A System Dynamics Model for Analyzing the International Diffusion of Emerging Climate Change Mitigation Technologies

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Abstract

Developing countries are rapidly increasing their emissions of greenhouse gases, which can have serious adverse effects on climate change mitigation efforts. The international diffusion of Climate Change Mitigation Technologies (CCMTs) can help changing this trend. However, the international diffusion of CCMTs poses difficult coordination challenges for developed and developing nations as is confronts them with hard to solve economic and environmental dilemmas. Therefore it has become essential to understand under which circumstances CCMTs can be adopted by both developed and developing countries. This paper describes a system dynamics model that takes into consideration several technological and macroeconomic processes for modeling the international diffusion of CCMTs. The behavioral analysis of this model provides insights on the importance of considering the technological potential of CCMTs and the economic differences among developed and developing countries in assessing the likelihood of stabilizing international CO_2 emissions at safe environmental levels.

Keywords: climate change mitigation technologies, developing countries, international climate technology policies, technological uncertainties.

I. Introduction

Policy Issue

In recent years developing countries have substantially increased their emissions of greenhouse gases. If current trends persist, by 2030 these countries will become the historical largest emitter of greenhouse gases, negatively impacting global efforts for stabilizing atmospheric greenhouse concentrations at safe levels (Wheeler and Ummel 2007). The international diffusion[1] of Climate Change Mitigation Technologies (CCMTs)[2] is a feasible political and economic alternative to change this trend (Mattoo and Subramanian 2013); however, there are ample economic, environmental and technological considerations that need to be taken into account when considering policy decisions in the coming years (Newell 2008). On the one hand, the international diffusion of CCMTs poses a difficult coordination challenge for developed and developing countries as this confronts them with hard to solve economic and environmental dilemmas[3]. On the other hand, the interplay of social and technological forces can significantly affect the results of policy interventions and the nature of international cooperation. In light of these challenges, from a policy perspective, it is essential to find cooperation schemes to support the diffusion of these technologies that are both economically and environmentally viable for developed and developing countries and sufficiently robust to endure future and unexpected changes in the social, economic and technological landscape.

The identified policy alternatives for supporting the international diffusion of CCMTs include technology creation policies such as: technology mandates, taxes, subsidies, seed investments in the research and development, and strengthening national systems of innovation; as well as technology transfer mechanisms, such as: licensing agreements or joint investments in research and development (Mattoo and Subramanian 2013; IPCC 2012; Gallagher 2006; Newell 2008). In fact, these two policy components: technology creation and technology transfer are the main focus of the IPCC Green Climate Fund's technology mechanism, which has been established with the objective of facilitating the international diffusion of CCMTs (IPCC 2012).

This paper describes a system dynamics model that takes into consideration the interaction of technological and economic forces for understanding the circumstances under which the international diffusion of CCMTs can be achieved over this century. The purpose of this model is not to predict likely outcomes of technology diffusion, but rather to understand which technological and economic processes lead to the diffusion of CCMTs in a country and in which way these

[1] The international diffusion of CCMTss requires the successful penetration of CCMTs in electricity markets in both developed and developing countries.
[2] This includes Sustainable Energy Technologies (SETs), such as solar energy based technologies, wind based technologies. It also includes more efficient Carbon Based Energy Technologies (CETs) and Pollution Control Technologies, such as Carbon Capture and Storage.
[3] Economic dilemmas for developed countries include: the loss of economic advantages against developing countries if these relax their licensing policies with respect to SETs. Developing countries face the dilemma of supporting expensive SETs in comparison with more affordable Carbon Intensive Technologies. Environmental dilemmas include the creation of pollution heavens in developing countries if developed nations implement more stringent environmental regulations and developing countries do not.

processes differ between develop and developing countries. More importantly, we hope that this application of system dynamics can be used to better understand the role of technology creation and technology transfer policies in enabling cooperation between develop and developing countries for the international diffusion of CCMTs.

Background

One stream of previous technological change studies have focused primarily on understanding technological change at the industry level (Nelson and Winter 1982; Arthur 1989; Dasgupta and Stiglitz 1980; Dawid 2006; Dosi 1988; Silverberg and Verspagen 1994). Another stream of research has focused on studying the relation between technological change and economic growth (Romer 1990; Aghion and Howitt 1992). Recent research in the field has begun considering social and environmental factors as well (Acemoglu et al. 2009). However, little work has been done in studying technological change in developing countries. Moreover, the policy recommendations that have been derived from studies of technological change, currently do not take into consideration the wide range of uncertainties that can affect the results of technology creation and technology transfer policies, such as the uncertainty associated with rapid social and economic changes in developing countries and the inherent technological uncertainty of CCMTs.

