right) = \left(\frac{\beta_1}{\beta_1 - 1}\right)P_{NPV}^* \qquad (15)$$

For $P < P_{ROA}^*$ the household holds onto its option to invest and for $P \geq P_{ROA}^*$ the household exercises its option and invests in solar PV. Since $\beta_1 > 1$, and since $P_{ROA}^* = \left(\frac{\beta_1}{\beta_1 - 1}\right)P_{NPV}^*$, hence $P_{ROA}^* > P_{NPV}^*$. Thus, when accounting for irreversibility, uncertainty and the ability to wait, the household requires a higher price than given by the standard NPV rule before they are willing to invest.

While a key result of the real options model has been to illustrate the effect of increased uncertainty on delaying investments, we extend the analysis to illustrate two significant dynamics that emerge - providing further insight into the differing paradigms of the NPV and ROA models of investment.

Proposition 1 *A higher rate of technological change in the nascent technology* <u>*delays*</u> *adoption in ROA - resulting in an increase the k* threshold by increasing the excess return required by the consumer before she is willing to give up the option to invest.*

This is illustrated in fig. 1 in terms of the k* threshold ratio, indicating that the consumer will adopt later, at a higher price of electricity for a given cost of solar, i.e. she demands a higher premium before adopting the nascent technology.

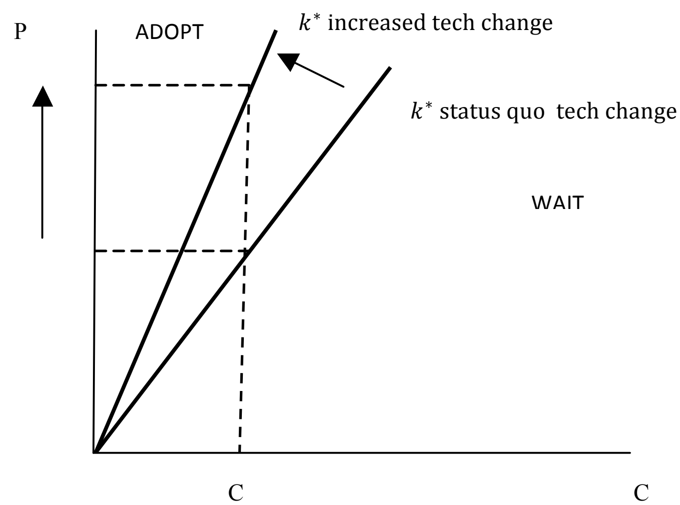

Fig. 1: k* Separating Region of Adoption and Waiting

This is a counterintuitive result of increased funding, R&D productivity and technological change, which are ultimately intended to promote adoption. On one hand, the asset has become cheaper – hence one would expect the consumer to be more likely to adopt the technology, and adopt it sooner. However, if the rate of cost decline increases, waiting instantly becomes more valuable and giving up the option to wait becomes more costly, hence the user will require a higher premium to give up this option. This is entirely consistent with the energy efficiency gap observed in consumer behavior.

This captures the essence of ROA, i.e. the tradeoff between immediate payoff, versus capital appreciation and the payoff associated with such. Postponing the investment entails giving up immediate payoff for the benefit of capital appreciation. And with the increased capital appreciation, giving up the option to invest becomes more costly.

Specifically, this effect is driven by the term $(\alpha_P - \alpha_C)$ the equation for β: [9]

$$\beta = \frac{1}{2} - \underbrace{(\alpha_P - \alpha_C)}_{\text{delay}}/\sigma^2 + \{ [\underbrace{\frac{(\alpha_P - \alpha_C)}{\sigma^2}}_{\text{adopt sooner}^{10}} - \frac{1}{2}]^2 + [2(r - \alpha_C)/\sigma^2]\}^{1/2}$$

[9]The term $(r - \alpha_C)$ encourages adoption unambiguously by discounting the cost of solar more in present value terms.

[10] If $\frac{(\alpha_P - \alpha_C)}{\sigma^2} > ½$.

The term $(\alpha_P - \alpha_C)$ represents the wedge between the price of electricity and cost of solar as illustrated in figure 2. An increase in this wedge essentially lends value to both the adoption of the asset, as well as to the value to waiting. The net effect is the one that dominates between the two. The condition for $\alpha_C \downarrow => \beta \downarrow$ is evident given the comparative statics for beta[11].

$$\frac{\partial \beta}{\partial \alpha_c} = \frac{1}{\sigma^2} - \frac{1}{\sigma^2}\left[\frac{(\alpha_P - \alpha_C)}{\sigma^2} + \frac{1}{2}\right] + \frac{1}{2}] / \{ [\frac{(\alpha_P - \alpha_C)}{\sigma^2} - \frac{1}{2}]^2 + [2(r - \alpha_C)/\sigma^2]\}^{1/2}$$

Where $\frac{\partial \beta}{\partial \alpha_c} > 0 \ iff \ r > \alpha_P$

And $\frac{\partial \beta}{\partial \alpha_c} \leq 0 \ iff \ r \leq \alpha_P$

given that β is the positive root of the fundamental quadratic

The relationship between r and α_P determines the switching condition independent of the relative magnitudes of α_P versus α_C, i.e. the rate of increase in price of electricity versus the rate of decrease in cost of solar. Intuitively, this result signifies that one will postpone to reap the benefits of further technological change in solar as long as it isn't prohibitively expensive to do so, i.e. as long as the price of electricity is not increasing at an increasing rate (in present value terms) while postponing the investment[12].

By comparison, the NPV threshold of investment remains unchanged irrespective of the rate of technological change, since it is a static "now or never" proposition and doesn't consider the option of postponing the investment decision and further technological change in the nascent technology.

[11] Unambiguously $\beta \downarrow => (\frac{\beta}{\beta-1}) \uparrow$ given beta is the positive root of the fundamental quadratic.

[12] One will postpone adoption if the price of electricity and cost of solar are both decreasing at a decreasing rate. Irrespective of the relative magnitudes of the rates of change and by virtue of their signs, the rate of decay of the cost of solar is greater than that of the price of electricity, in present value terms.

Proposition 2 *An increase in the interest rate <u>encourages</u> adoption in ROA - resulting in a lower k* threshold.*

This is a counterintuitive result, and contrary to the standard NPV calculation in which an increase in the interest rate delays adoption, by discounting the future value of the investment at a higher rate and breaking even later.

$$r \uparrow => P^*_{NPV} \uparrow$$

$$r \uparrow => k^* \downarrow$$

The comparative statics illustrate that β will always increase with an increase in the interest rate, implying a decrease in the hurdle rate[13].

$$\frac{\partial \beta}{\partial r} = \frac{1}{\sigma^2} \frac{1}{\{ [\frac{(\alpha_P - \alpha_C)}{\sigma^2} - \frac{1}{2}]^2 + [2(r - \alpha_C)/\sigma^2]\}^{1/2}} > 0$$

$$r \uparrow => \beta \uparrow => (\frac{\beta}{\beta - 1}) \downarrow$$

However, the key lies in recognizing that k* is composed of two opposing dynamics, which would further indicate that *ROA <u>should not</u> be as sensitive to the interest rate as NPV.*

$$k^* = \frac{\left(\frac{\beta}{\beta-1}\right)\downarrow \; P^*_{NPV} \uparrow}{C}$$

Intuitively, the hurdle rate always decreases with an increase in the interest rate because a higher interest rate implies that the current loss from postponing increases, while the future gain from postponing decreases. The net effect is a decrease in k*.

[13] The hurdle rate is given by the expression $\left(\frac{\beta}{\beta-1}\right)$, and is defined as the excess return required above the standard NPV calculation which determines the optimal investment threshold in ROA, as illustrated in equation (15).

