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Directed Technical Change, Unilateral Actions, and Climate Change

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Abstract

In this paper, I investigate the implications of policy-induced technological change based on a multi-region variant of the directed technical change model developed by Acemoglu et al. (2012). On top of the pollution externality accompanied by carbon dioxide emission, different regions are connected through a global market where energy-related machine producing firms monopolistically compete with each other. One of the main findings of the analysis is that unilaterally introduced climate policies in developed regions might have only a slight short-term impact at a global level, but later will turn out to be a basis for low-carbon development in developing regions as well as developed regions. The simulation results indicate that an extension of the Kyoto protocol, if appropriately designed, can trigger a long-term shift in energy use at a global level even without active involvement of the United States. Moreover, if the United States decides to join the treaty and a fairly moderate abatement target is agreed upon among the member states, the similar level of long-term environmental consequence as in the universal climate regime can be replicated without explicit participation of developing regions.

Keywords: Climate change, directed technical change, unilateral policy, innovation, Kyoto protocol

JEL codes: O31, O33, Q54, Q55, Q58

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1 Introduction

If a transition to a low-carbon economy is seriously pursued, technological change should play a key role. It is hard to imagine how our economy, which is heavily dependent on fossil-fuel consumption, can transform itself into a basis for sustainable development without the help of technological innovation. Technological innovation is especially needed in the field of energy production and consumption. Although an immediate and complete shift toward non-fossil fuel energy is theoretically possible, such a drastic option would entail unacceptably large cost to the society. Hence, any successful strategy to build a low-carbon economy must be based on a sensible and careful understanding of what kind of technological options are currently available and in which direction the technology will develop in the future.

The critical role of technology, however, does not imply that climate policies can play only a limited part in addressing the problem. It rather implies a potentially pivotal role of climate policies. While technological change is an essential element in designing a reasonable climate policy, a well-designed climate policy is crucial to technological change. As Popp (2005) points out, if environmental regulations reduce uncertainty surrounding the profitability of investment in environmentally friendly technologies, then sufficiently stringent environmental policies may trigger the research and development activities, which in turn lead to technological innovation. This claim is in fact supported by several empirical studies (Jaffe and Palmer, 1997; Berman and Bui, 2001). In addition, as empirical evidence provided by Popp (2002) suggests, energy-saving innovations might be induced by changes in energy prices. If this is the case, the introduction of a carbon tax on fossil fuel consumption would encourage innovation towards greater energy efficiency.

Another important aspect of technological change in the context of climate policy is the interplay between regions. Since globalization becomes more and more intense, economies in different regions are becoming increasingly intertwined with each other. In such a highly globalized world, an introduction of climate policy in one region does not only affect the decision making of domestic firms, but also influence behavior of firms operating in a global market. It then seems not very reasonable to assume the impact of technological change is restricted within regional boundaries. We should rather allow for the possibility that an endogenously induced technological innovation is transmitted from one region to another through globally operating economic agents. This aspect of policy-induced technological change is of great policy relevance since it might imply that unilateral climate policy in a group of countries can encourage clean technological innovation in countries outside the group.

Despite the intuitive appeal and the existing empirical evidence of policy-induced technological innovation, most economic models used for analyzing the interaction between climate and economy take technological development as an exogenous variable (Nordhaus, 1994; Nordhaus and Yang, 2007; Tol, 1999). Among a few exceptions is Popp (2004), who considered endogenous technological innovation in the energy sector. His model is based on the DICE model of Nordhaus (1994), which is in essence an aggregated macroeconomic model with a simple climate system on top of the economic module. Another notable exception is Grimaud et al. (2011), who also allowed for policy-induced technical change based on the ENTICE-BR model of Popp (2006).

In recent years, partly due to the growing recognition of critical role that technological change may play, the concept of "directed technical change" has been attracting much attention in the literature of economic theory (Acemoglu, 2002). Unlike the standard modeling of technological development, the directed technical change model explicitly describes the channel through which the direction of technical change, or which type of technology is developed, is endogenously determined. By applying the concept of directed technical change to a simple climate-economy model, Acemoglu et al. (2012) show that technical change can be "redirected" from dirty to clean technologies by policy intervention. Their result indicates that only a relatively short period of stringent climate policies can facilitate the switch from dirty innovation to cleaner ones. While these existing studies provide interesting insights, their analysis is based on a globally aggregated model, and hence fails to consider the role of the interplay between heterogeneous regions.

In this paper, I therefore investigate the implications of policy induced technological change based on a decentralized multi-region climate economy model. Following the approach of Acemoglu et al. (2012), I distinguish fossil-fuel and non-fossil-fuel energy production processes and allow for the possibility that innovation occurs at a particular type of energy production process. On top of the pollution externality accompanied by carbon dioxide emission, different regions are connected through a global market where energy-related machine producing firms monopolistically compete with each other. This way, I explicitly model a channel through which unilateral climate policies can have a dynamic influence beyond regional boundaries. In addition to theoretical analysis, I conduct a series of numerical simulations based on a calibrated model. Based on scenario analysis with specific climate policy, I derive concrete policy implications for the ongoing efforts in designing an effective international framework to combat climate change.

The remainder of this paper is structured as follows. Section 2 presents the model in detail. Based on the model described in section 2, section 3 analytically characterizes the equilibrium. By specifying functional forms and calibrating the entire model, section 4 examines more concrete policy implications based on numerical simulations. Section 5 concludes the paper.

2 The Model

I consider a stylized world consisting of $J > 1$ regions. Each region has its own economy within which households and firms interact with each other through a competitive domestic market. Interaction among different regions exists in two respects: climate damage and technological innovation. In line with the literature on climate-economy modeling, I assume that each region locally emit carbon dioxide as a byproduct of economic activities and thus contribute to the global atmospheric carbon concentration. The increased carbon concentration then changes the dynamics of global mean temperature, which in turn causes adverse climatic impacts across different regions. As another channel of interaction, I introduce an energy-related machine production sector where individual firms supply their machines in a global market. Following the literature on endogenous technical change, I assume these firms are monopolistically competitive and their profits are the driving force behind technological innovations. Since profits of these globally-operating firms naturally depend on energy demand of each region, policy interventions on regional energy sector affects the scale and the direction of technological development. In the following, I describe the model in detail.

Production

Each economy contains three production sectors: final output, final energy production, and primary energy production. Final output Y_{jt} of region j at period t is produced using capital K_{jt}, final energy input X_{jt}, and labor L_{jt} through the aggregate production function

$$Y_{jt} = \psi_{jt} K_{jt}^{\alpha} X_{jt}^{\beta} L_{jt}^{1-\alpha-\beta}. \tag{2.1}$$

So the profit Π_{jt} of the representative firm in the final output sector is given by

$$\Pi_{jt} = Y_{jt} - (r_{jt} + \delta^k) K_{jt} - p_{jt} X_{jt} - w_{jt} L_{jt}, \tag{2.2}$$

where r_{jt} is the interest rate, δ^k is the capital depreciation rate, p_{jt} is the price of energy input, and w_{jt} is the wage of labor input. The price of final output is normalized to unity.

The final energy input is supplied by the representative firm in the final energy-producing sector according to the production function

$$X_{jt} = \left\{ X_{jct}^{\frac{\epsilon-1}{\epsilon}} + X_{jdt}^{\frac{\epsilon-1}{\epsilon}} \right\}^{\frac{\epsilon}{\epsilon-1}}, \tag{2.3}$$

where X_{jct} and X_{jdt} denote the primary energy input based on non-fossil fuel (or 'clean') and fossil fuel (or 'dirty') resource, respectively. The parameter ϵ represents the elasticity of substitution between the two primary energy inputs. The two inputs are substitutes when $\epsilon > 1$ and complements when $\epsilon < 1$. Since non-fossil fuel inputs can usually substitute for fossil ones, I assume hereafter $\epsilon > 1$.

The main difference between the two primary energy inputs is that the 'clean' energy can be produced without emitting carbon dioxide whereas the 'dirty' one necessarily pollutes the climate. This fact is captured by assuming the level of carbon emission E_{jt} is determined by

$$E_{jt} = \sigma_{jt} X_{jdt}, \tag{2.4}$$

meaning that carbon emission only depends on the fossil-fuel-based energy input. If the level of carbon emission is to be controlled, governments can introduce a carbon tax τ_{jt} on the final energy producing firm. So the profit π_{jt} of the firm in energy-producing sector is given by

$$\pi_{jt} = p_{jt} X_{jt} - p_{jct} X_{jct} - p_{jdt}(1 + \tau_{jt}) X_{jdt}, \tag{2.5}$$

where p_{jct} and p_{jdt} denote the price of non-fossil fuel and fossil fuel primary energy input, respectively.

