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Climate Policy as Expectation Management?*

Daiju Narita

Abstract:

It is often emphasized that the primary economic solution to climate change is the introduction of a carbon pricing system (tax or tradable permits) anchored to the social cost of carbon. This standard argument, however, misses the fact that if emission reduction is sought through the use of technologies with network externalities, the level of emission reduction can become expectation-driven rather than uniquely determined by the level of carbon price. Using a simple model, the paper discusses the possibility that the effectiveness of carbon policy is influenced by firms' belief on carbon policy and technology penetration in the future – in extreme cases, expectations prevail over policy. This feature highlights the danger of overemphasis on finding the "right" carbon price in policy making and the role of climate policy as expectation management.

Keywords: climate policy, technology choice, expectations, multiple equilibria

JEL classification: Q54, O33

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1. Introduction

Importance of pricing carbon dioxide emissions to mitigate climate change, as a form of either tax or tradable permits, is often emphasized by economists. The standard argument says that the primary role of climate policy is to set a price for carbon dioxide emissions corresponding to their social costs. [1] The basic idea behind this view is that carbon dioxide, a public good (or public "bad"), cannot be properly priced in the private market, and that the role of environmental policy is to devise some mechanism to adjust the price to the socially optimal level, or if it is not feasible for the reason of strategic behavior, to set the price as close to the optimum as possible. This logic supports a consequential but detached role of government that refrains from dictating how the private sector should act in the face of the need for emission reduction, a role resembling a rule-setter or a referee rather than a coach in a game.

This view, however, does not explain the entire picture of carbon dioxide reduction. In countries where significant policy of carbon dioxide emission control is already in place (exemplified by EU's emission trading scheme (ETS)), carbon policy is a discernible factor for firms' investment decisions in energy infrastructure. A casual interpretation of the standard argument might suggest that the carbon price gives such companies a sufficient incentive to invest. In practice, however, the present level of the carbon price has only a limited meaning for their investment decisions. For example, the average lifetime of power plants exceeds a few decades, and it is considered that the carbon price could considerably change over such a time span (e.g., Clarke et al., 2009) – indeed, future climate policy could normally be known only for a short time horizon (ETS's

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[1] For example, Stern (2007) and Nordhaus (2008) might make two ends of a spectrum in opinion by estimating radically different optimal policy paths, but their difference comes primarily from the difference in social cost of carbon they estimate, not from any deviation from the conventional view by either of them.

existence is only guaranteed until 2020 so far). On the other hand, certain types of clean technologies, such as a hydrogen-based transportation system or CCS (carbon capture and storage) operations mutually linked by a carbon dioxide pipeline network, exhibit network externalities,[2] which make adopters' payoff influenced by other firms' technology choice in the future. In presence of these factors, an important driver of firms' investment decisions on clean technology is their expectations about future costs and benefits of technology, which are determined by both future carbon policy and future adoption rates of clean technology by others. Along with the level of carbon price, those expectations can influence the level of climate change mitigation. This feature might explain the apparent paradox of the McKinsey curve that some climate change mitigation technologies are not used even if the investment should bring net monetary gains (McKinsey & Co., 2010).[3] Also, this characteristic of expectations implies that there may be some room for an active role of government to align firms' expectations, like a coach guiding a team.[4] Note that this logic holds even without the necessity of technology R&D.

The role of expectations is sometimes pointed out by non-economists as a reason for targeted support for clean technologies (e.g., Peréz-Arriaga, 2010). However, formal economic analyses on this question are practically absent. In analyzing technology spillovers in the context of climate policy, Fischer (2008) discusses the policy incentive mechanisms for renewable technologies and mentions the role of expectations, but her model does not explicitly consider

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[2] Barrett (2003, Chapter 9) describes that there are many historical cases of environmental policy in which network externalities of abatement technologies determined policy effectiveness.

[3] IEA (2008) estimates similar cost patterns of mitigation technologies.

[4] A similar viewpoint is widely recognized in the field of development economics. A large body of evidence from studies of economic development suggests that while the market mechanism is an important element to achieve economic efficiency, strong and discretionary interventions by government often play a decisive role in a favorable transformation of economic structure. See for example, Hoff and Stiglitz (2001) for a review.

uncertainty. In a similar vein, Fischer and Newell (2008) compare policy schemes including subsidy schemes for renewable energy. However, their model also does not address uncertainty.