If however, the rate of technological change in solar were extremely low, such that the gain from postponing decreases further, this effect would drive down the hurdle rate further (consistent with Proposition 1) and k* could *increase* with an increase in the interest rate – in which case the NPV effect would dominate, and ROA would approach NPV.

$$k^* = \frac{\left(\frac{\beta}{\beta-1}\right)\downarrow\downarrow\ P^*_{NPV}\uparrow}{C}$$

$$r\uparrow \Rightarrow k^*\uparrow$$

$$P^*_{ROA} \rightarrow P^*_{NPV}$$

Similarly, if uncertainty were to tend to zero, ROA would approach NPV

$$\sigma^2 \rightarrow 0 \Rightarrow \left(\frac{\beta}{\beta-1}\right) \rightarrow 0$$

$$P^*_{ROA} \rightarrow P^*_{NPV}$$

illustrating that without option value, the mean effect is significant. With option value, both the mean and variance effects are significant. In the NPV scenario, a high interest rate reduces future value making adoption less likely. While in ROA, a high interest rate reduces the cost of high variance in the future, making adoption more likely[14]. In ROA the variance effect dominates - illustrating the differing paradigm of the two investment rules.

III. Empirical Model

The long term price of electricity and the cost of the solar PV unit are assumed to be uncertain, while all other inputs are modeled deterministically. The model is evaluated with a flat rate tariff structure for the price of electricity rather than time of use/real time pricing tariff rate structures.

14 Given the assumptions of GBM, the mean grows linearly with time, while the variance grows at a quadratic rate.

While there are numerous papers discussing the economics of solar PV with different tariff rate structures (Borenstein, 2007), we abstract from such issues and consider the base case of flat rate structure.

Price of Electricity

There have been numerous studies examining prices in electricity markets and the stochastic processes they may follow (Deng, 2000). Some studies contend that electricity price data might not be well represented by traditional commodity price models of GBM due to the fact that on-peak electricity spot prices are highly volatile and strongly mean reverting, while GBM does not capture this dynamic.[15]

However, Schwartz and Smith (2000) and Pindyck (2001) contend that for considerations of long term investment decisions, the long term factor is the decisive one, and GBM assumptions are appropriate even if they might ignore short term mean reversion in the price dynamics.

Consistent with this, we model the long-term electricity price process as a GBM process with the parameters based on futures contracts for PJM Interconnection Electricity Futures traded on the NYMEX[16].

The annual growth rate of the long term price of electricity is estimated from PJM electricity futures contracts for four consecutive years 2014-2017. Consistent with Fleten (2007), according to the GBM process the expected price of electricity evolves according to $E[P(t)] = P_0 e^{\alpha_P t}$ where α_P represents the annual rate of growth in the price of electricity, estimated as 2.89% using an exponential regression.

The annual historic volatility, which is a measure of the variance of the price distribution, is estimated using daily historical futures price changes of the daily prices of one-month ahead PJM electricity futures contracts traded three years in advance at the NYMEX. We have used prices for the trading period March 2009 – Feb 2013, such that the prices are for futures contracts delivery in March 2012 – Feb 2016. The resulting annual volatility was estimated as $\sigma = 14.09\%$.

In addition, as the future evolution of the price of electricity is crucial to the results, we also conduct simulations with electricity price parameters based on historical EIA average real residential and commercial electricity prices, for the years 1990 – 2002 and 2003 – 2009,

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15 Suggesting that combining a jump process with mean reversion can capture the salient features of daily electricity spot prices where GBM can't.

16 The PJM Interconnection, LLC, administers the largest electricity market in the world serving more than 44 million customers in the US.

resulting in much lower annual electricity growth rates of -0.2479% and 0.2011% respectively[17]. We discuss these results in addition to the results based on futures estimates, and present details in Appendix A.

Cost of Solar

Estimates of plausible rates of technological advancement in solar PV are based on historic installed cost data in the US (Barbose et al., 2012) as well as on expert elicitation (Rausser et al., 2010) to explore the possible link between R&D funding levels and technological advancement in solar, at two different levels.

Historic installed prices of solar PV units (<= 10kW) have exhibited a dramatic decline in costs in recent years in the US, driven primarily by falling module costs. Recent estimates of price declines for the period 2008-2011 indicate a decline of -11.20% per year, while the period 2009-2011 indicates an even higher decline of -14.20% per year.

Notwithstanding this recent precipitous decline in prices, we base our estimate of the long term historic rate of price declines on average declines exhibited during the period 1998-2011, corresponding with an annual growth rate of -4.41% in the cost of solar. And we base our estimates of the recent higher rate of cost declines observed during the years 2007-2011 as -9.30%, thereby adopting a more conservative view of rates that could plausibly be maintained in the future.

In addition, we perform expert elicitation to capture the possible impact of a modest increase in R&D spending levels on the corresponding rate of technological change, as an indication of optimal R&D funding levels.

Public R&D funding for solar has in general remained flat for the past two decades (mid 1980's – 2008) at an average level of $115 million per year. There has however been a recent spike in general R&D funding for renewable energy due to the Recovery Act in 2009, and an associated increase in solar funding at $417 million in 2009, $359 million in 2010, and $403 million in 2011.

We performed expert elicitation based on a random sample of renewable-energy experts working on technical/scientific breakthroughs in solar PV, drawing from public, private, and academic research institutions. Probability distributions of future costs were elicited for two scenarios: (i) A public R&D funding level of $115 million per year as a representation of baseline historic R&D funding levels. (ii) A scenario with a 50% increase in R&D spending levels corresponding with a funding level of $173 million per year.

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[17] The estimated real annual electricity growth rate for the time period 1990 – 2012 was 0%.

The elicited estimates were fitted to a distribution using R/SHELF software and aggregated using a linear pool. Linear regressions were fitted to obtain estimates of annual drift rates for baseline/status quo funding scenario as well as increased funding scenarios. The results were $\alpha_{C\ SQ}$= - 0.044/yr (a growth rate of -4.4% annually) for status quo funding, corresponding very closely with the historic rate of price declines based on Barbose et al. (2012), and $\alpha_{C\ IN}$= - 0.0563/yr (a growth rate of -5.63% annually) for the increased funding scenario.

Investment Cost

The current investment cost of a 10kW DC solar PV system[18] and corresponding levelized cost of electricity (LCOE) are based on California Energy Commission estimates.

Table 1 presents the average installed price of solar PV ($2012) given differing discount rates, including installation and replacement of inverters over the assumed 25 year lifetime of the solar unit, assuming a 1% aging factor per year in the output of the PV unit. Current average retail inverter cost for a 10kW system lies at approx. $7120, and we assume that costs will decline by 2% per year, consistent with Wiser et al., (2006) and Borenstein (2008).

Table 1 - Investment Cost and LCOE for a 10kW Solar PV Installation

Annual Real Interest Rate	**3%**	**5%**
Cost of PV Installation	$56,000	$56,000
Inverter replacement cost (8 yrs)	$6057	$6057
Inverter replacement cost (16 yrs)	$5153	$5153
Discounted Present Cost	**$63,993**	**$62,460**
Levelized Cost (per MWh)	**$295**	**$353**

Average Amount Produced

The parameter for average amount of solar electricity produced is based on estimates provided by Borenstein (2008). The data is based on TRNSYS simulations for production from a 10kW (DC) solar PV installation in San Francisco, Sacramento, and Los Angeles over the course of one year, in conjunction with weather data from the U.S. National Renewable Energy Laboratory (NREL), assuming the panels were mounted at a 30 degree tilt facing different directions, and a 16% derate conversion factor. The TRNSYS model produced hourly simulated production data

18 Corresponding with a large residential and small commercial system.

for one year, resulting in averages that ranged from 1.349 -1.650 (kWh/hr – AC). We use an estimate of 1.499 kWh/hr, representing an annual 13139 kWh of solar electricity produced.

Average Amount Used

One would ideally base the parameter for average amount of solar PV used on real usage patterns of households with installed solar PV units. However absent such detailed data, a next best estimation is made based on the fact that demand peaks at hours during the day and seasons during the year when solar production peaks.

Hence, given the broad overlap, we base our parameters on average U.S. household consumption. EIA estimates for the average annual electricity consumption for a U.S. residential utility household in 2011 was 11,280 kWh, averaging 940 kWh per month. Louisiana had the highest annual consumption at 16,176 kWh and Maine the lowest at 6,252 kWh.