The primary energy production sector consists of two representative firms: one for 'clean' energy and the other for 'dirty' energy. For $k \in \{c, d\}$, the corresponding primary energy input X_{jkt} is produced by using labor L_{jkt} and a variety of machines $x_{jkt(i)}$ supplied by a continuum of energy-related machine production firms in a global market. Following Acemoglu et al. (2012), I specify the production function by

$$X_{jkt} = L_{jkt}^{1-\gamma} \int_0^1 A_{jkt(i)}^{1-\gamma} x_{jkt(i)}^{\gamma} di, \tag{2.6}$$

where $A_{jkt(i)}$ represents the productivity of machine of type $i \in [0, 1]$ used by firm k in region j at time t. The profit of the firms in energy-technology sector is thus given by

$$\pi_{jkt} = p_{jkt} X_{jkt} - w_{jt} L_{jkt} - \int_0^1 p_{kt(i)} x_{jkt(i)} di, \tag{2.7}$$

where $p_{kt(i)}$ is the price of machine of type i used by firm k at time t.

In addition to these domestic sectors, I assume there exists a global market where a continuum of machine producing firms operates. As in Acemoglu et al. (2012), I assume that, regardless of the quality of machines and of the sector for which they are employed, producing one unit of any machine costs χ unit of a final good. This means that the profit of firms in the machine-producing sector is given by

$$\pi_{kt(i)} = (p_{kt(i)} - \chi) \sum_j x_{jkt(i)},$$

for $k \in \{c, d\}$ and $i \in [0, 1]$. Notice here that $p_{kt(i)}$ is independent of j. This is because the machine producing firms operate in the global market, and thus the price is equalized across regions.

Directed technical change

The innovation dynamics in productivity of the energy-related machine is governed by

$$A_{jkt+1} = [1 + g_{jkt}(s_t)]\, A_{jkt}, \quad \text{where} \quad A_{jkt} = \int_0^1 A_{jkt(i)} di \tag{2.8}$$

for $k \in \{c, d\}$. Here, g_{jkt} denotes the growth rate of A_{jkt}, which represents the average productivity of machines used for producing energy input of type k. The growth rate depends on s_t, the fraction of 'scientists' or 'entrepreneurs' who engage in the clean-energy related sector. We assume $\partial g_{jkt}(s_t)/\partial s_t > 0$ for $k = c$ and $\partial g_{jkt}(s_t)/\partial s_t < 0$ for $k = d$ so that the more scientists engage in a sector, the more likely innovations are induced in the sector.

A key assumption here is that these scientists work in the global job market or the global financial market if interpreted as entrepreneurs. In other words, s_t is intended to capture the global trend of energy-related research and development activities. It thus seems natural to assume that this trend is influenced by the relative profitability υ_t of clean energy industry,

$$s_t = F(\upsilon_t), \quad \text{where} \quad \upsilon_t = \int_0^1 \pi_{ct(i)} di \Big/ \int_0^1 \pi_{dt(i)} di, \tag{2.9}$$

for some distribution function F with support $\mathbb{R}_+$. I assume $F(1) = 0.5$ so that when $\upsilon_t = 1$, or the two different energy industries are equally profitable, the same number of scientists are allocated to each industry.

Households

I assume the utility of households depend on per capita consumption C_{jt}/N_{jt} and they behave so as to maximize the discounted sum of aggregate utilities over time

$$W_j = \sum_{t=1}^{T} \left(\frac{1}{1 + \rho} \right)^{t-1} N_{jt} \log(C_{jt}/N_{jt}) \tag{2.10}$$

subject to the budget constraints

$$r_{jt}K_{jt} + w_{jt}N_{jt} + \pi^{\theta}_{jt} = C_{jt} + K_{jt+1} - K_{jt} + T_{jt}, \tag{2.11}$$

and

$$N_{jt} = L_{jt} + L_{jct} + L_{jdt},$$

where T_{jt} is the lump sum tax imposed by regional governments. The profit gained by scientists is denoted as π^{θ}_{jt}, which is defined by

$$\pi^{\theta}_{jt} = \theta_{jt}\left[\int_0^1 \pi_{ct(i)}di + \int_0^1 \pi_{dt(i)}di\right], \quad \text{with} \quad \sum_j \theta_{jt} = 1, \tag{2.12}$$

where θ_{jt} is the share of the global stock of scientists living in region j at time t. For simplicity, I assume $\theta_{jt} = 1/J$, which means scientists are uniformly distributed across regions and this does not change over time.

Climate, damage, and government

Climate system of this model is a simplified version of the DICE model of Nordhaus (1994). As in the standard climate-economy model, the global carbon concentration M_t evolves over time according to the dynamic function

$$M_{t+1} = (1-\delta^c)M_t + \sum_{j=1}^{J} E_{jt}, \tag{2.13}$$

where δ^c is the depreciation rate of carbon stock in the air. Global mean temperature Z_t is then determined by

$$Z_{t+1} = Z_t + \iota\left(F^a_t + F^c_{\times 2}\frac{\log(M_t/M_{1750})}{\log(2)} - \frac{F_{\times 2}}{Z_{\times 2}}Z_t\right), \tag{2.14}$$

where F^a_t is the (exogenous) radiative forcing from other greenhouse gasses. Although this is much simpler than the original DICE model, I believe this specification can capture the essence of the climate-economy interaction without causing unnecessary complexities in the analysis.

As in the DICE model, the monetary valuation D_{jt} of climatic damage is determined by

$$D_{jt} = \frac{d_{jt}}{1+d_{jt}}Y_{jt} \quad \text{where} \quad d_{jt} = \xi_{1,j}Z_t + \xi_{2,j}Z_t^2. \tag{2.15}$$

I assume any damage caused by climate change is covered by governmental spending, which can be financed by the lump sum taxation on households or

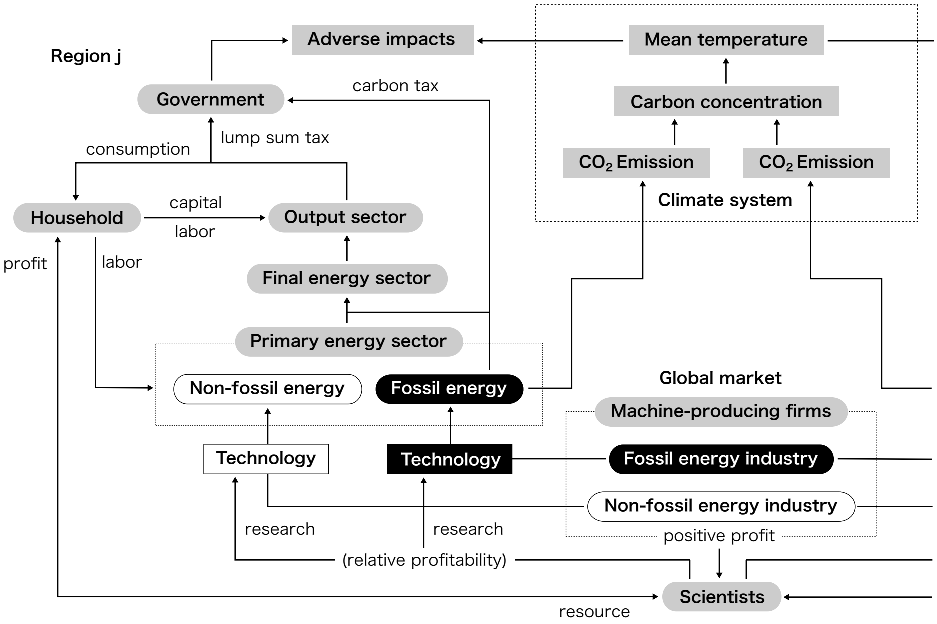

Figure 1: Model at a glance

the carbon tax on energy producing firms. Hence, the budget constraint of the government is given by

$$T_{jt} + p_{jdt}\tau_{jt}X_{jdt} = D_{jt}. \tag{2.16}$$

Notice that in the laissez-faire or business as usual scenario, where $\tau_{jt} = 0$ for all j and t, the adverse impacts of climate change are, in essence, directly borne by households.

Some aspects of our model is depicted in Figure 1. I define the equilibrium of this economy by a set of variables which simultaneously solves a) firms' profit maximization problems in each sector, and b) households' utility maximization problems, given the behaviors of the other regions and a fixed policy variable τ_{jt}.

3 Theoretical predictions

In this section, I briefly characterize the equilibrium with an emphasis on some important variables, although I do not go through technical details of each expression. Derivation of the equilibrium is relegated to Appendix A.1. The primary purpose of this section is to show that the model can provide a reasonable description of the reality, and thus can be readily applied to the numerical analysis in the next section to derive more concrete implications.

3.1 Laissez-faire economy

The laissez-faire economy, which is defined as the equilibrium with $\tau_{jt} = 0$, is a useful baseline scenario since it describes how the economy evolves over time without policy interventions. In particular, two aspects of the economy are highlighted: energy structure and technological innovation. First, energy structure, by which I mean how non-fossil fuel and fossil fuel primary energies are mixed to produce final energy, is important both in terms of environmental and economic variables. From an environmental point of view, it affects carbon intensiveness of the economy. As is clear from the production function (2.3) for final energy, various combinations of non-fossil fuel and fossil fuel primary energies are possible to produce a fixed level of final energy. Since carbon dioxide is emitted from using fossil fuel primary energy, more use of non-fossil fuel primary energy should be encouraged if low-carbon development is to be achieved.