Technical need

The model described in this paper intends to expand the traditional scope of technological change studies by incorporating critical technological and economic processes that can impact the effectiveness of policy interventions or that can also play a role in influencing transition dynamics within each region.

From a scientific perspective, the objective of this research design is to fill the current knowledge gap in technological change studies that take into consideration the diffusion of emerging technologies in developing countries and the interplay of social and technological forces (Hu, Hung, and Gao 2011).

From a policy perspective, the objective of this research is to provide international agencies concerned with the successful international diffusion of CCMTs with a detail understanding of the tradeoffs, economic costs and long term challenges of technology creation and technology transfer policies. This information can help improve current coordination mechanisms and provide insights into how to efficiently adapt these policies as new information about the technological potential of CCMTs and the social changes in developing countries becomes available.

II. Model Description

This section describes the general components of the system dynamics model used for this research. This model is based on the more recent technological change models, primarily on Acemoglu et al. (2009). The general structure of this model is described in Figure 1. The economic module describes the economic structure of two regions: a developed region and developing region. The environmental module connects the economic growth of these two regions with the rise of CO_2 emissions and global temperature. The technological module links the decisions of economic agents with the evolution of CCMTs.

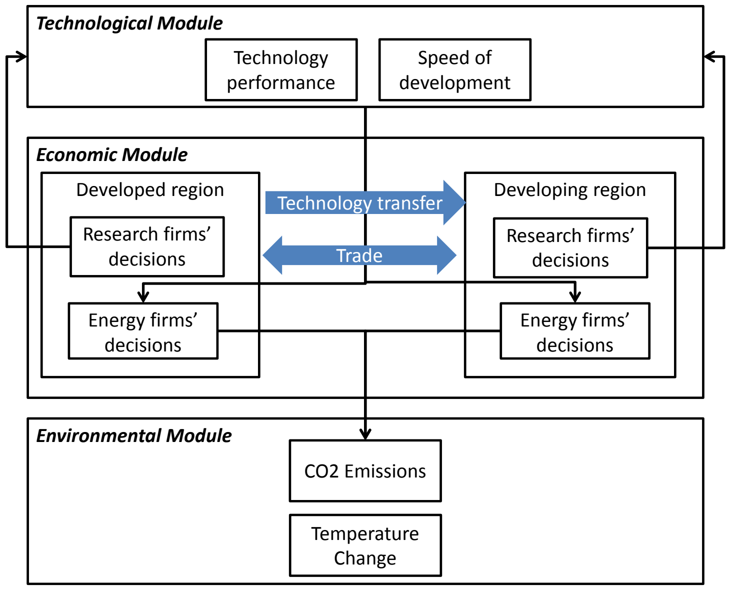

Figure 1: Model Architecture

Model Structure

The model provides an abstract representation of the multi-country context of the international diffusion of CCMTs. Therefore, it is not design to represent specific countries' contexts or for prediction purposes. Rather, its generic structure allows for a clearer identification of the mechanisms shaping the diffusion patterns of CCMTs and their effect on climate change mitigation. The following sections describe the underlying structure of the model.

i) Production of the energy and the environmental externality

The model depicts a global economy consisting of two regions: a developed region and a developing region. Each region produces a unique final good (i.e. Energy). This good is produced through two intermediary inputs: renewable energy (${Y_{re}}^k$) and carbon based energy (${Y_{ce}}^k$). These two regions are connected because environmental externalities are global; therefore the quality of the environment is degraded by the energy production of these two regions, according to the following expression:

$$\frac{dS}{dt} = -\xi\left({Y(t)_{ce}}^D + {Y(t)_{ce}}^d\right) + \delta S(t) \quad \ldots \text{ (1)}$$

where S[4] denotes the quality of the environment, ξ represent the marginal environmental damage per unit of carbon based energy produced in the two regions, and δ represents the average rate of natural environmental regeneration.