Solar Feed in Tariff Rates

The parameter used for the FIT rates are based on the CA PUC for different renewable energy technologies, including Solar. Feed-in tariffs are closely associated with solar PV panels, designed to encourage the adoption of renewable energy technologies. Under the feed-in-tariff, regional or national electric grid utilities are obliged to buy electricity generated from renewable energy sources and pay a guaranteed purchase price set in a long-term (10–25 year) contract. As of 2009, FIT policies have been enacted in sixty three countries, including over a dozen states in the United States.

We base our FIT parameter on the CA PUC rates effective January 2012, which range from \$0.07688/kWh - \$0.12326/kWh, depending on the contract start date and the length of the contract. We use an estimate of \$0.097412/kWh as a baseline parameter, representing the average rate for a 25 year contract, ignoring time of delivery (TOD) adjustment factors.

Average Historic Consumer Subsidies

Incentives to the residential and commercial sector (which have historically accounted for approximately 70% of solar generation) have ranged from up-front cash rebates, to renewable portfolio standards, and federal and state tax benefits. Incentives have coved an estimated 3% - 50% of total system cost (Peterson, 2011), ranging from \$500 - \$22,000 per installation in the states surveyed, averaging at \$14500 per installation.

Carbon Taxes

Carbon taxes remain controversial and surrounded by considerable uncertainty, and to date have not been enacted in the US on a national scale.

Aside from controversy regarding efficacy, growth and distributional effects, estimates of the of the social cost of carbon (SCC) themselves remain highly uncertain due to the underlying uncertainties in the science of climate change science, choice of discount rates, and valuation of economic impacts (Pindyck, 2013).

Current US government and NBER estimates set the SCC for 2010 at $21/ton CO2 ($2007) and $65/ton CO2 ($2007) representing estimates of "most likely" scenario and "potential higher-than expected" impacts respectively (Greenstone et al., 2011; Interagency Working Group, 2010). However, there is considerable disagreement regarding these estimates.

Pindyck (2013) asserts that while $21/ton CO2 or $65/ton CO2 estimates might provide a reasonable estimate of "most likely outcomes" and plausible events, they fail to assess more extreme outcomes and capture the possibility of catastrophic climate outcomes - which should be of major concern, and which might lead to a SCC as high as $100-$200/ton CO2.

Given the debate regarding the correct SCC, we measure the impact of carbon pricing policies at $21, $65 and $150/ton CO2.

We estimate the threshold of adoption under both the standard NPV investment rule as well as the ROA rule for various funding and technological advancement trajectories for a representative 10kW solar PV system, and examine the sensitivity of the hurdle rate and threshold of investment to uncertainty and correlation parameters.

Based on the results and parameters from the previous two sections (table 2), we illustrate how the price of electricity at which adoption of solar PV will occur exceeds that of the standard NPV calculation by a positive hurdle rate, which captures the excess return the consumer will require before making the irreversible investment:

$$P_{ROA}^{*} = \left(\frac{\beta_1}{\beta_1 - 1}\right) P_{NPV}^{*} \qquad (15)$$

Consistent with propositions 1 and 2, we illustrate how (i) Increased R&D funding and technological advancement in solar PV will lead to *delayed* adoption. (ii) An increase in the interest rate will *encourage* adoption in the ROA model.

Table 2 - Baseline Parameter Values (r = 3%)

Baseline Parameter Values	
C = \$0.295/kWh	P0 = \$ 0.1162/kWh
FIT = \$0.097412/kWh	$\gamma = 0$
asp = 13136 kWh/yr	asu = 11280 kWh/yr
α_P= + 0.0289/yr	σ_P= 0.1409/yr
$\alpha_{C\ SQ}$= - 0.0441/yr	$\sigma_{C\ SQ}$= 0.1409/yr
$\alpha_{C\ 50\%\ Incr}$= - 0.0563/yr	$\sigma_{C\ 50\%\ Incr}$= 0.1409/yr
$\alpha_{C\ High}$= - 0.093/yr	$\sigma_{C\ High}$= 0.1409/yr

Note: P0 is based on EIA "Electric Power Monthly Feb 2013" average retail price to residential consumers.

The baseline results are illustrated in tables 3 and 4 for r = 3% and 5% respectively, including the main result of the ROA k* threshold ratio - the constant ratio of P/C which separates the waiting region and adoption region (see fig. 1).

Table 3 - ROA Results for Baseline Parameters (r = 3%)

$\boldsymbol{\alpha_C}$	$\boldsymbol{\beta}$	**Hurdle Rate** $\left(\frac{\beta}{\beta-1}\right)$	$\mathbf{P^*_{ROA}} = \left(\frac{\beta}{\beta-1}\right)\mathbf{P^*_{NPV}}$	$\boldsymbol{k^*}$
-0.0441	1.012	85.62	\$0.876/kWh	**2.97**
-0.0563	1.0104	96.69	\$ 0.989/kWh	**3.35**
-0.093	1.0078	130.00	\$ 1.3298/kWh	**4.51**

Note: Drift rates α_C are presented on annual basis. P*npv = \$0.0102/kWh, C = \$0.295/kWh.

Table 4 - ROA Results for Baseline Parameters (r = 5%)

$\boldsymbol{\alpha_C}$	$\boldsymbol{\beta}$	**Hurdle Rate** $\left(\frac{\beta}{\beta-1}\right)$	$\mathbf{P^*_{ROA}} = \left(\frac{\beta}{\beta-1}\right)\mathbf{P^*_{NPV}}$	$\boldsymbol{k^*}$
-0.0441	1.2172	5.6049	\$0.797/kWh	**2.258**
-0.0563	1.1938	6.1611	\$0.8761/kWh	**2.482**
-0.093	1.1459	7.855	\$ 1.1171/kWh	**3.164**

Note: Drift rates α_C are presented on annual basis. P*npv = \$0.142/kWh, C = \$0.353/kWh.

In the baseline, the threshold price of adoption given by the standard NPV investment rule is P* electricity = \$0.0102/kWh for r=3%, and \$0.142/kWh for r= 5% (while LCOE from solar is \$0.295/kWh and \$0.353/kWh respectively) indicating the extreme sensitivity of NPV to interest rate assumptions. Furthermore, the NPV calculation remains the same between all three technological change scenarios since NPV is essentially a static, “now or never” calculation – which doesn’t incorporate the dynamic features of ROA.

The corresponding ROA threshold calculations are dependent on the rate of technological change in solar. The hurdle rate across all scenarios is significant, illustrating the large discrepancy between the two investment rules, i.e. by failing to account for the influence of uncertainty and irreversibility the NPV rule is biased in favor of early investment.

Consistent with proposition 1, an increase in the rate of technological change results in a higher k*, indicating delayed adoption. Consistent with proposition 2, and contrary to the standard NPV result, an increase in the interest rate (for a given level of technological change) results in a lower k* threshold – thereby encouraging adoption in the sense that ROA is approaching NPV.

Most importantly, given the P*roa and k* threshold results, for every price of electricity one can calculate the corresponding level of the cost of solar that will trigger adoption as illustrated in tables 5 and 6 for the historic lower rate of technological advancement and recent higher average cost decline scenarios respectively.

Table 5 – Threshold of Adoption for Historic Lower Rate of Technical Change (r = 3%)

$\left(\frac{\beta}{\beta-1}\right)$	K* = P/C	P Electricity ($/kWh)	C Solar ($/kWh)
85.62	**2.97**	0.876	0.295
85.62	**2.97**	0.743	0.25
85.62	**2.97**	0.594	0.20
85.62	**2.97**	0.297	0.10
85.62	**2.97**	0.149	0.05

Table 6 – Threshold of Adoption for Recent Higher Rate of Technical Change (r = 3%)

$\left(\frac{\beta}{\beta-1}\right)$	K* = P/C	P Electricity ($/kWh)	C Solar ($/kWh)
130	**4.51**	1.330	0.295
130	**4.51**	1.128	0.25
130	**4.51**	0.902	0.20
130	**4.51**	0.451	0.10
130	**4.51**	0.226	0.05

Robustness Analysis

The sensitivity of P* roa and the k* threshold to uncertainty and correlation parameters are as anticipated (see table 7). A decrease (increase) in uncertainty, i.e. in σ_C or σ_P parameters, reduces (increases) the k* threshold ratio as compared to baseline values, implying sooner (delayed) adoption. ROA illustrates that uncertainty can have impact on investment independent even under risk neutrality.