From an economic point of view, on the other hand, switching to 'clean' energy from 'dirty' one is not always desirable. This is primarily due to technological constraints. When the non-fossil fuel based energy production technology is immature relative to the fossil fuel counterpart and it is thus relatively difficult to produce 'clean' energy, switching the primary energy sources in favor of cleaner alternatives would be costly to the economy. In fact, at the laissez-faire equilibrium of this economy, the relative price of non-fossil fuel primary energy is determined by

$$\frac{p_{jct}}{p_{jdt}} = \left(\frac{A_{jdt}}{A_{jct}}\right)^{1-\gamma}. \tag{3.1}$$

This means that non-fossil fuel energy is more expensive when fossil fuel based technology is relatively more advanced (i.e., when $A_{jdt} > A_{jct}$).

At the laissez-faire equilibrium, where the hidden price of carbon emission is not internalized in individuals' decision making, the choice of energy structure is almost entirely driven by the relative cost of each energy source. Hence, a more technologically advanced and thus less expensive primary energy source is preferred. This point can be well illustrated by noting at the equilibrium, the energy structure, which is essentially captured by the ratio X_{jct}/X_{jdt}, is given by

$$\frac{X_{jct}}{X_{jdt}} = \left(\frac{p_{jct}}{p_{jdt}}\right)^{-\epsilon} = \left(\frac{A_{jct}}{A_{jdt}}\right)^{\epsilon(1-\gamma)}. \tag{3.2}$$

As a result, the fossil fuel energy input will continue to be used unless production process of non-fossil fuel energy is technologically advanced and becomes less expensive in the future.

This brings us to the second important question: how is the direction of technological development determined? As explained in the preceding section, it is assumed to depend on the global trend of energy-related research and development, and such a trend is affected by the relative profitability of each primary energy industry. Where a relatively large profit is expected, intellectual and financial resources flow into and, as a consequence, technological innovations are more likely to occur. This assumption is captured by (2.8) and (2.9) above.

A question of particular interest then is what the determinants of the relative profitability are. This question can be readily investigated by looking at the relative profitability of non-fossil fuel energy industry at the equilibrium, which is computed as

$$\upsilon_t = \frac{\sum_j L_{jct} p_{jct}^{\frac{1}{1-\gamma}} A_{jct}}{\sum_j L_{jdt} p_{jdt}^{\frac{1}{1-\gamma}} A_{jdt}} = \frac{\sum_j \left[A_{jct}^{\varphi}/(A_{jct}^{\varphi} + A_{jdt}^{\varphi})\right] Y_{jt}}{\sum_j \left[A_{jdt}^{\varphi}/(A_{jct}^{\varphi} + A_{jdt}^{\varphi})\right] Y_{jt}}, \tag{3.3}$$

where $\varphi := -(1-\gamma)(1-\epsilon) > 0$. Let us first examine the right-hand side of the first equality. This expression tells us the relative profitability depends on L_{jkt}, p_{jkt}, and A_{jkt}. As Acemoglu et al. (2012) points out, each of the three determinants encourages (i) innovation in the sector with greater employment, and thus with the larger market for machines, (ii) innovation towards the sector with higher prices, and (iii) innovation in the sector with higher productivity, which results from what they call the 'building-on-the-shoulders-of-giants' effect.

Taking a look at the very right-hand side of the equation reveals another insight. This expression clearly shows that the relative profitability is in large part determined by the relative productivity of each primary energy source. Hence, this result also indicates that a positive feedback effect or 'inertia' in technological innovations exists. When energy-related technology of a particular type is more advanced than the other, the corresponding energy industry would become relatively more profitable, attracting more intellectual and financial resources for research and development, and as a result, would enjoy further technological advancement in the future. Put differently, a currently advanced energy-related technology will be even more advanced in the future for the very reason that it is currently advanced. This is an alarming result in the context of climate change. It basically implies that if the fossil-fuel-based technology is relatively more advanced than the cleaner alternatives, we are and will continue to be locked in the current energy structure which produces a large amount of carbon dioxide.

Also worth noting here is that the direction of technological development can be reversed by changing the relative productivity of non-fossil fuel energy against fossil fuel energy, especially in regions with a large economy. As is clear from (3.3), not only the relative productivity *among different energy sources*, but also the relative size of economy *across different regions* (captured by the term Y_{jt}) play a part. If, for instance, the relative productivity of non-fossil fuel technology is significantly improved in large economies, then the global trend of energy-related research and development could be redirected toward cleaner technologies even if the fossil-fuel-based technology is currently more advanced in smaller economies. Consequently, the productivity of ‘clean’ technology could outweigh that of ‘dirty’ technology in smaller economies as well in the long run.

3.2 Temporary and dynamic impacts of policy interventions

Let us now turn to the case when governments introduce a carbon tax schedule $\tau_{jt} > 0$ in some regions. This policy intervention increases the effective price of fossil fuel primary energy from p_{jdt} to $p_{jdt}(1+\tau_{jt})$. So the energy structure, determined by (3.2) in the laissez-faire equilibrium, is now rewritten as

$$\frac{X_{jct}}{X_{jdt}} = \left(\frac{p_{jct}}{p_{jdt}(1+\tau_{jt})}\right)^{-\epsilon} = (1+\tau_{jt})^{\epsilon}\left(\frac{A_{jct}}{A_{jdt}}\right)^{\epsilon(1-\gamma)}, \tag{3.4}$$

which is increasing in τ_{jt}. This means that a carbon tax can facilitate a shift from fossil fuel to non-fossil fuel energy input for a given level of technologies. Hence, introducing a carbon tax in a region is actually effective in changing energy structure of the region in favor of climate. Yet, of course, this does not come without cost. A bit tedious algebra shows that a marginal increase of τ_{jt} from the laissez-fair equilibrium decreases the output Y_{jt} of final good whenever $\epsilon > 2-\gamma$. As we will see in the numerical analysis below, ϵ is likely to be larger than 2 in the case of energy production. Therefore, in the short run, switching from fossil fuel to non-fossil fuel energy can be realized only at the expense of economic benefit.

What is of greater interest, however, is the dynamic consequence of a carbon tax. Once a carbon tax is imposed on firms in the final energy sector, they replace a part of their demand for fossil fuel primary energy input with a non-fossil fuel alternative, which in turn affects the profit of globally-operating machine-producing firms in each energy industry. Such a change in the relative profitability of different energy industries then redirects intellectual and financial resources from one industry to the other, resulting in a dynamic shift of growth paths of energy-related technologies.

This can be formally shown by observing that the relative profitability of clean energy industry is now given by

$$\upsilon_t = \frac{\sum_j \left[A_{jct}^{\varphi}/(A_{jct}^{\varphi} + A_{jdt}^{\varphi}(1+\tau_{jt})^{1-\epsilon})\right] Y_{jt}}{\sum_j \left[A_{jdt}^{\varphi}(1+\tau_{jt})^{-\epsilon}/(A_{jct}^{\varphi} + A_{jdt}^{\varphi}(1+\tau_{jt})^{1-\epsilon})\right] Y_{jt}}. \tag{3.5}$$

Again, this is increasing in τ_{jt}, meaning that the introduction of a carbon tax changes the relative profitability in favor of non-fossil fuel energy. Hence, climate policy of this kind could help non-fossil fuel energy industry attract more resources for research and development. An immediate consequence of this is that technologies relating to cleaner energy production will be more advanced in the subsequent periods than they would be in the absence of a carbon tax. The improved productivity of non-fossil-fuel-based technologies then pushes down the cost of producing cleaner energy, making it more competitive in the market.

A less obvious, but perhaps more important role of the carbon tax is that it could even reverse the inertia in technological innovation mentioned above. We have already seen that innovation is more likely to occur in the relatively advanced type of energy. This finding is, on one hand, worrying. If the technology of fossil fuel energy production is already more advanced, the non-fossil fuel energy industry will have no chance of catching up with the fossil fuel counterpart. On the other hand, this same fact could be rather encouraging. If the carbon tax is imposed at a sufficiently high rate and for a sufficiently long period, up to the point where the growth paths of technologies are entirely redirected, switching from fossil fuel to non-fossil fuel energy will be autonomous thereafter. Taking into account this dynamic effect of the carbon tax, it might be stated that a temporal climate policy, if appropriately designed and implemented, would be sufficient to address climate change.