The unique final good is produced competitively using both intermediary inputs, according to:

$$Y(t) = \left(Y(t)_{re}^{\frac{\varepsilon-1}{\varepsilon}} + Y(t)_{ce}^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}} \ldots (2)$$

where $\varepsilon \in (0,+\infty)$ is the elasticity of substitution between the two sectors, within each region, and k is an index denoting each region, such that $k \in \{D,d\}$[5]. In each region, a number of economic agents interact for producing the intermediary inputs and the required technologies for production.

ii) Producers of intermediate inputs

There are two types of producers of intermediary inputs: producers of renewable energy and producers of carbon based energy. These agents produce the intermediary input using a continuum of sector-specific technologies: Sustainable Energy Technologies (SETs) and Carbon Based Energy Technologies (CETs), which is described by the following dynamic production function[6]:

$$Y(t)_j^k = L(t)_j^{k\,1-\alpha} \int_0^1 A(t)_{ji}^{k\,1-\alpha}\, x(t)_{ji}^{k\,\alpha}\, di \ldots (3)$$

where $Y(t)_j^k$ denotes the production of the intermediary input j in region k, $L(t)_j^k$ represents the labor used in sector $j \in \{re,ce\}$ in region k, $A(t)_{ji}^k$ is the productivity[7] of technology of type "i" used in sector "j" in region "k", and $x(t)_{ji}^k$ is the demand of technology type "i" in sector "j" in region "k", all at time "t". For the remainder of the discussion the time and region notation will be omitted, but it should be understood that all variables are a function of time and are associated to one of the two regions, unless otherwise indicated.

iii) Monopolist producers of technology "i" in sector "j"

In line with the framework of endogenous technological change, the technologies used in both sectors are supplied by competitive agents who have one period monopoly rights over the technology that they have successfully developed. Technology producers set the price and the supply of their technology which maximizes their profits, given by:

$$\pi_{ji}^m = (p_{ji} - \psi_j)x_{ji} \ldots (4)$$

[4] The calibration of the model is made such that the variable quality of the environment is associated with CO_2 emissions and temperature rise, as described by Acemoglu et al. (2009)
[5] D: Developed region, d: Developing region
[6] Due to space constraints, further detail has been omitted
[7] Productivity in this case indicates the ratio of energy production to installed power (e.g. MWh/MW)

where ψ_j denotes the costs of producing one unit of technology type "i" in sector "j", and p_{ji} denotes the market price of this technology.

iv) Technology entrepreneurs

Technology entrepreneurs work on improving existing technologies in their regions. In the developed region, entrepreneurs are successful in innovating with probability $\eta_j \epsilon (0,1)$ in sector "j" $\epsilon \{re, ce\}$, each successful innovation increases the productivity of technologies by a factor γ_j ; $\gamma_j > 0$. The evolution of productivity over time in the developed region is given by:

$$\dot{A}^D = \gamma_j \eta_j s_j^D A^D \ldots (5)$$

where s_j^D denotes the share of entrepreneurs working in sector "j". In the developing region, entrepreneurs focus on imitating the technology of the developed region. If they are successful, then they acquire technology that is equally productive than the technology in the developed region[8]. The following differential equation describes the evolution of productivity in the developing region:

$$\dot{A}^d = \nu_j \gamma_j \eta_j s_j^d A^D \ldots (6)$$

where ν_j denotes the probability of successful imitation in sector "j".

Entrepreneurs decide in which sector to work on. This decision making process is modelled using a nominal logic model, such that the share of entrepreneurs working in each sector is given by:

$$s_j^k = \frac{e^{\Pi_j^k}}{\sum_{i=re}^{ce} e^{\Pi_{j,i}^k}} \cdots (7)$$

where $\Pi_j = \int_0^1 \pi_{ji}^m di$ is the average profitability of each sector.

III. System's Dynamics

The dynamics of the system described in the previous section are given by how the equilibrium conditions in this economy change as technology productivity of SETs and CETs changes. For this we assume that at each time step this economy is in equilibrium, which assumes equilibrium between supply and demand for the technologies being produced by the technology entrepreneurs and the producers of the intermediary inputs.