A positive correlation of 0.3 between the price of electricity and cost of solar instead of the baseline assumption of no correlation, results in earlier adoption and a lower hurdle rate and k* threshold ratio, given the covariance of the variables. Correspondingly, a negative correlation of -0.3 between the price of electricity and cost of solar, results in delayed adoption and a higher hurdle rate and k* threshold.

Table 7 - Robustness Analysis Results (r=3%)

Parameter	**Value (old→ new)**	**Hurdle Rate $\left(\frac{\beta}{\beta-1}\right)$**	k^*
σ_C or σ_P (↓)	0.1409 → 0.10	81, 92, 125	**2.812, 3.196, 4.35**
σ_C or σ_P (↑)	0.1409 → 0.20	94, 105, 139	**3.29, 3.67, 4.82**
γ (↑)	0 → 0.30	80, 91, 124	**2.77, 3.16, 4.32**
γ (↓)	0 → - 0.30	91, 102, 135	**3.16, 3.54, 4.69**
Baseline Values		85.62, 96.69, 130	**2.97, 3.35, 4.5**

Note: All else constant at baseline values. Hurdle rate and k* are presented for three technological change scenarios (i.e. α_C = -0.0441, -0.0563 and -0.093) respectively.

IV. Results and Implications

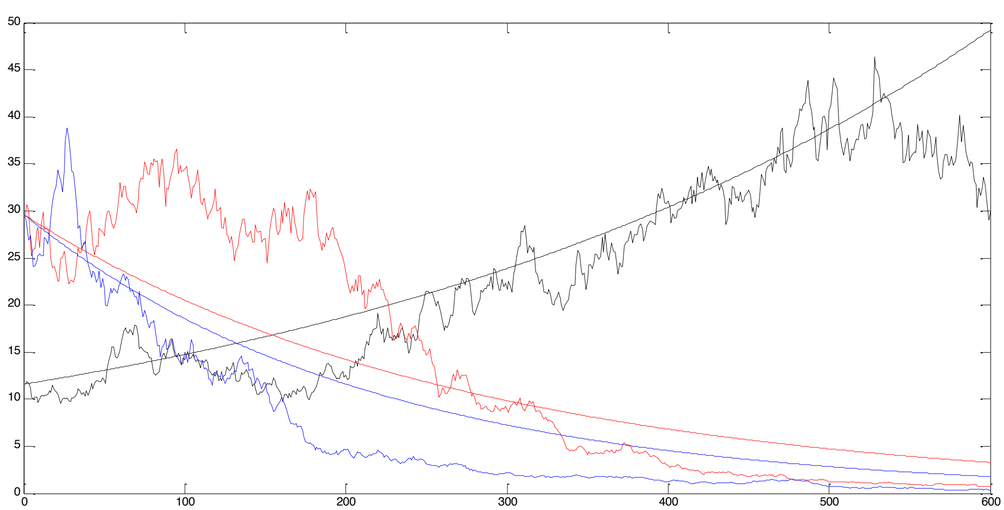

Fig. 2: Single Realization of GBM Stochastic Processes for the Price of Electricity and Cost of Solar

For illustrative purposes, we include figure 2 to show a single realization of the stochastic GBM price processes over 50 years, for the base case scenario free of any incentives or carbon pricing. In this realization, the price of electricity and the cost of solar for two alternative technological change assumptions are shown, together with the corresponding deterministic trend lines.

The relevant baseline k* threshold values of 2.97 and 3.35 for the respective trajectories can be seen as the ratio required between the price of electricity and cost of solar at a given time that will trigger adoption, thus translating the analytic results of the previous section into a threshold measure of time.

We base our results on 1000 realizations of each GBM stochastic price process, and develop an algorithm and simulation model based on a bivariate kernel density estimation to assess the joint distribution of the price and cost realizations, and corresponding k* distribution at each time step. This is crucial, as the extension of ROA to incorporate two stochastic processes renders the k* threshold of adoption as a ratio two unknown distributions at each time step.

Given the random nature of the distribution of prices, our analysis allows us to estimate the cumulative distribution of adoption (figures 3 – 5) as a function of various policy parameters, which has previously not been done with the real options approach. These estimates provide key information to assess the net social benefit from investments in R&D and consumer subsidies.

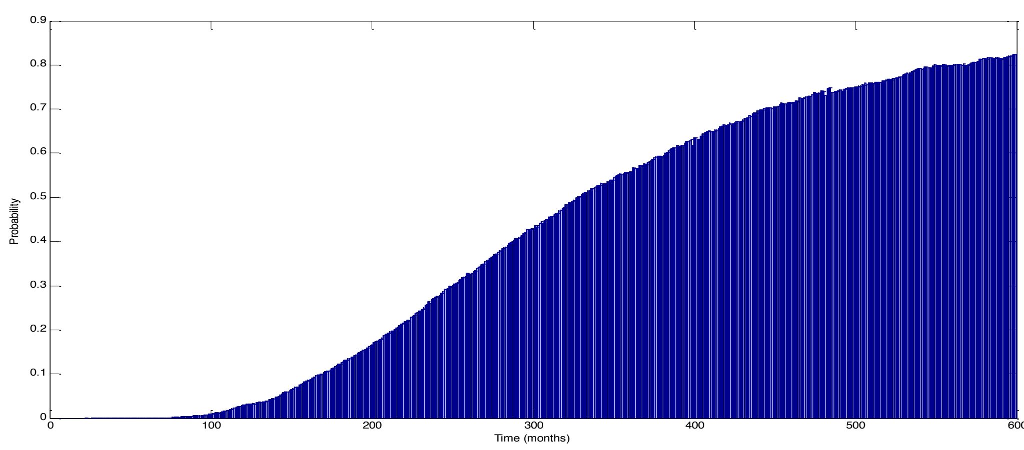

Fig. 3: Cumulative Likelihood and Timing of Adoption
Historic Lower rate of Technological Change in Solar Energy (r= 3%, $\alpha_C = -0.048$)

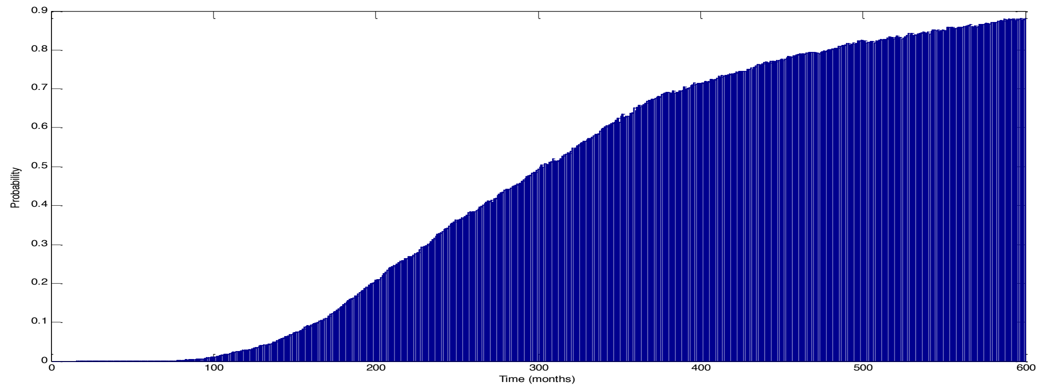

Fig. 4: Cumulative Likelihood and Timing of Adoption
50% Increased Funding and Technological Change in Solar Energy (r= 3%, $\alpha_C = -0.056$)