The significance of this observation can be highlighted if we notice that the introduction of a carbon tax only in a limited number of regions can trigger the redirection of technological development at a global level. In particular, the expression (3.5) tells us that the dynamic effect of the carbon tax on the direction of technological development is larger in regions with larger output. This implies that developed regions, which usually have larger output, play a relatively larger role in determining which type of energy-related technology is advanced at a global level. In other words, unilateral climate policies in developed regions could trigger a shift in energy use in developing regions and thus facilitate their low-carbon development in the future. This theoretical prediction will be examined in the following section by using a numerically calibrated model.

4 Numerical simulations

In order to derive more concrete policy implications, this section provides the results of numerical simulations based on the model described above.

4.1 Calibration and policy scenarios

The model is calibrated in such a way that the equilibrium path of the laissez-faire economy matches a version of the IPCC A2 scenario provided by Riahi et al. (2007). Following their regional specification, I divide the world into eleven different regions: Western Europe (WEU), Pacific OECD (PAO), Former Soviet Union (FSU), Eastern Europe (EEU), North America (NAM), China and centrally planned Asia (CPA), South Asia (SOA), Other Pacific and Asia (OPA), Latin America and the Caribbean (LAM), Middle East and North Africa (MEA), and Sub-Saharan Africa (AFR). The precise definition of these regions is presented in Table 2 of Appendix A.2. While each is treated as a separate economic unit throughout the simulations, we sometimes aggregate the last five regions into one region as the "rest of the world" or ROW, just for an illustrative purpose.

To calibrate the dynamics of technological development, I specify the functional forms of F, g_{jct}, and g_{jdt} as

$$F(\upsilon_t) = 1 - \frac{1}{1 + \upsilon_t^{-\eta}}, \tag{4.1}$$

and

$$g_{jct}(s_t) = \bar{g}_{jct} + \delta_c^a s_t, \quad g_{jdt}(s_t) = \bar{g}_{jdt} + \delta_d^a (1 - s_t), \tag{4.2}$$

respectively. In (4.1), the parameter η can be interpreted as an index of adjustment cost for scientists to switch from fossil fuel to non-fossil fuel energy industry. A smaller value of η, for example, means that scientists can easily switch industries depending on the relative profitability. The benchmark value of this parameter is $\eta = 0.5$. Given the current level of fossil fuel and non-fossil fuel primary energy consumption, this assumption implies that about 10% of scientists are currently engaging in cleaner energy industry while the rest are all in fossil-fuel-based energy industry. Following Acemoglu et al. (2012), we assume $\delta_c^a = \delta_d^a = 0.02$ (annual value). The exogenous trend of energy-related technological innovation which cannot be explained by changes in s_t is captured by the parameters $\bar{g}_{jkt}$'s.

Every other parameter value is pinned down from estimations and projections provided by Riahi et al. (2007) and Nordhaus and Boyer (2000). Among the most important parameters is ϵ, the elasticity of substitution between fossil fuel and non-fossil fuel primary energies. I choose the value of this parameter such that the difference between simulated and projected values of final energy is minimized. The calibrated value is $\epsilon = 8.81$. This means that, just as expected, fossil fuel and non-fossil fuel primary energy sources are highly substitutable.

As shown in Figure 2, carbon dioxide emission under the laissez-faire scenario grows very rapidly. This is a consequence of our calibration. The emission level is the same as in the IPCC A2 scenario, which assumes relatively large carbon emissions. In 2010, the largest contributor to the global carbon emission is NAM, which includes the United States and Canada. The WEU and PAO regions, which contain the rest of the developed countries, also account for a

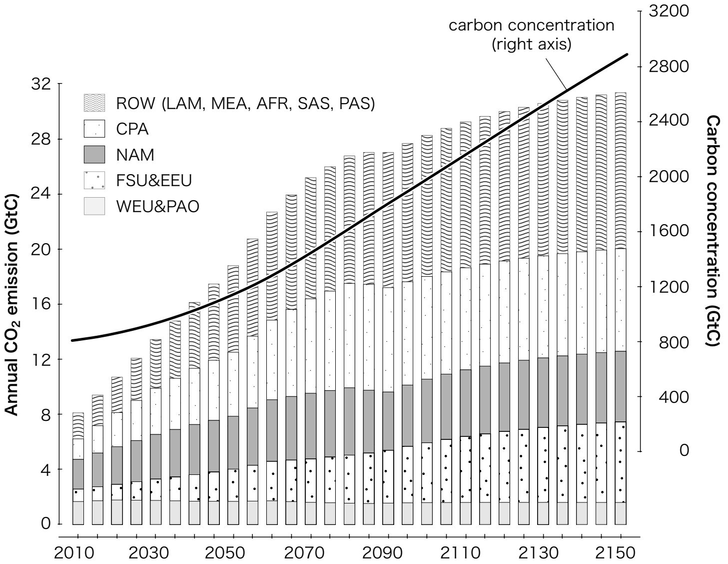

Figure 2: CO_2 emission and concentration in the baseline scenario (laissez-faire)

relatively large share of the total emission. Over time, however, the share of the developed regions declines and a larger part of the global carbon dioxide emission comes from developing regions. This predicted trend emphasizes the necessity of building a low-carbon economy, especially in developing countries. The level of carbon concentration rises from 810 GtC (or 380 ppm) in 2010 to 2888 GtC (or 1356 ppm) in 2150. This results in an increase of global mean temperature by 5.5°C relative to the level of 2010.

Taking the laissez-faire equilibrium as a baseline scenario, I consider six other scenarios with different assumptions on policy interventions. These scenarios are listed in Table 1. The first scenario is the Kyoto-low scenario. Under this scenario, a group of developed regions (WEU and PAO) introduces a common carbon tax scheme for a predetermined period of time (from 2015 to 2025). The common tax scheme in these like-minded regions is designed in such a way that the price of fossil-fuel based energy increases by 4%. This tax rate is more or less comparable to 35 US$ per tonne of carbon dioxide in these regions. In the light of the ongoing negotiation process of international climate treaties, it can be said that the assumption of this scenario corresponds to a weak extension of the Kyoto protocol. Neither the largest polluter among developed regions (namely, USA) or the rapidly growing developing regions (China in particular) joins the framework of international coordination. WEU and PAO take unilateral actions against climate change.

The second scenario, named Kyoto-high, assumes the same type of policy intervention within the same group of regions, but to a stronger extent. A higher

scenarios	policy intervention assumed in the scenario
Laissez-faire	No policy intervention assumed in any region
Kyoto-low	A low rate of carbon tax (4% increase in the price of fossil-fuel primary energy) is introduced in the WEU and PAO regions from 2015 to 2025
Kyoto-high	A high rate of carbon tax (6% increase in the price of fossil-fuel primary energy) is introduced in the WEU and PAO regions from 2015 to 2025
KyotoUS-low	A low rate of carbon tax is introduced in the WEU, PAO, and NAM regions from 2015 to 2025
KyotoUS-high	A high rate of carbon tax is introduced in the WEU, PAO, and NAM regions from 2015 to 2025
Global-low	A low rate of carbon tax is introduced in every region from 2015 to 2025
Global-high	A high rate of carbon tax is introduced in every region from 2015 to 2025

Table 1: Specification of policy scenarios

rate of carbon tax is introduced in WEU and PAO, which increases the price of fossil-fuel primary energy by 6%. This corresponds to around 50 US$ per tonne of carbon dioxide emission from fossil-fuel consumption. This scenario is intended to describe the situation in which the Kyoto protocol is extended by the like-minded countries with more ambitious abatement targets.

The third and fourth scenarios are labeled as KyotoUS-low and KyotoUS-high, respectively. These scenarios assumes an extension of the Kyoto protocol with the United States joining back to the treaty. To be more precise, in both scenarios, the NAM region as well as WEU and PAO introduce a carbon tax scheme. As in the Kyoto scenarios, 10 years of policy intervention is assumed from 2015. The two KyotoUS scenarios are only different in terms of the carbon tax rate. The former assumes a lower rate which causes 4% rise in the fossil-fuel energy price while the latter assumes a higher rate with 6% price hike in the fossil-fuel energy. These scenarios are relatively more optimistic than the first two. Yet participation of developing countries is still missing.

The last two scenarios, Global-low and Global-high, assume effective involvement of developing regions. In these scenarios, the carbon-tax regime is expanded to cover all the regions, including China and other developing countries. The tax scheme is designed in exactly the same way as in the first four scenarios; Global-low and Global-high assumes 4% and 6% increase in the fossil-fuel energy price, respectively. Notice that since the primary energy price is cheaper in developing regions, 4% price increase in the fossil-fuel energy leads to around 10 to 15 US$ per tonne of carbon dioxide in developing regions. For the same reason, 6% price increase in the fossil-fuel energy in developing regions leads to 15 to 24 US$ per tonne of carbon dioxide. Obviously, a universal participation of this kind is not likely to materialize in the near future. But these scenarios provide a useful benchmark against which other policy scenarios can be evaluated.