In this paper, we examine how such expectations may drive the dynamics of carbon dioxide reduction. We discuss a simple model in which forward-looking firms make investment decisions on a clean technology. The clean technology has positive externalities, and firms benefit from alignment of technology choice with others'. Expectations held by firms have a central meaning for the model. Expectations could be of two types. The first is the expectations about future carbon prices – this type of expectations reflects firms' subjective belief about government's future willingness (and also capacity) for action against climate change. The second is the expectations about others' adoption or abandonment of the clean technology. Both types of expectations could be shaped without a factual basis. In fact, the driver could be a sheer mood, such as optimism or pessimism. Under the influence of either form of expectations, the current level of carbon price would have only limited power over companies making investment decisions. In such circumstances, it might not be wise to counter firms' pessimism by a mere adjustment of the carbon price, as only a very high carbon price would be able to force companies to adopt a technology with few existing users. Rather, it would be useful to introduce additional mechanisms to influence firms' expectations, such as an announcement of medium-term policy targets or technology-specific supporting schemes. Meanwhile, the flip side of this argument is that a strongly punitive carbon pricing scheme may not be necessary if the government successfully manipulates firms' expectations about their future benefits.

Note that the type of uncertainty to be discussed in this paper markedly differs from the types of uncertainty commonly discussed in the literature of economics of climate change (e.g., Heal and

Kriström, 2002; Weitzman, 2009).[5] While most previous studies of the economics of climate change and uncertainty examine cases in which a unique optimal path of the future economy exists, in this paper's case the expectations about uncertain future can drive the outcome in more than one way.

It is also worth noting that the discussion here deals with coordination failure. Although coordination failure itself is not a new subject in the context of climate change,[6] an aspect associated with coordination failure, dynamic implications of multiple equilibria, has been largely ignored in previous studies on climate policy. An important exception is Karp (2008), who discusses existence of multiple equilibria due to the externality of climate change damage and argues that a tradable permit system could eliminate indeterminacy among equilibria. This paper is to highlight a different type of multiple equibria regarding climate policy, namely that from externalities of clean technology. Here in this model, unlike in Karp's, multiplicity of feasible paths could remain even under a price-based system of carbon regulation, and it opens up room for expectations to influence dynamics. In fact, as already described, this viewpoint is not particularly uncommon as a casual argument. This paper is an attempt to bridge the informal arguments on investment behavior of clean technologies and the more formal economic discussions centered on the carbon pricing mechanism.

This paper is organized as follows. In Section 2, we discuss a simple two-period model of clean technology use to sketch the problem. In Section 3, we extend the model to a multi-period case

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[5] Böhringer et al. (2009) reviews economic studies that investigate uncertainty specifically associated with climate change mitigation technologies and its effects on climate policy.

[6] For example, Barrett (2003, 2006) discusses effects of technology externalities in the making of international climate treaties.

by imposing two strong conditions, rational expectations by firms and a fixed climate policy (no policy uncertainty). The model framework used in this section is in fact similar in spirit to Krugman's (1991), which is discussed in a different context. Section 4 concludes.

2. Basic model: Two-period case

First, we consider a simple two-period case to illustrate the problem. Here, a firm faces a choice between introducing a low-emission ("clean") production technology, which involves an initial investment f but saves the amount of emission penalty linked to the carbon price, and keeping a conventional, high-emission ("dirty") production technology. Since the lifetime of equipment stretches over a significant time span, the firm makes its decision based on the current net payoff and the expected net future payoff, which is uncertain because of the uncertainty in future climate policy. The firm owner is a Bayesian decision maker, and he or she makes a subjective judgment regarding the future carbon policy based on a prior belief. When the lifetime of equipment consists of two periods, the expected net present values for both technologies are expressed as follows:

Dirty technology: $$V_{dirty} = \bar{y} - c_1 + \beta \cdot E[\bar{y} - c_2] \qquad (1)$$

Clean technology: $$V_{clean} = \bar{y} - f + \beta \cdot \bar{y} \qquad (2)$$

where $\bar{y}$, c_1, c_2, β are the (gross) production for each period, the carbon penalty for period 1, the carbon penalty for period 2, and the discount factor ($0<\beta<1$), respectively.

Now suppose that the carbon penalty in period 2, c_2, have two possibilities, a high case c_h and a low case c_l. One interpretation of this difference is that the high carbon price corresponds to the socially optimal level and the low carbon price to the most pessimistic case of failure in political decision making.[7]

We define p_a $(0 \leq p_a \leq 1)$ and $1 - p_a$ as the probabilities based on subjective belief (priors) with regard to the high and low carbon penalties in period 2, respectively. By using those probabilities, V_{dirty} is now expressed as:

$$V_{dirty} = \bar{y} - c_1 + \beta \cdot [\bar{y} - \{p_a c_h + (1 - p_a) c_l\}] \tag{3}$$

Defining ΔV as

$$\begin{aligned} &\Delta V \equiv V_{clean} - V_{dirty} \\ &= c_1 - f + \beta \cdot E[c_2] = c_1 - f + \beta \cdot [p_a c_h + (1 - p_a) c_l] = c_1 - f + \beta c_l + \beta p_a (c_h - c_l) \end{aligned} \tag{4}$$

the clean technology is introduced if $\Delta V > 0$, and the dirty technology remains to be utilized otherwise.[8]

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[7] Alternatively, in case that climate policy strictly reflects the social cost of carbon, it could be interpreted as the probabilities that the climate sensitivity to atmospheric carbon dioxide proves to be high and low.