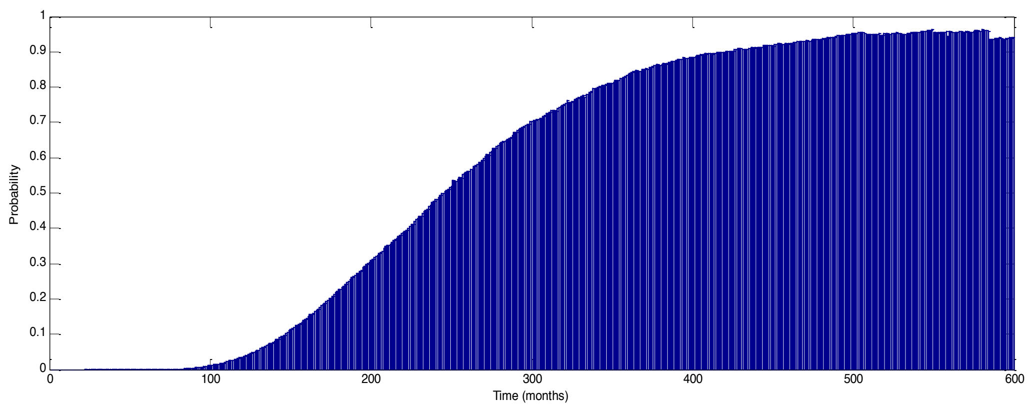

Fig. 5: Cumulative Likelihood and Timing of Adoption
Recent Higher Rate of Technological Change in Solar Energy (r= 3%, $\alpha_C = -0.093$)

We analyze the following scenarios based on baseline parameter values (table 2): (i) Baseline results for alternative solar R&D funding and technological change scenarios without consumer incentives or carbon pricing. This includes three technological change scenarios - a historic lower technological advancement in solar scenario corresponding with status quo R&D funding, a 50% increase in R&D funding corresponding with a modest increase in technological advancement as based on expert elicitation, and a third scenario corresponding with recent higher rates of technological advancement reflecting average cost declines observed during 2007-2011. (ii) The impact of historic average consumer subsidies of $14500 given alternative assumptions of technological change. (iii) The impact of $21/ton CO2, $65/ton CO2 and $150/ton CO2 carbon pricing given alternative assumptions of technological change.

In addition, we perform simulations for alternative electricity price parameters of -0.2479% and +0.2011% based on EIA historical average residential and commercial electricity prices (for the years 1990-2002 and 2003-2009 respectively). The results for these simulations are presented in

Appendix A, however in general they indicate the following: (i) As expected, a low or negative evolution of the price of electricity delays adoption considerably. (ii) Both consumer subsidies and carbon taxes display a modest increase in impact with lower growth rates of electricity prices. (iii) However, results remain consistent across all scenarios of differing electricity price trajectories with overall results demonstrating that further technological change is the crucial determinant and main driver of adoption.

Table 8 – Baseline Results for Likelihood and Timing of Adoption & Impact of Average Historic Consumer Incentives (r=3%)

PELEC +2.89%	**BASELINE**			**AV. CONSUMER INCENTIVES**		
Likelihood of Adoption	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)
10%	13y 9m	13y 5m	12y 1m	10y 11m	10y 10m	10y 4m
40%	23y 9m	22y 0m	18y 7m	20y 3m	18y 10m	16y 2m
50%	27y 3m	25y 1m	20y 4m	23y 5m	21y 4m	17y 9m
60%	31y 9m	28y 3m	22y 6m	27y 3m	24y 0m	19y 6m
70%	36y 7m	32y 4m	24y 11m	31y 10m	27y 8m	21y 8m
80%	45y 8m	39y 6m	28y 2m	40y 2m	33y 4m	24y 8m
90%	Not within 50 years	Not within 50 years	34y 2m	Not within 50 years	43y 4m	29y 4m

Base Case[19]*:* Results for the cumulative likelihood and timing of adoption for the average consumer are shown in table 8 across alternative R&D and technological advancement scenarios in solar.

Independent of any incentives or carbon pricing, projections indicate that if historic lower technological change rates are maintained, there is a 70% likelihood of adoption within approx. 37 years, and a 80% likelihood within approx. 46 years. However, if the higher average cost declines observed within the recent years are maintained, it would accelerate adoption considerably, resulting in a 70% likelihood of adoption within 25 years, and a 80% likelihood within 28 years. In this latter scenario, under an entirely plausible rate of technological change, projections indicate that there could be a widespread shift towards solar in under 30 years in the residential and commercial sector – without any incentives or carbon pricing.

This result is consistent with Chakravorty et al. (1997) who show an endogenous substitution amongst energy sources and a shift towards solar energy across all sectors in 52 – 92 years[20] and

[19] We present the simulation results for r = 3%. However, consistent with the analytical results which illustrate the relative insensitivity of ROA to interest rate changes, the simulation results are very similar across r = 3% and 5%, exhibiting the same key dynamics.

the subsequent implications for global warming. They use an optimal control framework, without uncertainty, to simulate an economy wide energy demand model with multiple exhaustible resources and multiple demand sectors with solar as the representative and most likely backstop technology across all sectors, including transportation. While they acknowledge that a mix of technologies may eventually dominate, our results indicate a dominant role for solar in the residential and commercial sector, and solar as a viable part of our future energy mix plausibly in under 30 years.

Results based on expert elicitation (Rausser et al., 2010) suggest that a $60 million increase over historic status quo funding levels of $115 million/year may accelerate adoption by approx. 5-6 years on average as compared to baseline results. This suggests policy conclusions about levels of R&D funding that may be necessary to attain desired levels of adoption, and that a modest increase of $60 million may not be enough to accelerate adoption at a significant rate.

Average Historic Consumer Incentives: Recent cost declines in solar PV have been accompanied with declining consumer incentives across most states - which many fear will dampen the overall consumer economics of solar adoption. Our results strongly suggest that these concerns are overstated.

Results indicate (table 8) that if recent cost declines are maintained, average historic consumer incentives have a minimal impact of accelerating adoption by approximately 3 years as compared to the base case scenario, i.e. a widespread shift would be observed with 70% likelihood within 22 years, and 80% likelihood within 25 years.

In the scenario with the lower historic rate of technological advancement, projections indicate a slightly higher impact of consumer incentives, accelerating adoption by an approximately 5-6 years as compared to the base case, albeit with widespread adoption still occurring only within 32 - 40 years.

In general, the results indicate a difference of 3-6 years depending on cost decline scenarios - strongly suggesting the policy conclusion that average historic incentives have a modest impact in encouraging adoption of solar technologies, and virtually no impact if the recent higher cost declines are maintained.

[20] By 2065 – 2105, depending on technological change scenario.

Table 9 – Impact of $21/ton CO2 Tax on Likelihood and Timing of Adoption (r=3%)

PELEC +2.89% **CO2 Tax ($21/ton CO2)**	**COAL**			**NATURAL GAS**		
Likelihood of Adoption	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)
10%	12y 3m	12y 2m	11y 2m	12y 11m	12y 5m	11y 7m
40%	22y 3m	21y 5m	17y 0m	23y 4m	20y 10m	17y 5m
50%	25y 1m	24y 3m	18y 10m	27y 2m	24y 1m	19y 2m
60%	29y 4m	27y 7m	20y 11m	31y 9m	27y 6m	21y 2m
70%	34y 5m	31y 8m	23y 0m	36y 5m	31y 9m	24y 6m
80%	42y 11m	39y 1m	25y 9m	45y 11m	38y 3m	26y 11m
90%	Not within 50 years	Not within 50 years	31y 4m	Not within 50 years	Not within 50 years	32y 1m

Carbon Taxes At $21/ton CO2 and $65/ton CO2: Results for a carbon tax of $21/ton CO2 and $65/ton CO2, representing SCC estimates for "most likely" and "higher-than expected" impact scenarios are shown in tables 9 and 10 respectively.

Projections indicate that a $21/ton CO2 carbon tax accelerates adoption by an average of 0-3 years, with a consistently lower impact in the scenario with the higher rate of technological advancement. The carbon tax would accelerate adoption by 2-3 years if the source of electricity were derived from coal, and by 0-1 years if derived from natural gas. Projections strongly suggest the policy conclusion that while this may be the most feasible level of carbon pricing, it is also the most ineffective and has a modest impact in accelerating adoption. Notwithstanding growth and distributional effects - a carbon tax of $21/ton CO2 would raise the price of a gallon of gasoline by $0.19 and a barrel of crude oil by $9.03.