4.2 Results

I have discussed in the preceding section that the most direct impact of policy interventions can be found in the relative size of non-fossil fuel energy consumption, X_{jct}/X_{jdt}. This index plays a key role in addressing climate change since it controls how much carbon dioxide E_{jt} is emitted from final energy consumption. Table 3 and 4 summarize the results of these variables in seven different scenarios for selected regions. Table 3 shows that under the laissez-faire scenario, non-fossil-fuel based primary energy is not utilized much in all regions. The share of non-fossil fuel energy gradually increases over time, especially in WEU. Even in the WEU region, however, non-fossil fuel energy consumption does not catch up with fossil fuel energy until 2060. In NAM and CPA, fossil fuel will continue to be a dominant source of primary energy even in 2060. Consequently, a sharp increase of carbon dioxide emission can be seen over the next fifty years, especially in NAM and CPA. This is depicted in Table 4.

Tables 3 and 4 are around here

Once a carbon tax scheme is introduced in a region, primary energy use in the region experiences a temporary shift in favor of non-fossil fuel energy sources. In WEU, for instance, introduction of a low rate of carbon tax increases the ratio X_{jct}/X_{jdt} from 0.36 to 0.53 in 2020 under the Kyoto-low scenario. A higher tax rate introduced under the Kyoto-high scenario pushes the same index further up to 0.64. As a result, carbon dioxide emission in WEU declines by 14% relative to the laissez-faire scenario in the case of the low tax rate. The reduction rate is 21% if the higher rate of carbon tax is imposed. The carbon tax scheme works in the same way in other regions as well. In the KyotoUS-low and KyotoUS-high scenarios, both of which assume a successful return of the United States to the Kyoto protocol, immediate shifts toward more use of cleaner primary energy are seen in NAM in 2020, resulting in 11% and 17% reduction in the regional carbon dioxide emission, respectively. If developing regions join the carbon tax regime, as assumed under the Global-low and Global-high scenarios, carbon dioxide emission in CPA, which primarily consists of China, is reduced by 15% in the case of the low tax rate and by 22% in the case of the high tax rate right after the introduction of the carbon tax. These results are just as expected from the theoretical analysis above.

It should be noticed here that as far as the short-term impact is concerned, a carbon tax has almost no influence on the carbon emission from the regions outside the regime. In 2020, under the Kyoto scenarios, energy structure and carbon emission of NAM and CPA remain almost the same as in the laissez-faire scenario Hence, a unilateral carbon tax is not effective outside the tax regime, at least in the short run. Also worth noting is that the impacts generated by the introduction of the carbon tax significantly weaken after the tax is lifted in 2025. This is particularly the case in the Kyoto-low scenario. Table 4 shows that in 2030, right after policy intervention ceases, carbon dioxide emission in the WEU region regains the momentum and the emission level bounces back toward the level of the laissez-faire scenario. This 'rebound effect' is more or less true for the other scenarios as well. Therefore, at first glance, a temporary carbon tax seems to just make a short-lived push toward a low-carbon economy only in the regions within the cooperative regime.

In the long run, however, a carbon tax makes a striking difference even though the policy intervention itself is only temporary. Under the Kyoto scenarios, for example, the energy structure of WEU continuously shifts toward more use of clean energy even after the carbon tax is lifted, and the difference from the laissez-faire scenario becomes wider and wider as time goes by. This long-term consequence of a temporary carbon tax is more clearly highlighted if a higher tax rate is chosen and when a larger number of regions join the tax regime during the period of policy intervention. In the KyotoUS-high scenario, the share of non-fossil fuel in the total primary energy consumption reaches 94% (since $X_{jct}/X_{jdt} = 15.64$) in WEU in 2060 compared with 53% in the laissez-faire equilibrium. This remarkable shift in energy use is accompanied by an 85% reduction of regional carbon dioxide emission relative to the laissez-faire. The Global-low scenario has a slightly weaker, yet reasonably comparable long-term consequence.

The results indicate that seemingly small impacts of a carbon tax turn out to be very huge in the long run. This is primarily due to the dynamic impact of carbon tax discussed in the previous section. When a carbon tax is introduced in a region, the final energy sector of the region shifts the demand for primary energy from fossil fuel to non-fossil fuel sources. This means that regional demand for those machines required to produce fossil-fuel primary energy is temporarily suppressed, which in turn decreases the profit of machine-producing firms in the fossil-fuel industry at a global level. On the flip side, relative profitability of machine-producing firms in non-fossil fuel industry temporarily surges, encouraging scientists or entrepreneurs to redirect their intellectual and financial resource from fossil fuel to non-fossil fuel industry. In this model, this

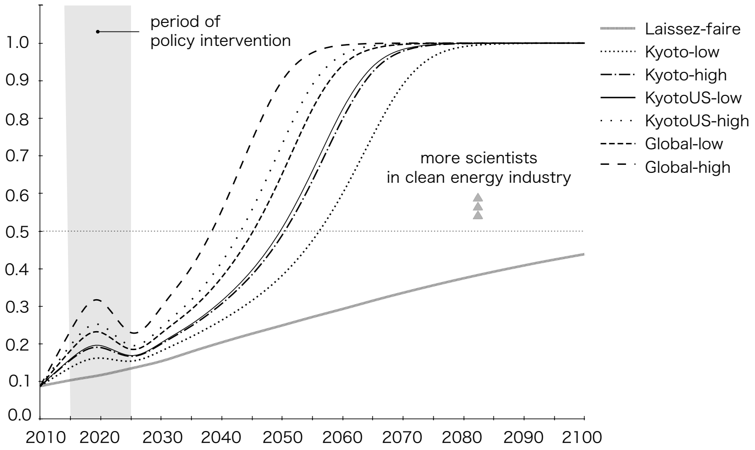

Figure 3: Fraction of scientists engaging in clean industry

phenomenon is nicely captured by the expression (3.5) and is numerically well confirmed in the simulations.

Figure 3 illustrates the dynamic impact of carbon tax on the direction of technological development. According to the calibration results, the fraction of scientists engaging in clean energy industry only gradually changes over time in the laissez-faire scenario, rising from 10% in 2010 to 44% in 2100. Put differently, scientists in the energy industry hesitantly migrate from fossil fuel to non-fossil fuel sector. This is reasonable since without policy intervention, profit of machine-producing firms in clean energy industry is and will continue to be smaller than the firms in the fossil-fuel industry. When a carbon tax is introduced in some regions, the global market for fossil-fuel energy production shrinks, tilting up the relative profitability of the clean energy industry, and thus prompting an earlier migration of scientists to the non-fossil energy sector. As a result, innovation in clean-energy related technologies becomes more likely to occur than in the laissez-fare scenario. In other words, direction of technological development in energy industry is changed in favor of clean energy. As is clear from the figure, how much the technological development is redirected depends on the magnitude of the carbon tax imposed and on how many regions join the tax regime.

Also clear from the figure is that the ‘gold-rush effect’ in the clean energy sector during the period of policy intervention fades away after the carbon tax is lifted. Yet those scientists who migrate to the clean energy industry do not completely go back to the fossil fuel energy industry. Moreover, unlike the laissez-faire scenario, scientists switch from the fossil fuel to the non-fossil fuel energy sector at an accelerating pace after 2025. This is due to the positive feedback nature of technological innovation. The gold rush brings about significant changes in the determinants of relative profitability mentioned above. The market for clean energy expands during the period of intervention, and the shoulder of the giants becomes higher thanks to the temporary surge of innovation in clean energy sector. Since those changes do not disappear even after the end of the policy intervention, relative profitability of clean energy industry remains relatively higher than the laissez-faire scenario even after 2025. Although small in the beginning, this change provides a basis for the positive feedback effect of clean innovation in the subsequent periods.

Another important point to note is that the dynamic impact of a carbon tax stretches beyond the boundary of the tax regime. In fact, it can be seen from Table 3 and 4 that the regions outside the regime are, in the long run, affected by a unilateral policy intervention. In the Kyoto scenarios, where a carbon tax is introduced only in WEU and PAO, the policy intervention at first does not affect energy structure nor carbon emission in NAM and CPA. But the dynamic impact gradually kicks in, not only to WEU, but also to NAM and CPA, changing the energy structure and reducing carbon emission in those regions. This result indicates that unilateral actions, if appropriately designed, do play a positive role in reducing global carbon emission in the long run although they seem to make little difference at first. If, for example, the United States come back to the Kyoto protocol and all the members to the treaty agree on a stricter abatement target as assumed in the KyotoUS-high scenario, that kind of agreement can significantly reduce carbon dioxide emission at a global level even without effective participation of developing countries.

Having said that, burden sharing among regions is a matter of great concern both form normative and practical point of views. Although detailed discussion about the burden sharing is beyond the scope of this paper, we can still ask ourselves how different the distributional consequence would be under different scenarios. To investigate this point, I take the Global-low and KyotoUS-high scenarios, and compare them in terms of final output in each region. These two scenarios assume different policy intervention and different members of the tax regime, but result in a similar long-term consequence. Global mean temperature under these scenarios gradually rises over time up until the year 2100, then bends downward as carbon concentration is reduced, peaking at around 2.1°C relative to the level of 2010. Then the question of interest is, if this environmental benefit is to be achieved, how the burden is shared across regions in each scenario.