[8] In fact, from a purely economic standpoint, the firm is indifferent between two choices when $\Delta V = 0$. But it is fair to assume that the firm has a slight preference for the status quo when the technology switching involves no economic benefit.

The above formulation (4) means that firm's preference for the clean technology increases with p_a, as ΔV is an increasing function of p_a. In other words, there are certain cases in which different levels of p_a result in a difference in technology choice – regardless of what the subjective belief is based on. The government can in principle exercise more control on technology choice by adjusting the current carbon penalty c_1, but this way of control is difficult if $\beta(c_h - c_l)$ is much larger than the possible range of c_1. It is also worth noting that (4) implies that the adoption of the clean technology is favored by firms less prone to bankruptcy (i.e., with a large β), as ΔV is an increasing function of β.

For further interpretations of the model, let us now assume that there exists the real probability for the high carbon penalty, $\hat{p}$, in place of p_a. A mismatch between $\hat{p}$ and p_a leads to a mismatch of technology decisions that would be made by adopting either of probabilities. An illustrative case is that the government announces the future carbon penalty to be high and indeed commits to the goal (i.e., $\hat{p} = 1$) but the firm has disbelief on government's announcement (i.e., $p_a < 1$). If this is the case and also $1 > \frac{f - c_1 - \beta c_l}{\beta(c_h - c_l)} > p_a$, the dirty technology is chosen by the firm despite the policy signal justifying the other. Meanwhile, a contrasting case is that the government has no intention to implement the high carbon penalty ($\hat{p} = 0$) but firms still believe some chance of the high-penalty case (i.e., $p_a > 0$). If this is the case and also $p_a > \frac{f - c_1 - \beta c_l}{\beta(c_h - c_l)} > 0$, the clean technology is "wrongly" chosen against the actual policy stance.

A potential determinant of firms' subjective belief on future policy is government's record of successful policy making. For example, assuming a simple Bayesian formulation in which the government has a track record of M_s times of policy success (successful implementation of a socially optimal policy) and M_f times of policy failure (policy is made according to special interests rather than based on the social good), the probability p_a (with which the high, socially-optimal carbon price will be put in place) is expressed as:

$$(5) \qquad p_a = \frac{M_s}{M_s + M_f}$$

Clearly, the firms are more inclined to introduce the clean technology under a successful government rather than a failing government. Further, under a government with a successful track record of policy implementations, firms make their technology choice *as if* the future carbon policy is bound to be stringent, even if the carbon price in period 2 proves to be low in the end.

Following this reasoning, it is possible that the same level of carbon pricing has a stronger effect on firms' investment into emission-saving technologies in a country with a stable and effective political environment than in a country with a fractious and volatile political environment.

This simple discussion indicates that climate policy may enhance its effectiveness if it can offer firms some guarantee on future stringency of policy. In practice, however, the democratic government is subject to term limits and election cycles, and it is difficult for the government to make credible prior announcements on the future levels of carbon tax or the future amounts of emission permits in more than several years (not to mention the very existence of those systems in a distant future). This characteristic gives some justification for policy schemes of direct control on technology switching, such as technology standards or a compulsory renewable portfolio. The government may also design a promotion scheme of investment by specifically addressing this problem. For example, it may provide firms with loans for investment in clean technology whose repayment is conditional on the future levels of carbon price – firms may be obliged to repay only if the carbon price becomes higher than a certain level, or the amount of repayment is indexed to the level of carbon price). Such a scheme could mitigate firms' perceived risk, or reduce the information problem with regard to government's commitment to climate policy in the future.

A similar argument to the uncertain policy case could be constructed for the case of the technology possessing a scale effect originating from a network externality. Here, for clarity of discussion, we introduce the assumption that the use of the clean technology is only meaningful in presence of some emission penalty, in other words, firms using the clean technology produce less emissions than those with the dirty one do, but the clean technology is less efficient in gross output (i.e., output exclusive of the effect on emissions). The penetration rate of the clean technology is x ($0 \leq x \leq 1$). The clean technology has a scale effect that benefits the users of the technology as the number of adopting firms increase. The effect could have two components. The first is the emission saving $\kappa(x)$ (per firm: $1>\kappa>0$, $\kappa' \geq 0$) from the emission level of the dirty technology that is normalized at 1. With the carbon penalty c per unit emission, carbon costs for individual firms with the dirty and clean technologies are c and $[1-\kappa(\mathrm{x})]c$, respectively. As x rises, $[1-\kappa(x)]c$ declines (or $\kappa(x)$ rises). The second is the loss of gross output $l(x)$ (per firm: $l > 0$, $l' \leq 0$) from the output level of the dirty technology $\bar{y}$ ($> l(0)$). For simplicity, we also consider that the initial investment in the clean technology in period 1 only enables a firm to use the technology from period 2 but the adopting firm receives an exemption of carbon penalty in period 1. The net present value for the clean technology in this case is expressed as:

(6) $$V_{clean} = \bar{y} - f + \beta \cdot E[\bar{y} - l(x) - (1 - \kappa(x))c_1]$$

We assume that firms believe that the penetration rate of the clean technology in period 2 (*x*) could be either 1 with probability p_b $(0 \leq p_b \leq 1)$ or 0 with probability $1 - p_b$. To show the role of expectations regarding the scale effect of clean technology, here we consider that there is no uncertainty of climate policy in period 2. If the level of future carbon penalty (in period 2) is known to be c_h, V_{clean} and V_{dirty} are expressed as follows:

(7) $$V_{clean} = \bar{y} - f + \beta \cdot [\bar{y} - \{p_b l(1) + (1 - p_b) l(0)\} - \{1 - p_b \kappa(1) - (1 - p_b)\kappa(0)\} c_h]$$

(8) $$V_{dirty} = \bar{y} - c_1 + \beta \cdot [\bar{y} - c_h]$$

Similar to the policy uncertainty case, we consider $\Delta V = V_{clean} - V_{dirty}$.

(9) $$\begin{aligned}\Delta V &= c_1 - f + \beta \cdot [-\{p_b l(1) + (1 - p_b) l(0)\} + \{p_b \kappa(1) + (1 - p_b)\kappa(0)\} c_h] \\ &= c_1 - f + \beta \cdot [-l(0) + \kappa(0) c_h] + \beta p_b [-l(1) + l(0) + \{\kappa(1) - \kappa(0)\} c_h]\end{aligned}$$

Again, the clean technology is introduced if $\Delta V>0$, and the dirty technology remains to be utilized otherwise.

Similar to the policy uncertainty case, the above formulation (9) means that firm's preference for the clean technology increases with p_b, as ΔV is an increasing function of p_b. There are certain cases in which different levels of p_b result in a difference in technology choice – regardless of what the subjective belief is based on. Again, the government can in principle exercise more control on technology choice by adjusting the current carbon penalty c_1, but this method is difficult if $\beta[-l(1)+l(0)+\{\kappa(1)-\kappa(0)\}c_h]$ is much larger than the possible range of c_1.

Due to the scale effect of technology, the firms can get most benefit when the technology choice is fully aligned for either the clean technology or the dirty technology. However, the firms shape their belief arbitrarily and may not be able to achieve alignment. This mismatch between expectations and the best possible cases causes a mismatch in technology choice. If $c_1 - f + \beta \cdot [-l(1)+\kappa(1)c_h] > 0$, it is beneficial for all firms to adopt the clean technology altogether. But if also $1 > \frac{f - c_1 - \beta \cdot [-l(0)+\kappa(0)c_h]}{\beta[-l(1)+l(0)+\{\kappa(1)-\kappa(0)\}c_h]} > p_b$ is satisfied, the use of the clean technology is favorable but the dirty technology remains to be used. By contrast, if $c_1 - f + \beta \cdot [-l(1)+\kappa(1)c_h] < 0$, it is beneficial for all firms not to adopt the clean technology. But if $p_b > \frac{f - c_1 - \beta \cdot [-l(0)+\kappa(0)c_h]}{\beta[-l(1)+l(0)+\{\kappa(1)-\kappa(0)\}c_h]} > 0$ is also the case, the clean technology is introduced although the use of the dirty technology is favorable.

Unlike the case of uncertain future carbon policy, the choice of policy instrument to implement the carbon price, a carbon tax or a tradable permit system, has an effect on firms' decisions in this case. Indeterminacy only appears under a carbon tax system, not under a tradable permit system since the level of technology penetration is determined by policy for the latter. However, in this model's context, a tradable permit system (for which it is clearly most meaningful when the cap is set at the level of full adoption of the clean technology) is essentially the same as a mandate for the use of the clean technology. In other words, in this case also, indeterminacy disappears only by government's explicit control on technology choice.

As for implications of the model, note that the multiplicity of periods and the resultant uncertainty of future carbon policy and future choice by other firms have a critical meaning. In fact, the problem of coordination on technology adoption does not become explicit in a one-period model. For example, in the context of international environmental treaty, Barrett (2003, 2006) notes multiple equilibria associated with technology adoption, but his models are represented in a single stage. Accordingly, he simply mentions the necessity of coordination among the players (which are countries in his case) in terms of technology adoption and does not discuss the difficulty of coordination when the problem has a time horizon.