Projections for carbon pricing at $65/ton CO2 in general indicate an acceleration of adoption by an average of 2-5 years, once again with a consistently lower impact in the scenario with the higher rate of technological advancement.

Specifically, if the recent average cost declines in solar are maintained, results indicate that a widespread shift would be observed with 70% likelihood within 21 years (22 years if natural gas), and 80% likelihood within 23 years (26 years if natural gas), indicating an average of 4-5 years difference if derived from coal and 2-3 years difference if derived from natural gas.

Only in the scenario with historical lower rates of technological advancement and coal as the incumbent source of electricity will the tax have a more significant impact of accelerating adoption by an average of 8 years – however projections still indicate that widespread adoption will occur on average in almost 34 years in this scenario.

Table 10 – Impact of $65/ton CO2 Tax on Likelihood and Timing of Adoption (r=3%)

PELEC +2.89% **CO2 Tax ($65/ton CO2)**	**COAL**			**NATURAL GAS**		
Likelihood of Adoption	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)
10%	10y 1m	9y 10m	9y 7m	11y 6m	11y 5m	10y 7m
40%	18y 10m	17y 10m	14y 11m	20y 4m	19y 1m	15y 10m
50%	21y 4m	20y 6m	16y 6m	23y 2m	21y 4m	17y 10m
60%	25y 1m	23y 5m	18y 5m	28y 0m	25y 0m	19y 10m
70%	30y 5m	27y 4m	20y 7m	32y 10m	29y 3m	22y 5m
80%	36y 11m	32y 2m	23y 4m	42y 6m	33y 10m	26y 2m
90%	Not within 50 years	46y 4m	28y 7m	Not within 50 years	45y 9m	32y 5m

Results indicate that the impact of a $65/ton CO2 tax would be modestly higher than in the scenario with consumer incentives or the $21/ton CO2 tax – accelerating adoption by 2-4 years if the incumbent electricity source were derived from natural gas, and 4-8 years if derived from coal. Consistent with previous results, the impact is diminished in the case of the higher rate of technological change.

Concurrently, a carbon tax of $65/ton CO2 would raise the price of a gallon of gasoline by $0.58, and a barrel of crude oil by $27.95.

Carbon Taxes At $150/ton CO2: While a carbon tax of $150/ton CO2 has not been included in government estimates of the social cost of carbon (SCC), it has been suggested as representing considerations of catastrophic climate outcomes more accurately than lower estimates (Pindyck 2013).

The results for the impact of a carbon tax of $150/ton CO2 are shown in table 11. If the recent rates of cost decline are maintained, the carbon tax would result in a widespread shift within 18.5

– 20.5 years, albeit this representing a moderate acceleration of an average of 6-8 years above baseline results free of any incentives.

Table 11 – Impact of $150/ton CO2 Tax on Likelihood and Timing of Adoption (r=3%)

PELEC +2.89% **CO2 Tax ($150/ton CO2)**	**COAL**			**NATURAL GAS**		
Likelihood of Adoption	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)
10%	6y 9m	6y 10m	7y 3m	8y 10m	8y 9m	8y 11m
40%	13y 11m	13y 0m	11y 10m	17y 4m	16y 1m	14y 1m
50%	16y 3m	15y 2m	13y 5m	19y 11m	18y 5m	15y 9m
60%	19y 2m	17y 9m	15y 5m	23y 4m	20y 10m	17y 5m
70%	22y 11m	21y 3m	17y 5m	27y 11m	24y 1m	19y 4m
80%	29y 3m	26y 5m	20y 3m	33y 7m	29y 3m	22y 4m
90%	46y 7m	36y 11m	25y 3m	Not within 50 years	39y 6m	26y 7m

The impact will be more significant in the scenario with historical lower rates of technological advancement – accelerating adoption by an average of 10.5 and 15.5 years, given the incumbent source of electricity is derived from natural gas and coal respectively. However projections still indicate a widespread shift within an average of 31 and 26 years respectively.

Projections indicate that a tax of $150/ton CO2 applied to the lower technical change scenario will replicate the baseline results for the higher rates of technical change free of any incentives, if the incumbent source of electricity is derived from coal. However, it will <u>not</u> replicate baseline results for electricity derived from natural gas – a higher carbon tax than $150/ton CO2 would be necessary to do so.

Concurrently, a $150 carbon tax would raise the price of a gallon of gasoline by $1.33, and the price of a barrel of crude by approx. $65. In addition, a $150 tax would more than double the current price of electricity (if derived from coal), rendering it almost as high as the current cost of solar free of incentives.

V. Conclusion

This paper considers the question of how to transition to a meaningful percentage of solar energy in a sustainable way and which policies are most effective in accelerating adoption. We develop a stochastic dynamic real options model evaluating the threshold and timing of the consumer's optimal investment decision given two sources of uncertainty, and obtain a cumulative likelihood and timing of substitution amongst energy resources and towards solar under plausible rates of technological change, subsidies and carbon taxes.

Based on our specification, results indicate that there will be a widespread shift towards solar PV in the residential and commercial sector in under 30 years – and that this can occur independent of downstream incentives and carbon pricing policies (at $21/ton CO2, $65/ton CO2 and $150/ton CO2). In general, results across all scenarios consistently indicate that average historic consumer subsidies and carbon pricing policies have a modest effect in accelerating adoption, and may not be an effective part of climate policy in this regard.

The results demonstrate that R&D support and further technological change is the crucial determinant in accelerating widespread adoption of solar PV - suggesting that subsidies and taxes don't make a substantial difference in a technology that's not viable, while research does. This further suggests that optimal policies may change over time, however current continued R&D support and technological advancement is the crucial determinant of widespread transition to solar and plausibly other backstop technologies – and that it should play a key role in policy measures intended to combat climate change.

The results do not imply that carbon pricing shouldn't play a role in climate policy in general. Carbon pricing may be effective in reducing emissions and encouraging the transition towards other clean technologies – however it has a decidedly modest impact in accelerating adoption of solar PV at levels up to $150/ton CO2. Suggesting, that if a widespread transition to solar energy is likely to happen in this sector, it will be because of R&D and technological advancement.

There are several limitations of this study that should be addressed in further research. One, that we are assuming that R&D and technological change are independent of adoption. In reality, the innovation process is a continuum, such that the R&D and manufacturing processes are integrated and exhibit learning by doing effects. Inasmuch, taxes and subsidies may provide an incentive for adoption that enhances learning - which has not been included in this study. Despite the analysis by Nemet (2006) suggesting that learning by doing only weakly explains changes in the most important factors influencing cost reductions in solar PV over the past 30 years, the current omission of such effects should be addressed in future research. Another limitation is that this study cannot capture the effect of subsidies that reduce the initial cost, but which tend to expire - which would aim to counter the Dixit Pindyck effect and would affect the results.

Further, the implications of a widespread shift towards solar in this sector should be examined in further detail in terms of GHG emissions and climate change outcomes. We have seemingly assumed the shift towards solar in this sector as desirable, however this should ultimately be evaluated against the prospects and impact of other technologies - including solar adoption in the utility sector.

Additionally, the estimated probability of adoption at each moment which we were able to derive as a function of each policy provides a key tool to assess the expected rate of return of various policies, which should be evaluated in future research.

Nevertheless, the results of this study remain robust across varying levels of interest rate, technological change and incentives - with significant policy implications about the relationship between research subsidies and consumer subsidies in accelerating the widespread adoption of solar PV.

The results consistently indicate that average historic consumer subsidies and carbon taxes will have a decidedly modest impact in encouraging the adoption of a technology that is not viable. Instead, continued R&D support and technological advancement is the crucial determinant and main driver of adoption, outweighing the effect of subsidies and taxes - and it should play a key role in climate policy.

APPENDIX A.