Therefore, the equilibrium prices of technologies are given by:

$$\mathrm{p_{ji}} = \frac{\psi_j}{\alpha} \ldots (8)$$

Monopolists' profits will be given by:

[8]Following the same approach as in Acemoglu et al. (2009), entrepreneurs work only on one technology type, and there is a one-to-one match between technologies and entrepreneurs

$$\pi_{jit}^{m} = \psi_j \left(\frac{1-\alpha}{\alpha}\right) x_{jit} \ \ldots (9)$$

Expected sectors profits are given by:

$$\Pi_{jt} = \eta_j \psi_j \left(\frac{1-\alpha}{\alpha}\right) \left(\frac{\alpha^2 p_{jt}}{\psi_j}\right)^{\frac{1}{1-\alpha}} L_{jt} A_{jt} \ \ldots (10)$$

The demand of technologies is given by:

$$x_{jit} = \left(\frac{\alpha^2 p_{jt}}{\psi_j}\right)^{\frac{1}{1-\alpha}} L_{jt} A_{jit} \ \ldots (11)$$

The equilibrium relative prices of intermediary inputs are given by (derivation in appendix 3):

$$\frac{p_{ct}}{p_{dt}} = \left(\frac{A_{ct}}{A_{dt}}\right)^{-(1-\alpha)} \left(\frac{\psi_d}{\psi_c}\right)^{-\alpha} \ \ldots (12)$$

The equilibrium level of relative employment is given by:

$$\frac{L_{ct}}{L_{dt}} = \left(\frac{\psi_c}{\psi_d}\right)^{\frac{\alpha}{1-\alpha} * (1-\alpha)(1-\varepsilon)} \left(\frac{A_{ct}}{A_{dt}}\right)^{-(1-\alpha)(1-\varepsilon)} \ \ldots (13)$$

Finally, the equilibrium level of intermediary inputs production is given by:

$$Y_{jt} = \left(\frac{\alpha^2 p_{jt}}{\psi_j}\right)^{\frac{\alpha}{1-\alpha}} L_{jt} A_{jt} \ \ldots (14)$$

IV. Model Behavior

Figure 2 presents an initial conceptualization of the processes that shape the behavior of the system. Under this conceptualization the competition for RD&D resources and for market power are the central forces that direct technological change towards CETs or SETs. There are three feedback loops which are central for supporting the development and penetration of a given technology and that create the complex dynamics in the model, these are: the price effect, the RD&D effect and the market size effect. The evolution of each technology's productivity plays an important role in changing prices of the energy being produced with that technology, and also in creating incentives for investing in its RD&D and in the creation of new firms that use this technology for energy production. The productivity of each technology is a function of its technological potential (γ) and of its speed of development (η). The technological potential refers to the marginal increase in productivity per incremental innovation, and the speed of development refers to the frequency at which these innovations occur. The energy mix produced using CITs and SETs impacts directly the environmental quality of the region, for example, by increasing greenhouse gases per unit of energy produced.