Figure 4 summarizes the result. Each panel of the figure shows the percentage change in final output in five aggregated regions under the Global-low and KyotoUS-low scenarios, respectively, relative to the level of the laissez-faire scenario. The first point to observe is that the cost of policy intervention continues to be felt until around 2060, followed by a sequence of growing benefits thereafter. This is another consequence of the dynamic impact of the carbon tax. As

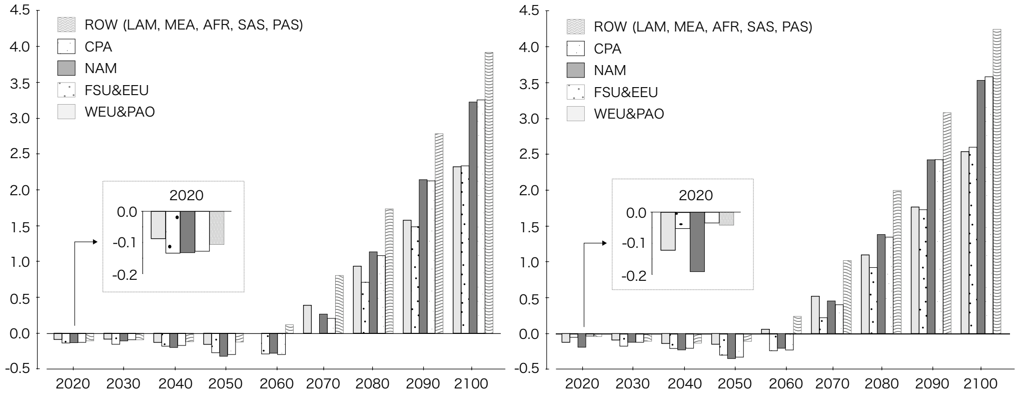

Figure 4: Final good output in Global-low (left panel) and KyotoUS-high (right panel) scenarios relative to the laissez-fare (percentage)

discussed above, the introduction of a carbon tax redirects the resource flow from fossil to non-fossil fuel energy production. This means that the fossil fuel primary energy sector, which at least in the short run can produce final energy in a more efficient way, enjoys a smaller amount of intellectual and financial resource than it would in the case of laissez-fare. As a result, economies suffer from a relatively less efficient energy production process until the clean energy sector becomes sufficiently productive and, more importantly, until the corresponding climate benefits materialize to make up for the loss. This phenomenon takes place at a global level. This is why the long-term burden of policy intervention is felt by the regions outside the regime as well. Thus, in the long run, impacts of policy intervention on the final output growth are almost the same under the two scenarios. What is noticeably different is its short-term impact, especially during the period of policy intervention. In the Global-low scenario, the short-term cost of policy intervention is evenly shared by all regions while the burden is relatively more concentrated on WEU, PAO, and NAM in the KyotoUS-high scenario.

From the perspective of policy design, it will be also of interest to policy makers if we could evaluate the impact of longer commitment periods. The benchmark simulations assume for all policy scenarios the same commitment period of 10 years, which might seem a bit short. Henc, I have also conducted simulations with a longer period (20 years, from 2015 to 2035) of policy intervention as a variant for each scenario. Another question of practical importance concerns the timing of policy intervention. Considering the fact that political feasibility of any effective multilateral agreement is questionable under the current circumstance, we could not deny the possibility that the ongoing international negotiation might end up with delayed policy intervention. With this

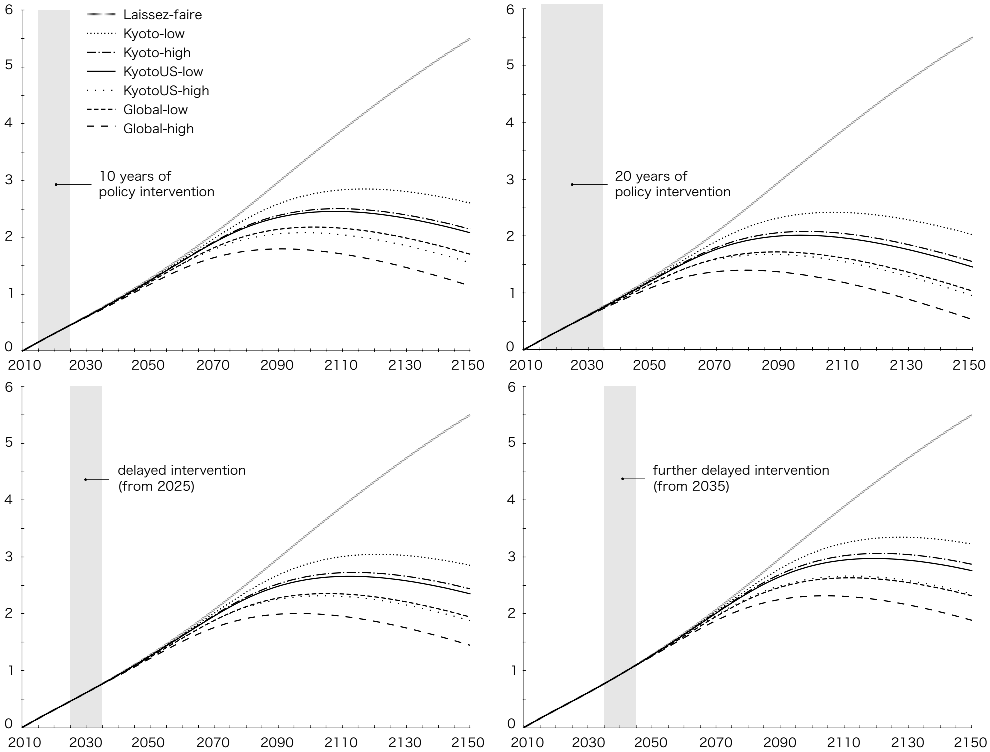

Figure 5: Temperature changes for different duration and timings of policy intervention

political conundrum of climate negotiation in mind, two extra simulations have been conducted with different timings of policy intervention; one starting from 2025, and the other initiated at 2035.

The results of these extra simulations are well summarized in Figure 5. The top left panel of the figure shows the benchmark result, which assumes 10 years of policy intervention starting from 2015. The top right panel presents the consequence of longer period of policy intervention. As shown in the figure, the temperature increase would be better controlled if carbon tax can be introduced for a longer period of time. For each scenario, the peak of the temperature curve is pushed down by about 0.4°C on average. Delays of policy intervention, on the other hand, naturally push up the peak of the temperature curves. The bottom panels of the figure show that the temperature reaches its peak at 0.2°C higher level than in the benchmark result if the effective intervention is delayed by 10 years. The difference from the benchmark will be 0.6°C if the effective intervention is delayed by 20 years. Although these results are in line with the conventional wisdom about climate policy, this extra experiment provides an additional insight with respect to its concrete consequence.

5 Conclusions

The relationship between policy intervention and technological innovation has long been discussed in the context of climate change. In particular, it is often argued that such a policy intervention as carbon tax promotes research and development activities in non-fossil fuel energy sectors, and thus encourages innovation in cleaner energy production technologies. While this line of argument captures some important aspects of reality, policy-induced technological innovations have not been treated in a satisfactory way, especially in the literature of climate-economy modeling. In most of the existing studies, both extent and direction of technological development are exogenously given or are endogenously determined only at a highly aggregated level. A more satisfactory approach requires a decentralized model which explicitly describes decision making process of individual agents as a driving force behind the endogenous innovation.

Another missing piece in the literature lies in the interaction among different regions. Despite the widely recognized nature of climate change as a global public good, research on the endogenous technological development has often been conducted based on a globally aggregated model, and hence fails to consider the role of interplay between heterogeneous regions. Moreover, as globalization intensifies, economies in different regions are becoming increasingly intertwined with each other. Given such a globalized world, introduction of climate policy in one region does not only affect the decision making of domestic firms, but also influences behavior of firms operating in a global market or entrepreneurs working all around the world. It then seems reasonable to ask ourselves how an endogenously induced technological innovation is transmitted from one region to another via globally operating economic agents.

In this paper, I therefore have investigated the implications of policy-induced technological innovation based on a decentralized multi-region climate-economy model. I distinguished fossil-fuel and non-fossil-fuel energy production and described the process in which innovation occurs at a particular type of energy production process. Hence, unlike the conventional treatment of technological development, direction of innovation was endogenously determined. In addition to the standard pollution externality accompanied by carbon dioxide emission, different regions are connected through a global market where energy-related machine producing firms monopolistically compete with each other. This way, I explicitly modeled a channel through which unilateral climate policies can have a dynamic influence beyond regional boundaries. Taking into account these new features in a full-blown climate-economy model, the theoretical and numerical analysis together provide some novel insights.