Overall, the results of the simulations for electricity price parameters based on EIA historical average residential and commercial electricity prices of -0.2479% and 0.2011% (for the time periods 1990-2002 and 2003-2009 respectively) indicate the following: (i) As expected, a low or negative evolution of the price of electricity delays adoption considerably. (ii) Both consumer subsidies and carbon taxes display a modest increase in impact with lower growth rates of electricity prices. (iii) However, results remain consistent across all scenarios of differing electricity price trajectories with overall results demonstrating that further technological change is the crucial determinant and main driver of adoption.

Table 12 – Baseline Results for Likelihood and Timing of Adoption & Impact of Average Historic Consumer Incentives (r=3%)

PELEC -0.248%	**BASELINE**			**AV. CONSUMER INCENTIVES**		
Likelihood of Adoption	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)
10%	21y	19y 6m	15y 6m	16y 7m	15y 8m	13y 2m
40%	44y 10m	36y 3m	24y 9m	34y 5m	30y 9m	22y
50%	54y 2m	42y 9m	27y 8m	40y 1m	36y 11m	25y 1m
60%	66y	47y 10m	31y 1m	53y 10m	44y 4m	28y
70%	84y 10m	59y 11m	34y 11m	69y	60y 1m	31y 10m
80%	Not within 90 years	87y 5m	40y 5m	Not within 90 years	79y 2m	37y 1m
90%	Not within 90 years	Not within 90 years	Not within 90 years	Not within 90 years	Not within 90 years	56y 8m

Table 13 – Baseline Results for Likelihood and Timing of Adoption & Impact of Average Historic Consumer Incentives (r=3%)

PELEC +0.2011%	**BASELINE**			**AV. CONSUMER INCENTIVES**		
Likelihood of Adoption	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)
10%	19y 3m	18y 3m	15y 1m	15y 3m	14y 7m	13y 1m
40%	38y 8m	33y 8m	23y 7m	32y 4m	27y 7m	20y 9m
50%	48y 5m	39y 4m	26y	38y 8m	32y 4m	23y 4m
60%	58y 2m	46y 2m	29y 2m	50y 11m	39y 9m	26y 2m
70%	85y 7m	55y	32y 10m	67y 6m	46y 11m	29y 9m
80%	Not within 90 years	67y 2m	38y 11m	Not within 90 years	68y 8m	34y 3m
90%	Not within 90 years	Not within 90 years	54y 10m	Not within 90 years	Not within 90 years	53y 3m

Base Case[21]*:* Results for the cumulative likelihood and timing of adoption for the average consumer are shown in tables 12 and 13 across alternative R&D and technological advancement scenarios in solar. Table 12 shows results for annual electricity price growth rates of -0.2479% , while table 13 shows the results for annual electricity price growth rates of +0.2011% as based on EIA historic average residential and commercial electricity prices.

Projections for annual electricity price growth rates of -0.2479% indicate that independent of any incentives or carbon pricing, if historic lower technological change rates are maintained, there is a 50% likelihood of adoption within approx. 54 years, and a 60% likelihood within approx. 66 years. However, if the higher average cost declines observed within the recent years are maintained, it would accelerate adoption considerably, resulting in a 50% likelihood of adoption within 28 years, and a 60% likelihood within 31 years. In this latter scenario, under an entirely plausible rate of technological change, and with negative growth in electricity prices, projections indicate that there could be a widespread shift towards solar in under 30 years in the residential and commercial sector – without any incentives or carbon pricing.

These results are similar to those for annual electricity price growth rates of +0.2011%, which indicate that independent of any incentives or carbon pricing, if historic lower technological change rates are maintained, there is a 50% likelihood of adoption within approx. 48 years, and a 60% likelihood within approx. 58 years. If the higher average cost declines observed within the recent years are maintained, in this scenario, it would accelerate adoption considerably, resulting in a 50% likelihood of adoption within 26 years, and a 60% likelihood within 29 years. Again, in this scenario, under an entirely plausible rate of technological change, projections indicate that there could be a widespread shift towards solar in under 30 years in the residential and commercial sector – without any incentives or carbon pricing. Additionally, as expected, higher growth rates in electricity prices accelerate adoption in general as compared to the previous scenario with negative growth in electricity prices.

Average Historic Consumer Incentives: Recent cost declines in solar PV have been accompanied with declining consumer incentives across most states - which many fear will dampen the overall consumer economics of solar adoption. Consistent with the results for annual electricity price growth rate of +2.89%, our results strongly suggest that these concerns are overstated, even in the scenario with lower annual growth rates of electricity prices of -0.2479% and 0.2011%.

Results for annual electricity price growth rates of -0.2479% (table 12) indicate that if recent rates of cost decline are maintained, average historic consumer incentives will have a minimal impact of accelerating adoption by approximately 3 years as compared to the base case scenario.

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21 We present the simulation results for r = 3%. However, consistent with the analytical results which illustrate the relative insensitivity of ROA to interest rate changes, the simulation results are very similar across r = 3% and 5%, exhibiting the same key dynamics. In addition, we discuss results at the 50-60% likelihood level.

This is consistent with results for both electricity price growth rates of +0.2011% (table 13) and +2.89% (table 8).

In the scenario with the lower historic rate of technological advancement, projections indicate a slightly higher impact of consumer incentives, accelerating adoption by an approximately 13 years (versus 8 years and 5-6 years for the scenarios with electricity price growth rates of +0.2011% and +2.89% respectively) as compared to the base case, albeit with widespread adoption occurring only within 47 years.

In general, the results indicate a difference of 3-13 years depending on cost decline scenarios (versus 3-8 years and 3-6 years for the scenarios with electricity price growth rates of +0.2011% and +2.89% respectively), strongly suggesting the policy conclusion that in general, average historic incentives have a modest impact in encouraging adoption of solar technologies, and virtually no impact if the recent higher cost declines are maintained. The impact does however show a relative increase in scenarios with lower technological change and declining electricity price rates.

Table 14 – Impact of $21/ton CO2 Tax on Likelihood and Timing of Adoption (r=3%)

PELEC -0.248% **CO2 Tax ($21/ton CO2)**	**COAL**			**NATURAL GAS**		
Likelihood of Adoption	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)
10%	17y 5m	16y 9m	14y 2m	19y 3m	18y	14y 10m
40%	37y 10m	33y 1m	22y 4m	42y 10m	33y 11m	23y 10m
50%	47y 5m	39y 3m	24y 10m	53y 2m	39y 5m	26y 11m
60%	59y 1m	46y 7m	28y	64y 4m	48y 7m	29y 8m
70%	74y 8m	59y 11m	32y 4m	Not within 90 years	58y 4m	33y 4m
80%	Not within 90 years	87y 6m	38y 2m	Not within 90 years	Not within 90 years	38y 10m
90%	Not within 90 years	Not within 90 years	61y 2m	Not within 90 years	Not within 90 years	52y 2m

Table 15 – Impact of $21/ton CO2 Tax on Likelihood and Timing of Adoption (r=3%)

PELEC +0.2011% **CO2 Tax ($21/ton CO2)**	**COAL**			**NATURAL GAS**		
Likelihood of Adoption	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)
10%	16y 4m	15y 7m	13y 7m	17y 5m	16y 8m	13y 11m
40%	33y 4m	29y 10m	21y 10m	36y 8m	31y 2m	21y 2m
50%	41y 3m	34y 1m	24y 8m	47y	37y 4m	24y 5m
60%	52y 3m	40y 8m	27y 6m	56y 9m	43y 3m	27y 4m
70%	64y 9m	46y 9m	32y 3m	72y	51y 11m	31y 6m
80%	Not within 90 years	68y 11m	37y 9m	Not within 90 years	69y 9m	36y 2m
90%	Not within 90 years	Not within 90 years	Not within 90 years	Not within 90 years	Not within 90 years	52y 10m

Carbon Taxes At $21/ton CO2 and $65/ton CO2: Results for a carbon tax of $21/ton CO2 and $65/ton CO2, representing SCC estimates for "most likely" and "higher-than expected" impact scenarios are shown in tables 14 - 17 respectively.