3. Multi-period case

In a multi-period case, anticipation of technology adoption has even a stronger meaning for the dynamics of the system. Here, expectations and decisions at individual time steps have an accumulative effect on the dynamics in the future, in other words, expectations can be self-fulfilling. Importantly, such self-fulfilling dynamics can emerge even without uncertainty of climate policy.

To clarify this point, here we impose two stringent additional assumptions onto the model. First, carbon policy is fixed over time and thus has no uncertainty.[9] Second, expectations are not arbitrary – the firms form their expectations in a rational way, and the firms also know that other firms form their expectations rationally and behave rationally.[10] Indeed, the model is a reframed version of the "history versus expectations" model discussed by Krugman (1991),[11] which is originally used for investigating shifts of labor force between the traditional and modern industries in a pre-industrial economy. In the version below, the sectoral difference is replaced with the difference in technologies with regard to emission intensities. Here, the climate policy requires carbon dioxide emitters to pay carbon tax commensurate to the amount of emissions (or equivalently, to buy tradable permits whose price is determined exogenously) – note that the pricing scheme is not a domestic tradable permit system, which is equivalent with direct quantity control in this single-technology model as discussed in the previous section. The international climate policy is strong enough to keep climate change below a level that does not cause significant damage on the economy.

The economy is composed of *N* (fixed) firms with identical size and cost structures. Firms have perfect access to the international financial market with a constant interest rate *r* (>0,

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[9] As already discussed, it is not easy for this condition to hold in practice. The condition might be realized only under fairly special circumstances, for example, when the policy is endorsed by all political parties with a legally binding scheme, and the firms are also fully convinced of the policy's continuity.

[10] The assumption of perfect knowledge about others' incentive structures and rationality is consistent with that of most game-theoric studies, but it is in fact not obvious that this condition could realistically sustain since the firms generally do not possess a means to know that others have perfect knowledge. This question is addressed in the general literature of game theory and of its applications to economics (See for example, Aumann and Brandenburger, 1995).

[11] A more generalized version of the model is discussed by Matsuyama (1991).

$1/(1+r)=\beta$).[12] The firms have two technology choices, the dirty and clean technologies, which have different emission potentials. Firms can freely choose technologies in consideration of future benefits and current installation costs. The switching of technology requires fixed costs of firms at the time of introduction. Let the total fixed costs for all firms switching technology denote *F*.

The national income of the economy (*Y*) is expressed as the combination of gross output, carbon costs, and the initial costs (*F*) regarding technology switching between the dirty and clean technologies. With the same definitions of *c* (carbon penalty), *x* (penetration rate of clean technology), *l*(*x*) (clean technology's efficiency loss), and *κ*(*x*) (clean technology's emission saving) as in the previous section, *Y* is expressed as:

$$(10) \qquad Y = N\bar{y} - Nl(x)x - N\left[1 - x\kappa(x)\right]\cdot c - F$$

The social planner would seek to maximize the present value of output flow.

$$(11) \qquad \max W = \int_0^\infty Ye^{-rt}dt$$

In fact, actual economic decisions are taken by private firms, which do not internalize externalities (besides the carbon externality incorporated in the carbon penalty). Hence, below we

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[12] In general, the number of firms in an economy can change when the economy has perfect access to the international financial market (as market entry should be possible). An implicit assumption behind the fixed firm number of this model is that the labor force is internationally immobile, and that the size of labor limits expansion of the firm number.

focus our attention to the case of private decisions. Appendix sketches the conditions for the social optimum regarding this model. The firms make their technology choice by weighing the initial switching costs and the present-value expected increase of profit by switching its technology – they switch technologies when the present-value net expected return exceeds the initial costs. Let us define the “shadow value of having the clean production technology instead of the dirty technology” as *q*. The shadow value represents the present value of per-firm net benefit of having the clean technology and is expressed as:

$$(12) \qquad q(t) = \int_{t}^{\infty} (\kappa_s c_s - l_s) e^{-r(s-t)} d$$

Note that the parameters κ, c and l could be time-dependent (the subscript s is put to the parameters in (1) to signify that they represent values at time s). Also note that q depends on the expected future levels of x, in other words, the level of q reflects how others firms will behave in the future. If the economy is at equilibrium as it progresses, this shadow value q should be matched with the marginal (instantaneous) cost of technology switching.