One of the main findings of the analysis is that unilateral climate policies can have a significantly large impact at a global level. As far as the short-term consequence is concerned, the introduction of a carbon tax in a region does not affect carbon dioxide emission in other regions. It only encourages a temporary change in local energy use and reduces the corresponding amount of carbon emission in the region. In the long run, however, the locally implemented carbon tax can cause a dynamic shift in favor of non-fossil fuel energy at a global scale. It is shown by theoretical analysis that this dynamic and global impact of carbon tax can be particularly large when such a climate policy is implemented in a region with large output. This indicates that unilaterally introduced climate policies in developed regions might have only a slight short-term impact at a global level, but later will turn out to be a basis for low-carbon development in developing regions as well as developed regions.

This theoretical prediction is well confirmed by numerical simulations. The simulation results essentially indicate that an extension of the Kyoto protocol, if appropriately designed, can trigger a long-term shift in energy use at a global level even without active involvement of the United States. Moreover, if the United States decides to join the treaty and a fairly moderate abatement target is agreed upon among the member states, the similar level of long-term environmental consequence as in the universal climate regime can be replicated without explicit participation of developing regions. Although disputes surrounding the burden sharing among regions remain unsolved, the controversy might be less intense than commonly expected. What is implied by the simulation analysis is that the abatement cost is only differentiated during the period of policy intervention and the policy intervention is necessary only for a decade or so. Nevertheless, this result is conditional on the feasibility of a sufficiently stringent carbon tax scheme or some other comparable climate policies implemented at the right timing.

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A Appendices

A.1 Solving for the equilibrium

The first-order conditions of the profit maximization in the final output sector imply

$$\alpha Y_{jt}/K_{jt} = (r_{jt} + \delta), \tag{A.1}$$

$$\beta Y_{jt}/X_{jt} = p_{jt}, \tag{A.2}$$

$$(1-\alpha-\beta)Y_{jt}/L_{jt} = w_{jt}. \tag{A.3}$$

The first-order conditions of the profit maximization in the final energy sector are given by

$$p_{jt}X_{jt}\left[\frac{X_{jkt}^{(\epsilon-1)/\epsilon}}{X_{jkt}^{(\epsilon-1)/\epsilon} + X_{jdt}^{(\epsilon-1)/\epsilon}}\right]\frac{1}{X_{jkt}} = \begin{cases} p_{jct} & k = c \\ p_{jdt}(1+\tau_{jt}) & k = d \end{cases} \tag{A.4}$$

which imply

$$p_{jt}^{1-\epsilon} = p_{jct}^{1-\epsilon} + \left[p_{jdt}(1+\tau_{jt})\right]^{1-\epsilon}. \tag{A.5}$$

The first-order conditions of the profit maximization in the primary energy sector imply

$$(1-\gamma)p_{jkt}X_{jkt}/L_{jkt} = w_{jt}, \tag{A.6}$$

$$\gamma p_{jkt}L_{jkt}^{1-\gamma}A_{jkt(i)}^{1-\gamma}x_{jkt(i)}^{\gamma}/x_{jkt(i)} = p_{kt(i)}, \tag{A.7}$$

for $k \in \{c,d\}$. The first-order conditions of the profit maximization in the machine-producing sector imply

$$p_{kt(i)}\sum_j\left(1+\frac{\partial x_{jkt(i)}}{\partial p_{kt(i)}}\frac{p_{kt(i)}}{x_{jkt(i)}}\right)x_{jkt(i)} = \chi\sum_j\frac{\partial x_{jkt(i)}}{\partial p_{kt(i)}}\frac{p_{kt(i)}}{x_{jkt(i)}}x_{jkt(i)}, \tag{A.8}$$

where $x_{jkt(i)}$ is the inverse demand function defined by (A.7).

Note that (A.1), (A.2), and (A.3) imply

$$\frac{1-\alpha-\beta}{\beta}\frac{p_{jt}X_{jt}}{L_{jt}} = w_{jt}, \quad \frac{\alpha}{\beta}\frac{p_{jt}X_{jt}}{K_{jt}} = r_{jt}+\delta. \tag{A.9}$$

Also, (A.4) imply

$$\frac{X_{jct}}{X_{jdt}} = \left(\frac{p_{jct}}{p_{jdt}(1+\tau_{jt})}\right)^{-\epsilon}, \tag{A.10}$$

and thus (A.6) implies

$$\frac{L_{jct}}{L_{jdt}} = \frac{p_{jct}}{p_{jdt}}\frac{X_{jct}}{X_{jdt}} = \left(\frac{p_{jct}}{p_{jdt}}\right)^{1-\epsilon}(1+\tau_{jt})^{\epsilon}. \tag{A.11}$$

Note (A.7) and (A.8) imply $p_{kt(i)} = \chi/\gamma$. Hence,

$$x_{jkt(i)} = L_{jkt} A_{jkt(i)} \left[(\gamma^2/\chi) p_{jkt}\right]^{1/(1-\gamma)}, \tag{A.12}$$

which, together with (A.6), implies

$$\begin{align} L_{jkt} &= \left[\int_0^1 A_{jkt(i)}^{1-\gamma} x_{jkt(i)}^{\gamma} di\right]^{1/\gamma} \left[\frac{(1-\gamma)p_{jkt}}{w_{jt}}\right]^{1/\gamma} \tag{A.13} \\ &= L_{jkt} A_{jkt}^{1/\gamma} (\gamma^2/\chi)^{1/(1-\gamma)} (1-\gamma)^{1/\gamma} p_{jkt}^{1/\gamma(1-\gamma)} w_{jt}^{-1/\gamma}, \tag{A.14} \end{align}$$

or

$$p_{jkt} = \frac{(\chi/\gamma^2)^{\gamma}}{(1-\gamma)^{(1-\gamma)}} A_{jkt}^{-(1-\gamma)} w_{jt}^{1-\gamma}, \tag{A.15}$$

for $k \in \{c, d\}$. This means

$$\frac{p_{jct}}{p_{jdt}} = \left(\frac{A_{jdt}}{A_{jct}}\right)^{1-\gamma}, \tag{A.16}$$

which in turn implies

$$\frac{X_{jct}}{X_{jdt}} = \left(\frac{A_{jct}}{A_{jdt}}\right)^{\epsilon(1-\gamma)} (1+\tau_{jt})^{\epsilon}, \quad \frac{L_{jct}}{L_{jdt}} = \left(\frac{A_{jct}}{A_{jdt}}\right)^{\varphi} (1+\tau_{jt})^{\epsilon}. \tag{A.17}$$

Therefore,

$$\frac{X_{jkt}}{X_{jt}} = \begin{cases} (A_{jct}/A_{jt})^{\epsilon(1-\gamma)} & k = c \\ (A_{jdt}/A_{jt})^{\epsilon(1-\gamma)} (1+\tau_{jt})^{-\epsilon} & k = d \end{cases} \tag{A.18}$$

where $A_{jt} := [A_{jct}^{\varphi} + A_{jdt}^{\varphi}(1+\tau_{jt})^{1-\epsilon}]^{1/\varphi}$ and

$$\frac{L_{jct}}{L_{jct} + L_{jdt}} = \frac{A_{jct}^{\varphi}}{A_{jct}^{\varphi} + A_{jdt}^{\varphi}(1+\tau_{jt})^{-\epsilon}}. \tag{A.19}$$

Also observe that (A.5) and (A.16) imply

$$\frac{p_{jkt}}{p_{jt}} = \left(\frac{A_{jkt}}{A_{jt}}\right)^{\gamma-1}, \tag{A.20}$$

and hence, noting that $(L_{jt} + L_{jct})/N_{jt} = 1 - L_{jdt}/N_{jt}$, (A.2), (A.3) and (A.6) then imply

$$\begin{align} \frac{1-\alpha-\beta}{\beta(1-\gamma)} \left(\frac{1 - L_{jt}/N_{jt}}{L_{jt}/N_{jt}}\right) &= \frac{p_{jct}X_{jct} + p_{jdt}X_{jdt}}{p_{jt}X_{jt}} \\ &= \underbrace{\frac{A_{jct}^{\varphi} + A_{jdt}^{\varphi}(1+\tau_{jt})^{-\epsilon}}{A_{jct}^{\varphi} + A_{jdt}^{\varphi}(1+\tau_{jt})^{1-\epsilon}}}_{=:\Omega_{jt}}. \tag{A.21} \end{align}$$

meaning that

$$L_{jt} = \frac{1}{1+\zeta\Omega_{jt}} N_{jt}, \quad L_{jct} + L_{jdt} = \frac{\zeta\Omega_{jt}}{1+\zeta\Omega_{jt}} N_{jt}, \tag{A.22}$$

where $\zeta := \beta(1-\gamma)/(1-\alpha-\beta)$. On the other hand, (A.12) implies

$$\begin{aligned} X_{jkt} &= (\gamma^2/\chi)^{\frac{\gamma}{1-\gamma}} L_{jkt} A_{jkt} p_{jkt}^{\frac{\gamma}{1-\gamma}} & \text{(A.23)} \\ &= (\gamma^2/\chi)^{\frac{\gamma}{1-\gamma}} \frac{L_{jkt}}{L_{jct}+L_{jdt}} \frac{A_{jkt}}{A_{jt}} \left(\frac{p_{jkt}}{p_{jt}}\right)^{\frac{\gamma}{1-\gamma}} (L_{jct}+L_{jdt}) A_{jt} p_{jt}^{\frac{\gamma}{1-\gamma}}. & \text{(A.24)} \end{aligned}$$