Projections for annual electricity price growth rates of -0.2479% indicate that a $21/ton CO2 carbon tax accelerates adoption by an average of 1 – 7 years, with a consistently lower impact in the scenario with the higher rate of technological advancement (table 14). This result is only slightly higher that the results for both electricity price growth rates of +0.2011% (1-6.5 years) and +2.89% (0-3 years) as shown in tables 15 and 9 respectively.

For electricity price growth rates of -0.2479%, the carbon tax would accelerate adoption by 1-1.5 years if the source of electricity were derived from natural gas, and by 3-7 years if derived from coal. Projections strongly suggest that while this may be the most feasible level of carbon pricing, it is also the most ineffective and has a modest impact in accelerating adoption across all growth rates for the price of electricity. Notwithstanding growth and distributional effects - a carbon tax of $21/ton CO2 would raise the price of a gallon of gasoline by $0.19 and a barrel of crude oil by $9.03.

Projections for annual electricity price growth rates of -0.2479% indicate that a $65/ton CO2 carbon tax accelerates adoption by an average of 3-9 years (table 16), once again with a consistently lower impact in the scenario with the higher rate of technological advancement. These results are again only slightly higher that the results for both electricity price growth rates of +0.2011% (3.5-6.5 years) and +2.89% (2-5 years) as shown in tables 17 and 10 respectively.

Specifically, if the recent average cost declines in solar are maintained, results indicate an average of 3 years difference if derived from natural gas and 6 years difference if derived from coal.

Only in the scenario with historical lower rates of technological advancement and coal as the incumbent source of electricity will the tax have a more significant impact of accelerating adoption by an average of 12.5 years – however projections still indicate that widespread adoption will occur on average in almost 47.5 years in this scenario with 50-60% likelihood. This result is slightly higher that the results for this scenario for both electricity price growth rates of +0.2011% (11 years) and +2.89% (8 years) as shown in tables 17 and 10 respectively.

Table 16 – Impact of \$65/ton CO2 Tax on Likelihood and Timing of Adoption (r=3%)

PELEC -0.248% **CO2 Tax (\$65/ton CO2)**	**COAL**			**NATURAL GAS**		
Likelihood of Adoption	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)
10%	14y 9m	14y 8m	11y 8m	17y 4m	15y 6m	13y 7m
40%	34y 3m	28y 6m	19y 7m	36y 5m	30y 4m	21y 11m
50%	42y 10m	34y	21y 11m	44y 10m	37y 3m	24y 9m
60%	52y	41y 1m	24y 11m	57y 5m	45y 5m	27y 9m
70%	69y 8m	50y 1m	28y 6m	71y 6m	61y 10m	31y 7m
80%	Not within 90 years	65y 5m	33y 3m	Not within 90 years	Not within 90 years	37y 5m
90%	Not within 90 years	Not within 90 years	42y	Not within 90 years	Not within 90 years	52y 5m

Table 17 – Impact of $65/ton CO2 Tax on Likelihood and Timing of Adoption (r=3%)

PELEC +0.2011% **CO2 Tax ($65/ton CO2)**	**COAL**			**NATURAL GAS**		
Likelihood of Adoption	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)
10%	13y 6m	12y 7m	11y 9m	16y	15y 4m	12y 6m
40%	30y 4m	25y	18y 10m	34y 3m	28y 11m	20y 1m
50%	36y 6m	29y 4m	21y 4m	41y 11m	34y	22y 7m
60%	47y 5m	36y 5m	24y 2m	50y 8m	40y 11m	25y 5m
70%	63y 9m	45y 2m	27y 7m	63y 10m	49y 7m	28y 9m
80%	Not within 90 years	69y 9m	32y 10m	Not within 90 years	63y 11m	33y 7m
90%	Not within 90 years	Not within 90 years	42y 11m	Not within 90 years	Not within 90 years	42y 9m

Concurrently, a carbon tax of $65/ton CO2 would raise the price of a gallon of gasoline by $0.58, and a barrel of crude oil by $27.95.

Carbon Taxes At $150/ton CO2: While a carbon tax of $150/ton CO2 has not been included in government estimates of the social cost of carbon (SCC), it has been suggested as representing considerations of catastrophic climate outcomes more accurately than lower estimates (Pindyck 2013).

The results for the impact of a carbon tax of $150/ton CO2 with electricity growth rates -0.2479% are shown in table 18, while results for electricity growth rates of +0.2011% are shown in table 19.

Projections for annual electricity price growth rates of -0.2479% indicate that if recent rates of cost decline are maintained, the carbon tax would accelerate adoption by a modest 6-10 years above baseline results free of any incentives. This result is only slightly higher than the results for this scenario for both electricity price growth rates of +0.2011% (6-8.5 years) and +2.89% (6-8 years) as shown in tables 19 and 11 respectively.

Table 18 – Impact of $150/ton CO2 Tax on Likelihood and Timing of Adoption (r=3%)

PELEC -0.248% CO2 Tax ($150/ton CO2)	COAL			NATURAL GAS		
Likelihood of Adoption	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)
10%	9y 9m	9y 5m	9y 2m	14y 5m	13y 1m	11y 2m
40%	25y 10m	21y 2m	15y 5m	32y 3m	26y 7m	18y 10m
50%	32y 11m	24y 9m	18y	40y	31y 7m	21y 7m
60%	41y	31y 1m	20y 7m	49y 7m	38y 6m	24y 8m
70%	58y 3m	37y 10m	23y 9m	69y 10m	49y 2m	28y 4m
80%	90y	58y	28y 2m	Not within 90 years	68y 4m	34y 3m
90%	Not within 90 years	Not within 90 years	40y 4m	Not within 90 years	Not within 90 years	51y 10m

Table 19 – Impact of $150/ton CO2 Tax on Likelihood and Timing of Adoption (r=3%)

PELEC +0.2011% CO2 Tax ($150/ton CO2)	COAL			NATURAL GAS		
Likelihood of Adoption	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)	Historic lower tech advancement (-4.4%)	50% Increase in R&D funding (-5.6 %)	Recent higher Av. Cost Decline (-9.3%)
10%	9y 5m	9y 5m	9y 1m	12y 4m	11y 10m	10y 7m
40%	22y 10m	20y 1m	15y 4m	28y 7m	23y 8m	17y 4m
50%	27y 7m	24y 4m	17y 6m	34y 7m	27y 6m	19y 10m
60%	34y 7m	28y 11m	20y 3m	44y 3m	32y 10m	22y 6m
70%	45y	37y 5m	23y 6m	57y 6m	41y 1m	25y 8m
80%	74y 1m	50y 5m	27y 10m	89y 3m	57y 5m	30y 1m
90%	Not within 90 years	Not within 90 years	35y 11m	Not within 90 years	Not within 90 years	44y 2m

The impact is more significant in the scenario with historical lower rates of technological advancement – accelerating adoption by an average of 15 and 23 years, given the incumbent source of electricity is derived from natural gas and coal respectively. These results are again only slightly higher than projections for the scenarios with electricity price growth rates of

+0.2011% (13.5 and 21.5 years respectively) and +2.89% (10 and 15.5 years respectively) as shown in tables 19 and 11 respectively.

However, projections indicate that a tax of $150/ton CO2 applied to the lower technical change scenario (for both electricity derived from coal and natural gas) will still not replicate the baseline results for the higher rates of technical change free of any incentives – a higher carbon tax than $150/ton CO2 would be necessary to do so. In general, this result holds for all three electricity price growth rate scenarios (i.e. -0.2479%, +0.2011% and +2.89%)[22].

Concurrently, a $150 carbon tax would raise the price of a gallon of gasoline by $1.33, and the price of a barrel of crude by approx. $65. In addition, a $150 tax would more than double the current price of electricity (if derived from coal), rendering it almost as high as the current cost of solar free of incentives.

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[22] With the exception of the case with electricity price growth at +2.89%, the lower technical change scenario and the incumbent source of electricity derived from coal - in which case a tax of $150/ton CO2 will replicate baseline results for the higher rate of technical change free of any incentives.

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