The marginal switching cost (increase of F by entry of a new firm) may show some proportional relationship to the total number of firms switching at that time point[13] – it suppresses an instant technology switching by all firms and thus makes the case more realistic and a dynamic analysis more illustrative. Such functions may be of various forms, but here we adopt Mussa’s (1978) formulation of switching cost of production technology: The costs of technology switching

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[13] This is the case when, for instance, installation costs of equipment reflect the supply curves of inputs. A supportive fact for this assumption is that the construction costs of new fossil-fuel power plants in recent years have risen rapidly mainly due to a demand increase in emerging economies (e.g., “Price of new power plants rises sharply,” New York Times, July 10, 2007).

exclusively fall on the “moving industry,” which takes care of all necessities associated with a shift of production technologies (“moving”). The moving industry is competitive, and the production of moving firms is determined by a fixed stock of resources specific to the industry and a variable factor (labor). This leads to the feature that the technology for the moving industry shows a diminishing return to the variable input. Based on this logic, Mussa as well as Krugman (1991) assume that the aggregate amount of technology switching costs across agents follows a quadratic function to the number of agents switching their mode of production at each time point. Applying this formulation to our case, we assume that the marginal switching cost (denoted by *f*) takes a linear cost function of the number of firms switching.

The function could be expressed as $\alpha\dot{x}$ where α (>0) is a constant (note that N is fixed). At each time point, firms switching technologies move into either of the directions in unison, as individual firms clearly benefit from bandwagoning.[14] At equilibrium, the marginal switching cost should be matched with q, therefore:

(13) $\alpha\dot{x} = q$

Meanwhile, the functional form of (1) leads to the following differential equation on q:

(14) $r \; = q(\kappa c - l) + \dot{q}$

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[14] If firms were rational and perfectly knew others’ motives for movements at each step, nonconformist shifts countering others’ choices would be suppressed because such shifts do not benefit the firms.

The equations (2) or (2′) and (3) determine the dynamics of the system. General solutions for such a model would involve multiple stationary states in the interior of the system that produce complex dynamic patters.[15] But the model is presented for the purpose of illustration, and finding complete solutions for this particular model does not carry central importance to the discussion. As for simplification of the model, a representation of technology externality as a linear function (in line with Krugman) would significantly reduce complexity of the model and allow us clear interpretations of results. From this standpoint, we narrow our scope to one illustrative case with the assumptions of $\kappa(x) = \phi x - \kappa^*$, $l(x) = l^* - \theta x$, $\phi c - \kappa^* c - l^* + \theta > 0$ $(\varphi, \kappa^*, l^*, \theta, c > 0)$. With these formulations, the clean technology is advantageous over the dirty one with a full penetration (x=1) but disadvantageous with a zero penetration (x=0) – it sets up two equilibria for the system, and then the question is whether and how the system moves to either of these equilibria.

The paths of x and q are obtained by tracing them backwards from two long-run equilibria (where x=0 or 1). The roots of exponential functions to determine the system defined by (13) and (14) are

$$\text{(15)} \qquad \rho = \frac{1}{2}\left[r \pm \sqrt{r^2 - \frac{4(\phi c + \theta)}{\alpha}} \right]$$

Note that $r^2 - \dfrac{4(\phi c + \theta)}{\alpha}$ can be both positive and negative. If positive, the system has a real positive root. If negative, the system has a complex root with a positive real part.

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[15] Matsuyama (1991) investigates this aspect by using a similar model

Figure 1 illustrates the dynamics of two cases. Let us first examine the case with a real root (Figure 1(i)). With a real root, the system is determinate and hence does not show expectation-driven dynamics. Two paths could be drawn from A_c or A_d and reach either of the two equilibria (G^c_0 and G^d_0 for $c=c_0$). The equilibrium with $x=1$ is preferable to that with $x=0$ for the social planner as well as for the firms, but both equilibria might be attained as the dynamics evolve through a succession of private decisions without a coordination mechanism. A positive q exceeding the instantaneous switching (moving) costs sets an incentive for individual private firms to switch to the clean technology, while the a negative q greater in magnitude than the instantaneous switching costs to the dirty technology induces firms to abandon the clean technology and switch to the dirty one. The graph shows that each value of x could correspond to at most one point on either of the trajectories. In other words, the initial state uniquely determines the long-run penetration rate of the clean technology – either a full penetration ($x=1$) or a zero penetration ($x=0$). With a higher level of carbon penalty ($c=c^*$), the path to full technology adoption starts with a lower x, and the path to a full technology abandonment also starts with a lower x relative to the lower penalty case (paths G^{c*} and G^{d*}). This feature is consistent with the intuition that a higher carbon price should promote the clean technology and should discourage a continuous use of the dirty one.