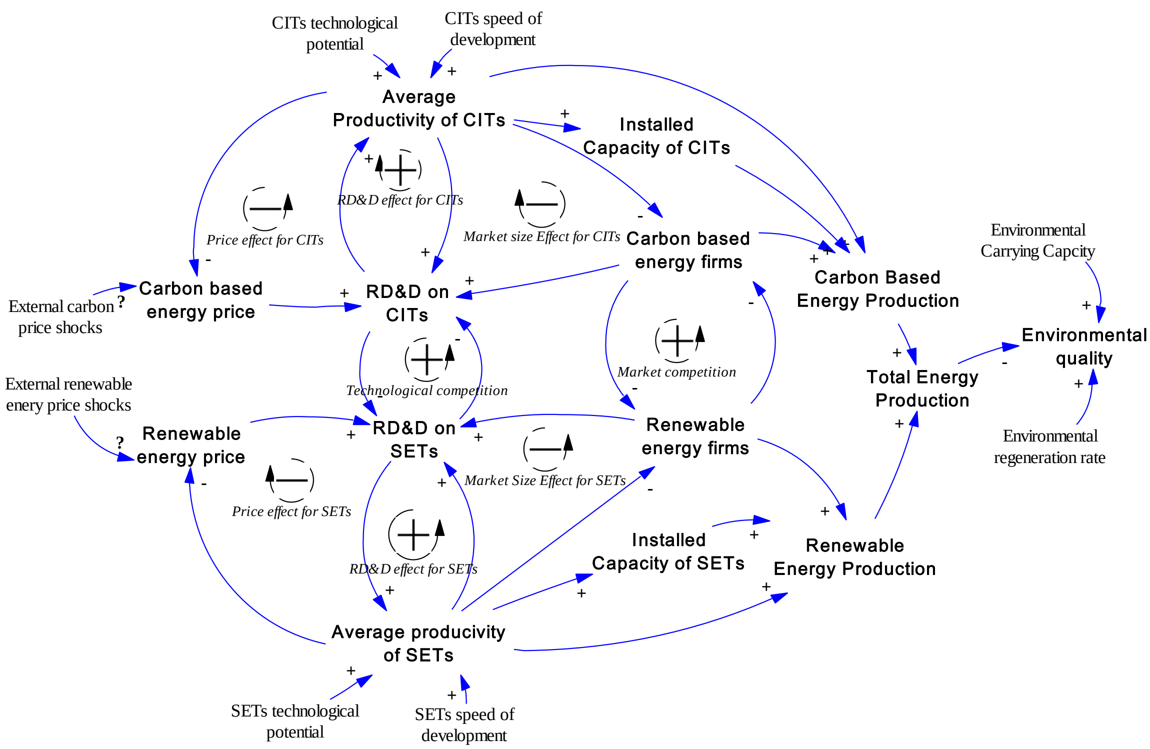

Figure 2: Regional Diffusion System Diagram

Figure 3 presents one case of the many possible cases that result from different parameter specifications. This particular parameter specification displays two characteristics: 1) initially the productivity of the developed region is higher than the productivity of the developing region and 2) the technological potential of SETs is higher than the technological potential of CETs ($\gamma_{re} > \gamma_{ce}$). All other parameters are the same for both regions. This example depicts a future in which the production of renewable energy increases rapidly in both regions. However, it also shows that global temperature increases by 3.5 C° with respect to the temperature levels before the industrial revolution[9].

[9] The calibration of the environmental module is an undergoing task. These temperature changes are likely to be adjusted as the model is improved.

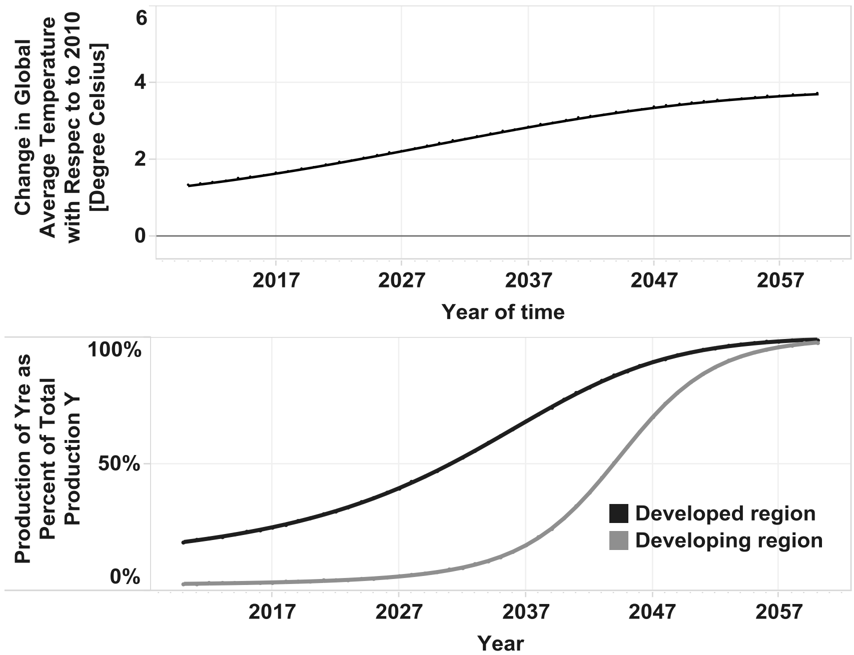

Figure 3: Example of model behavior

Criticality

As explained in the previous sections, the evolution of productivity is crucial for this system, given its role in the three major feedback loops in the model. Figure 4 shows how the system responds to changes in relative productivity (Are/Ace) in both regions. It is possible to see that there is a threshold of relative productivity for which the system begins transitioning into clean energies, and that this transition point is different for the two regions.