Hence,

$$X_{jt} = X_{jct} \left(\frac{A_{jct}}{A_{jt}}\right)^{\frac{\epsilon\varphi}{1-\epsilon}} = \left(\frac{\gamma^2}{\chi}\right)^{\frac{\gamma}{1-\gamma}} \frac{\zeta}{1+\zeta\Omega_{jt}} N_{jt} A_{jt} p_{jt}^{\frac{\gamma}{1-\gamma}}. \tag{A.25}$$

Then (A.9) and (A.1) implies

$$p_{jt}^{\frac{1}{1-\gamma}} = \beta \left(\frac{\gamma^2}{\chi}\right)^{\frac{-\gamma}{1-\gamma}} \left(\frac{\zeta}{1+\zeta\Omega_{jt}}\right)^{-1} \frac{Y_{jt}}{N_{jt}A_{jt}}, \tag{A.26}$$

and thus

$$X_{jt} = \left(\frac{\gamma^2\beta}{\chi}\right)^{\gamma} \left(\frac{\zeta}{1+\zeta\Omega_{jt}}\right)^{1-\gamma} N_{jt}^{1-\gamma} A_{jt}^{1-\gamma} Y_{jt}^{\gamma}. \tag{A.27}$$

Therefore

$$Y_{jt} = \psi_{jt}^{*} K_{jt}^{\frac{\alpha}{1-\beta\gamma}} N_{jt}^{\frac{1-\alpha-\beta\gamma}{1-\beta\gamma}} [A_{jct}^{\varphi} + A_{jdt}^{\varphi}(1+\tau_{jt})^{1-\epsilon}]^{\frac{\beta}{(1-\beta\gamma)(\epsilon-1)}}, \tag{A.28}$$

where

$$\psi_{jt}^{*} := \psi_{jt}^{\frac{1}{1-\beta\gamma}} (\beta\gamma^2/\chi)^{\frac{\beta\gamma}{1-\beta\gamma}} \zeta^{\frac{\beta-\beta\gamma}{1-\beta\gamma}} (1+\zeta\Omega_{jt})^{-\frac{1-\alpha-\beta\gamma}{1-\beta\gamma}}. \tag{A.29}$$

Finally, observe

$$\begin{aligned} \int_0^1 x_{jkt(i)} di &= (\gamma^2/\chi)^{\frac{1}{1-\gamma}} p_{jkt}^{\frac{1}{1-\gamma}} L_{jkt} A_{jkt} \\ &= \begin{cases} (\beta\gamma^2/\chi)\, Y_{jt} (A_{jct}/A_{jt})^{\varphi} & k = c \\ (\beta\gamma^2/\chi)\, Y_{jt} (A_{jdt}/A_{jt})^{\varphi} (1+\tau_{jt})^{-\epsilon} & k = d \end{cases} \end{aligned} \tag{A.30}$$

and hence

$$\begin{aligned} \upsilon_t &= \int_0^1 \sum_j (\chi/\gamma - \chi) x_{jct(i)} di \Big/ \int_0^1 \sum_j (\chi/\gamma - \chi) x_{jdt(i)} di \\ &= \frac{\sum_j \left[A_{jct}^{\varphi}/(A_{jct}^{\varphi} + A_{jdt}^{\varphi}(1+\tau_{jt})^{1-\epsilon})\right] Y_{jt}}{\sum_j \left[A_{jdt}^{\varphi}(1+\tau_{jt})^{-\epsilon}/(A_{jct}^{\varphi} + A_{jdt}^{\varphi}(1+\tau_{jt})^{1-\epsilon})\right] Y_{jt}}. \end{aligned} \tag{A.31}$$

A.2 Regional specification

Abbr.	Regional specification
NAM	**North America**: Canada, Guam, Puerto Rico, United States of America, Virgin Islands
WEU	**Western Europe**: Andorra, Austria, Azores, Belgium, Canary Islands, Channel Islands, Cyprus, Denmark, Faroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Isle of Man, Italy, Liechtenstein, Luxembourg, Madeira, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom
PAO	**Pacific OECD**: Australia, Japan, New Zealand
FSU	**Former Soviet Union**: Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
EEU	**Eastern Europe**: Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, The former Yugoslav Rep. of Macedonia, Hungary, Poland, Romania, Slovak Republic, Slovenia, Yugoslavia
LAM	**Latin America and the Caribbean**: Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guyana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Santa Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela
MEA	**Middle East and North Africa**: Algeria, Bahrain, Egypt, Iraq, Iran, Israel, Jordan, Kuwait, Lebanon, Libya/SPLAJ, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria, Tunisia, United Arab Emirates, Yemen
AFR	**Sub-Saharan Africa**: Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Cote d'Ivoire, Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Saint Helena, Swaziland, Tanzania, Togo, Uganda, Zaire, Zambia, Zimbabwe
CPA	**China and centrally planned Asia**: Cambodia, China, North Korea, Laos, Mongolia, Viet Nam
SAS	**South Asia**: Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka
PAS	**Other Pacific and Asia**: American Samoa, Brunei Darussalam, Fiji, French Polynesia, Gilbert-Kiribati, Indonesia, Malaysia, Myanmar, New Caledonia, Papua, New Guinea, Philippines, Republic of Korea, Singapore, Solomon Islands, Taiwan, Thailand, Tonga, Vanuatu, Western Samoa

Table 2: Definition of the regions

	2020			2030			2040			2050			2060		
	WEU	NAM	CPA	WEU	NAM	CPA	WEU	NAM	CPA	WEU	NAM	CPA	WEU	NAM	CPA
Laissez-faire	0.36	0.19	0.30	0.49	0.22	0.29	0.70	0.26	0.30	0.92	0.31	0.31	1.12	0.36	0.33
Kyoto-low	0.53	0.20	0.31	0.55	0.25	0.33	0.86	0.32	0.36	1.35	0.45	0.44	2.46	0.78	0.70
Kyoto-high	0.64	0.20	0.32	0.59	0.27	0.35	0.99	0.36	0.40	1.77	0.58	0.57	4.47	1.39	1.23
KyotoUS-low	0.54	0.29	0.32	0.60	0.27	0.35	1.01	0.37	0.41	1.85	0.61	0.59	4.95	1.54	1.36
KyotoUS-high	0.67	0.35	0.33	0.69	0.31	0.40	1.33	0.48	0.53	3.38	1.08	1.03	15.64	4.70	4.03
Global-low	0.56	0.29	0.46	0.65	0.30	0.38	1.20	0.44	0.48	2.68	0.87	0.84	10.42	3.17	2.75
Global-high	0.70	0.37	0.58	0.81	0.37	0.46	1.87	0.67	0.72	7.08	2.20	2.05	44.73	13.00	10.76

Table 3: Relative size of non-fossil-fuel primary energy consumption, X_{jct}/X_{jdt}, under different scenarios. Shaded cells indicate that values in the cells are under direct influence of policy intervention.

	2020			2030			2040			2050			2060		
	WEU	NAM	CPA	WEU	NAM	CPA	WEU	NAM	CPA	WEU	NAM	CPA	WEU	NAM	CPA
Laissez-faire	1.25	2.73	2.48	1.22	3.24	3.35	1.15	3.64	4.08	1.12	3.84	4.65	1.13	4.47	5.78
Kyoto-low	1.07	2.71	2.45	1.17	3.15	3.25	1.05	3.45	3.86	0.92	3.41	4.15	0.70	3.33	4.40
Kyoto-high	0.99	2.69	2.44	1.13	3.09	3.18	0.98	3.32	3.72	0.78	3.10	3.79	0.46	2.48	3.34
KyotoUS-low	1.06	2.42	2.44	1.13	3.08	3.17	0.97	3.29	3.69	0.76	3.04	3.72	0.42	2.34	3.17
KyotoUS-high	0.97	2.26	2.41	1.06	2.96	3.05	0.84	3.01	3.38	0.51	2.33	2.90	0.16	1.09	1.55
Global-low	1.05	2.40	2.12	1.09	3.01	3.09	0.89	3.12	3.50	0.60	2.60	3.21	0.23	1.46	2.04
Global-high	0.95	2.22	1.94	0.99	2.82	2.90	0.69	2.65	2.98	0.29	1.54	1.96	0.06	0.48	0.71

Table 4: CO_2 emission from fossil-fuel consumption under different scenarios (GtC). Shaded cells indicate that values in the cells are under direct influence of policy intervention.