Meanwhile, expectations play a prominent role in the case with a complex root. In this case, the trajectories show oscillatory patterns, and their arms could cover wide ranges of x. When the two arms have an overlap over a span of x (an example shown in Figure 1 (ii)), the initial state does not determine the direction the path moves – in fact, there are numerous feasible paths that the economy can take. In such a circumstance, it is agents' expectations about future technology penetration that determine the growth (or decline) of technology penetration, as exogenous factors (such as the carbon penalty) do not condition the economy to follow a unique path.[16] In other words, even if there is a feasible path leading to the full penetration of the clean technology (for example, Z_c on the graph), sheer pessimism about future adoption by others could prevent the economy from taking the path and instead could make it follow the trajectory to the zero adoption (Z_d). It is worthwhile to note that given the formulation of ρ, a high level of carbon penalty is a factor that may shift the system towards a one with a complex root, and therefore the system would become more indeterminate.

One obvious solution to this indeterminacy problem is to raise the carbon price to the level at which firms can gain relative benefits from clean technology even if its penetration rate is zero, in other words, to force the firms to switch technologies through a very high carbon price. Such a drastic raise of carbon price, however, is not likely to be the best policy choice. As the carbon pricing mechanism is in effect an indirect taxation scheme, a high price itself is a factor to reduce economic efficiency with a large deadweight loss (given that the same amount of emission reduction could in principle be obtained at a lower carbon price). In fact, as suggested by some examples of major energy technologies such as the hydrogen-based energy system, the level of price incentive may need to be very high for forcing companies to adopt a technology with few existing users with whom they could share infrastructure or technical information. A better approach would be to influence firms' expectations about technology penetration through schemes such as technology standards and targets. In fact, a reverse argument of the above suggests rather a bright prospect of expectation-oriented policy schemes: a strongly punitive

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[16] This is essentially the same argument as Krugman's (1991), which is applied to a different context.

carbon pricing scheme may not be necessary if the government successfully manipulates firms' expectations about their future benefits.

In the second case, the firms take the low-equilibrium path not because they think that future climate policy will be weak, but because they fear that others will not adopt the clean technology for whatever reason. A possible criticism against such an expectation model is that pessimism could not be sustained for a long period since the existence of a favorable equilibrium is public knowledge. This is a legitimate argument and could indeed be the case. One can, however, point out some factors why the expectation aspect should not be overlooked in the context of climate policy in particular. As for climate change mitigation, there are many potential beliefs that could discourage companies from investment, such as the false understanding that climate change will never become significant, or the prospect that tough regulations could be blocked through political bargaining. After all, the need for actions against climate change has not been a common perception by major energy companies for a long time (e.g., Levy, 2005), and in a way, is still not. One should be reminded that such pessimistic perceptions do not have to be the majority view among companies for determining the path. Dynamics could change if only those minority perceptions could induce the majority to think that others would desert the emission-reducing technology.

4. Conclusion

The model is a simple representation of technology switching by firms in response to a price-based climate policy. It highlights the role of firms' expectations about future policy and future adoption of technology by other firms. Uncertainty about future carbon policy could weaken the effectiveness of the present carbon policy. When a new technology has a scale effect, expectations about future adoption of technology by other firms could determine the level of mitigation as well. In a multi-period case, the model shows that the path of emission reduction could progress as a self-fulfilling prophecy under certain conditions, in which firms' perception about future outcomes, i.e., optimism or pessimism, plays a role in determining the trajectory. While the carbon pricing generally drives firms towards more emission reduction, it may not help eliminate – in fact may even amplify – the ambiguity of emission reduction paths. A remedy for the problem is an introduction of policy schemes to align firms' expectations about future penetration of clean technology. This insight would provide a support for non-price-based mechanisms of climate policy, such as the EU's targets for renewable energy, because such policies may effectively align firms' expectations about technology adoption. Note that it is possible for such non-price-based schemes to be effective without incurring private costs in some cases.

A limitation of this paper is that much of its discussions are based on the assumption of network externality. Admittedly, not all emission reduction technologies exhibit a network externality. For example, a single operation of CCS consisting of on-site carbon dioxide capture and on-site gas storage (injection) does not deal with any network. However, if interpreted in a broad sense, network effects are prevalent in energy-related technologies. The transport sector, which produces a large proportion of total emissions, is subject to network effects as a whole because most modes of transportation are substitutable with public transportation, which is of network.

Also, even if a technology is not strictly network-dependent, it could still be subject to some scale effect coming from decrease in production costs of inputs with an expanding market size, as the case of CFC substitutes under the Montreal Protocol suggests (Barrett, 2003). Even in CCS's case, too, some indicate that large-scale deployment of CCS should accompany extensive pipeline networks for carbon dioxide transport from emission centers to gas storage sites (Haszeldine, 2009).