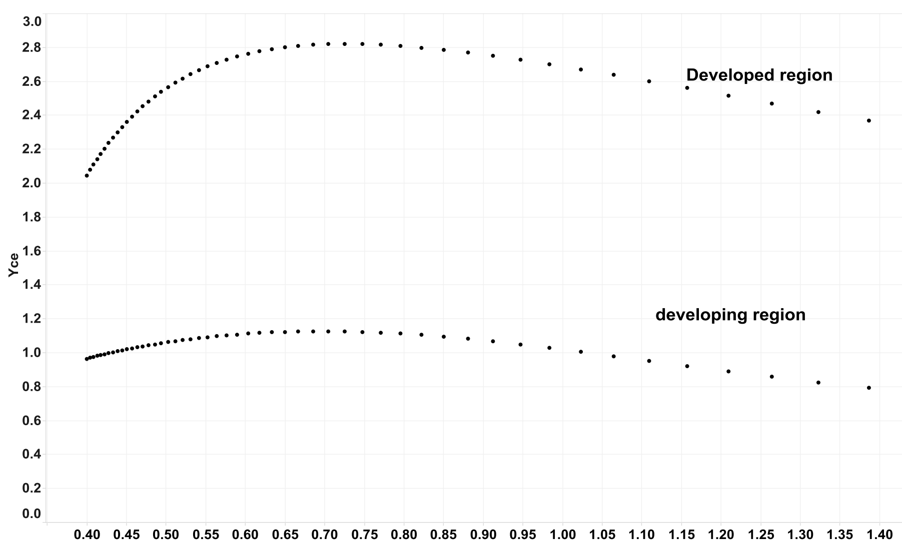

Figure 4: System's criticality

This transition point is also sensitive to other economic parameters in the model, such as the elasticity of substitution (ε), and the technological parameters (γ,η). Figure 5 shows how this behavior is affected by different values of ε. It is possible to see that the larger the elasticity of substitution, the faster the transition towards SETs. This is a relevant issue because the available empirical data today does not allow us to determine with precision which the elasticity of substitution between renewable energy and carbon based energy.