The aim of this paper is to highlight the potential importance of expectations and not to argue that all carbon-pricing schemes are destined to be nullified by the bandwagon dynamics. It is also important to note that general solutions from more general model settings could of course look different from this model's. Some important arguments made by previous studies of indeterminacy dynamics were not addressed in the model: for example, findings by some studies imply that indeterminacy may not emerge if the system is subject to some randomness and there is some likelihood that the use of either of technologies become the dominant strategy through a random development of the system (Morris and Shin, 1998; Frankel and Pauzner, 2000). Such factors omitted in the model could make expectations less relevant. On the other hand, however, it is fair to assume that complexity of the actual energy system should leave more grey zones where expectations drive dynamics than a simple model does. As a future research, it would be interesting to examine more complex cases, such as that of competing mitigation technologies. In general history of technology, examples of technology lock-in are prevalent, such as the wide adoption of the QWERTY keyboard despite its obvious inefficiency (David, 1985).

Finally, it is worthwhile to stress that this paper's discussion does not mean that we should reject the idea of market-based solution of climate change mitigation. It does suggest, however, that there might be a missing perspective in the conventional view of climate policy, that is, the effectiveness of market-based climate policy partly rests on people’s expectations. In a way, climate policy should be *expectation management*.

Appendix: Conditions for the social optimum in the multi-period case

The Hamiltonian is expressed as follows

(A1) $H = N\bar{y} - Nlx - N[1 - x\kappa] \cdot c - F(\dot{x}) + q\dot{x}$

where *q* is the co-state variable corresponding to the shadow value of having a unit of the clean technology rather than the dirty technology (which in fact identical with *q* discussed in text). The control and state variables for the Hamiltonian are x dot and x, respectively.

The first-order conditions are:

(A2) $\dfrac{\partial H}{\partial \dot{x}} = -\alpha\dot{x} + q = 0$

(A3) $\dfrac{dq}{dt} = \dot{q} = rq - \left[(\kappa c - l) + \left(\dfrac{d\kappa}{dx} c - \dfrac{dl}{dx} \right) x \right]$

Note the correspondence between the second condition (A3) and $rq = (\kappa c - l) + \dot{q}$ (condition (14) in the main text). The latter is a special case of the former when κ and l are exogenous. In the latter, the private agent does not consider the value from externality regarding *x*.

With $\kappa(x) = \phi x - \kappa^*$, $l(x) = l^* - \theta x$ (as in the private decision case), the condition (A3) is expressed as:

(A4) $\dot{q} = rq - \left[2(\phi c + \theta)x - \kappa^* c - l^* \right]$

The conditions (A2) and (A4) imply the basic patterns of private solutions hold the same for the social optimum as well. Now the roots are:

$$\text{(A5)} \qquad \rho' = \frac{1}{2}\left[r \pm \sqrt{r^2 - \frac{8(\phi c + \theta)}{\alpha}} \right]$$

and when q=0 $x = \left(\kappa^* c + l^*\right)/\, 2(\phi c + \theta)$

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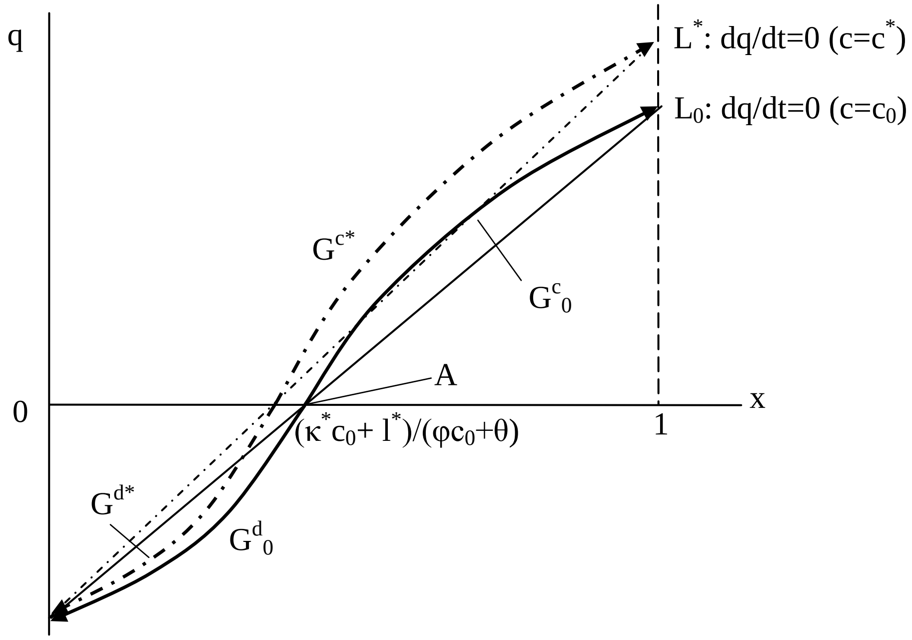
Figure 1. Possible dynamic structures of the system

(i) The roots are real



(ii) The roots are complex (when arms overlap over a range of x)