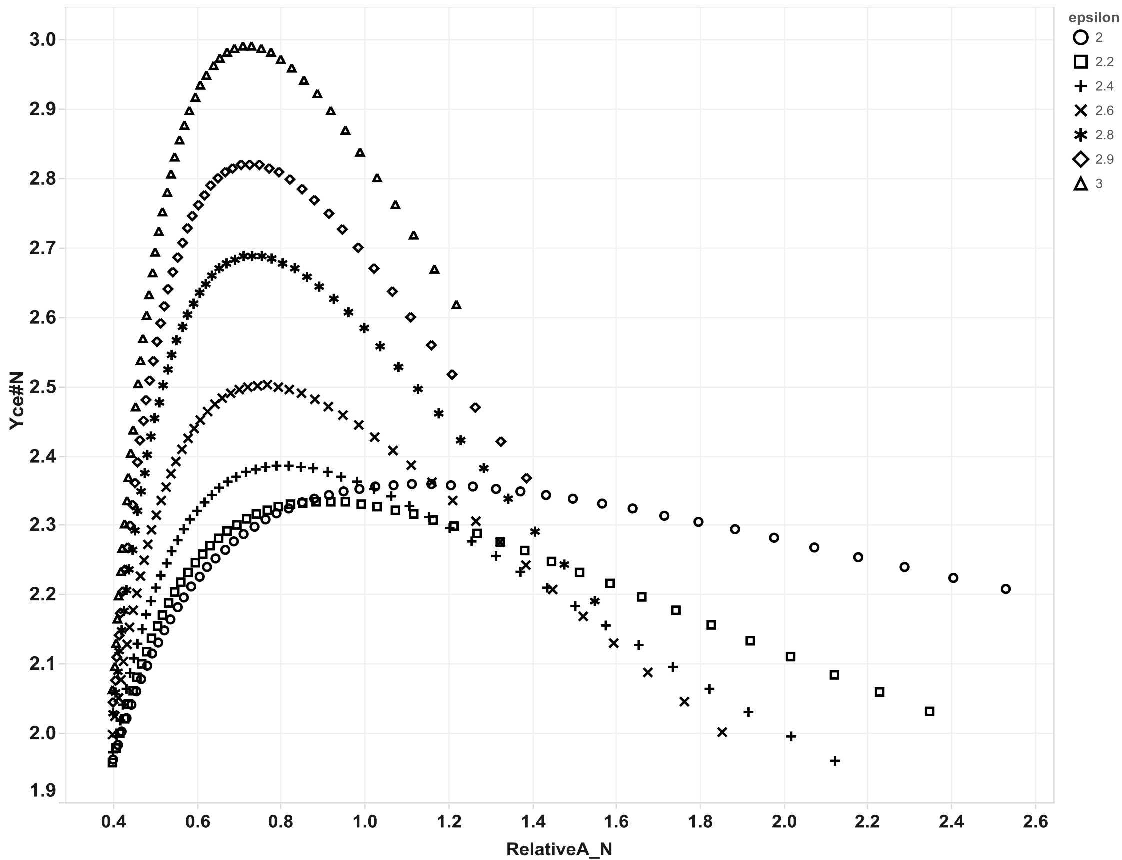

Figure 5: Elasticity's effect on criticality

Using Scenario Discovery for Finding Policy Relevant Scenarios

Figure 4 presents the results of using the scenario discovery method (Bryant and Lempert 2010). This approach consists of using clustering algorithms (e.g. Patient Induction Method-PRIM) to identify the regions of the experiment that are more relevant from a policy perspective. In this example, the cases denoted as "vulnerable future" are those futures in which the global temperature increases surpasses 5 C^{o}[10] . In this example, the vulnerable region is characterized by those futures in which the development of SETs stagnates in the developed region, which limits the development of SETs in the developing region too. This is an interesting example of the relation between developed and developing countries in achieving climate change mitigation objectives.

[10] According to Stern (2007) increases in temperature beyond 5 C^{o} will lead to the melting of the Greenland Ice Sheet.

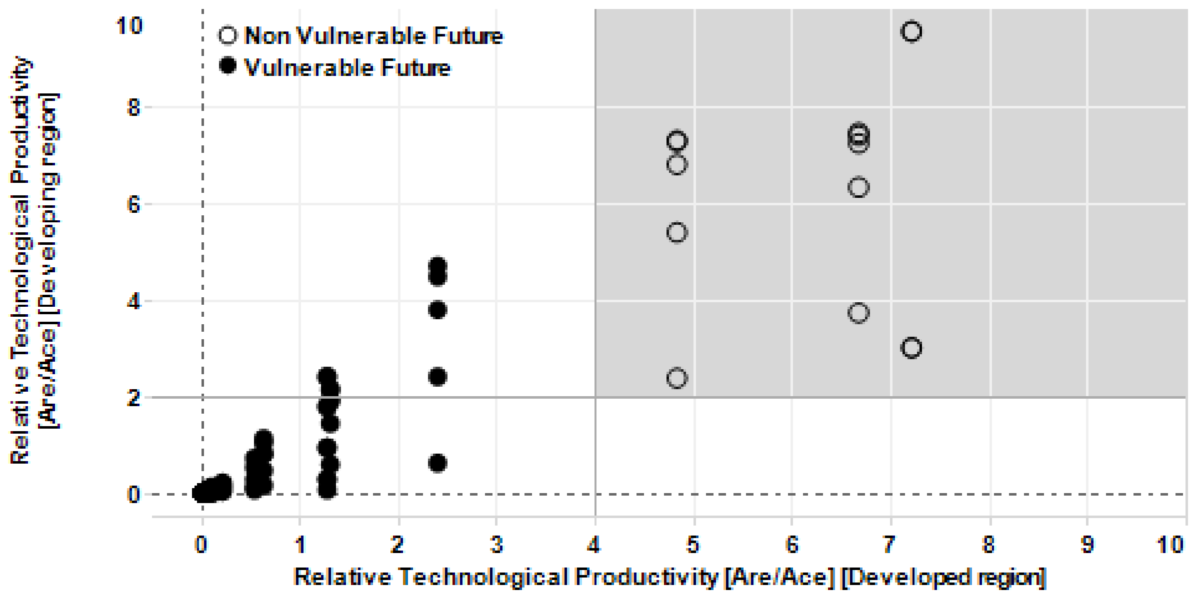

Figure 6. Example of Policy Relevant Cluster

V. Conclusions

This paper describes a system dynamics model that can be used to analyze the international diffusion of climate change mitigation technologies. It is argued that the international diffusion of SETs occurs in a complex environment in which the actions of developed countries and developing countries are closely linked.

We have shown that the transition towards SETs occurs in a complex technology competition context associated with several technological and economic processes. In particular we have shown that the technological potential and the speed of development of sustainable energy technologies and carbon based energy technologies can play and important role in shaping the diffusion paths of climate change mitigation technologies. Regarding the economic parameters of the model, it was shown that the elasticity of substitution between renewable energy and carbon based energy also plays a significant role in shaping the diffusion dynamics.

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