The Role of Technological Innovation in Global Climate Policy: Analysis of Gerlagh (2008)

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Abstract

We made a comprehensive analysis about the Gerlagh (2008) paper called "A climate change policy-induced shift from innovations in carbon-energy production to carbon-energy savings". In our paper, we think Gerlagh's work have several errors and some misleading parts: (i) the initial value of energy related research and development (R&D) expenditures was too high (Shiell and Lyssenko (2014)), (ii) the appropriation rate "ω" needs to be added into the first order conditions of the technology variables (A_{YE}, A_{MZ}, A_{EZ}), (iii) in the dynamic model programming part, Gerlagh maximizes the welfare function again in GAMS software which may lead to a second best result, (iv) in the business as usual scenario (BAU), Gerlagh takes into account the duplication effect (internalized) and in fact he should not, and that will result in too little R&D expenditure relative to the real case (Shiell and Lyssenko (2014)). Having realized these problems, the next step is to correct them. Firstly, we recalibrate the model taking account of (i) and (ii). Secondly, we re-run Gerlagh's model with the new values taking account of (iii) as well. We show that, after correcting these problems, Gerlagh's conclusion towards carbon taxes to address environmental climate change is still valid: ITC has a significant positive impact on abatement cost of greenhouse gas emissions.

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I. Introduction

In order to address the climate change issues, we may use the market base instruments (MBI) such as carbon taxes or tradable permit system. By using the carbon taxes as our climate change policy, it would induce research and development (R&D) in energy-related technologies or induced technological change (ITC) made by firms and suppliers. Nowadays, there are two major schools debating whether induced technological change will have a significant impact on the cost of emissions abatement. Especially, Popp (2004) points out that ITC or R&D component increases the welfare impact of the optimal climate policy by only 9.4 percent in the central scenario, it is a very modest change and there are lots of inefficiencies. Therefore, Popp holds a pessimistic view towards this issue. However, Gerlagh (2008) presents a very optimistic view about the carbon taxes, concluding that, after ITC has been considered into the model, the abatement cost of achieving the 450 ppmv environmental target becomes negligible in the case of full flexibility. After recognizing these different views, it would be desirable to explain and reconcile some of these differences of results in the literature. The present paper is a comprehensive empirical analysis of Gerlagh (2008).

There are some errors and misleading parts in Gerlagh (2008). First, the base year value of energy related research and development expenditure was too high relative to the real case. Gerlagh estimates the share of output allocated to energy related R&D expenditure in the first period (2005) to be 0.73 percent. It is a very high value of share and it is bigger than it should be. In contrast, Popp (2004) and Shiell and Lyssenko (2014) argue that a better estimate of the share of output allocated to energy related R&D expenditure is 0.04 percent.

The second problem is that Gerlagh (2008) neglects to fully account for inter-firm knowledge spillovers in his model. Inter- firm knowledge spillover means firms are not successful in capturing all the benefits they create, lots of other benefits flow out into other firms free of charge. As a result firms spend too little on R&D and the value is much less than social optimal level (Jones and Williams 2000). This is a technical issue concerning the inclusion of a knowledge appropriation parameter in all appropriate places in his economic model. As a result of this error, Gerlagh (2008) likely overestimates the role of induced innovation in meeting the emissions target.

A third problem with Gerlagh (2008) is that he solves for second best solutions of his model, which is not appropriate. Gerlagh sets up his model as the maximization problem of a representative agent and solves it analytically. Based on this step, we can derive all behavioral equations from FOCs. Then the solution to these behavioral equations, taken together with all structural equations, initial starting values of state variables, and transversality conditions, would give us the equilibrium of the model. Therefore, it is not necessary to maximize welfare function again in GAMS software. But this is what Gerlagh does. This approach leads to a second best result, where there is a social planner trying to maximize welfare function subject to the behavior of private agents.

A fourth problem is that, in the business as usual scenario (BAU), Gerlagh (2008) takes into account the duplication effect and in fact he should not, and that will result in too little R&D expenditure in the BAU. From Shiell and Lyssenko (2014), "a duplication externality refers to the phenomenon whereby individual firms inadvertently duplicate a portion of each other's research findings, such that a doubling of aggregate R&D expenditure yields less than a doubling of new knowledge. This consideration is external to the individual firm's calculation, however, since the firm expects a payoff from knowledge that it creates regardless of the activities of other firms. Therefore, the duplication externality causes firms to spend too much on R&D *ceteris paribus* (Jones 1995, Jones and Williams 2000)" (Page.1). According to the literature, environmental economists face an important issue that is how to treat correctly the duplication externality. Popp (2004) and Gerlagh (2008) build the duplication factor into their models but they do not treat it as an externality. Instead, in the BAU scenario, the firms should not take duplication externality into account. If private firms in BAU treat duplication externality as an external factor they will overestimate the benefits of R&D and in that case too much R&D will be generated compared with the socially efficient level. In contrast, if private firms in BAU take into account duplication externality they will invest less in R&D. Shiell and Lyssenko (2014) argue that Popp and Gerlagh have a scenario where duplication externality is high, and they miss that, in BAU scenario, firms should not take into account the duplication externality. According to the theory, we need to consider the duplication externality as an external factor when modeling the BAU scenario.

The present paper aims to correct these problems in Gerlagh's (2008) paper. The remainder of this paper is structured as follows. Section II talks about the literature review. Section III presents a revised version of Gerlagh's model. Section IV presents the calibration process of parameters in the dynamic model. Section V presents our results which are generated from four different experiments. Experiment 1 is the base case which generates results from Gerlagh's approach directly. Experiment 2 shows the results if we fully account for inter-firm knowledge spillovers in the model. Experiment 3 shows our findings if we constrain the base year value of energy related research and development expenditure to 0.04 percent of gross output, rather than Gerlagh's value of 0.73 percent. Experiment 4 gives us the comprehensive results of combining experiments 2 and 3, i.e. both fully accounting for inter-firm knowledge spillovers and constraining the base year value of energy related research and development expenditure to 0.04 percent of gross output. Then we can make some analysis and comparisons within each experiment and between these four experiments. We have shown that after we correct all these problems, Experiment 4 shows Gerlagh's (2008) conclusion towards carbon taxes to address environmental climate change issues is still working. In section VI, there is a conclusion.

II. Literature review.

Pollution damage is the classic case of an external cost. For example, Individuals make their decisions of how much fuel they are going to use but in fact when they use the fuel they actually do not take into account all the potential costs. Some of these environmental costs would fall on other people. Therefore in order to achieve the efficient allocation of resources we need a method to induce all individuals to take into account all potential environmental costs. Consequently, a fundamental lesson of environmental economics is about the tax. For every liter of energy consumption by an individual, if we put a tax on it, that is going to reflect the true cost of the environmental damages that result from the pollution. We refer to this method as market based instrument (MBI). If we use this method, people would face a full amount of cost of using fossil fuel, but in our business as usual scenario that tax is not faced by all consumers.

Another public policy issue is that R&D (innovation) generates benefits to all society but it is usually undertaken by private firms. Firms are not successful in capturing all the benefits they create, as lots of other benefits flow out into other firms free of charge. These benefits are called inter-firm knowledge spillovers. Private firms as a result spend too little on R&D compared with the socially optimal level

(Jones and Williams 2000).

To deal with inter-firm knowledge spillovers, the government should subsidize firms to encourage them to undertake more R&D, because, from the social welfare's view, the spillover benefits are a good thing but private firms might view them as a bad thing since there is no extra money for them. Altogether, there is a tax on the fossil fuel to reduce consumption of fossil fuel since firms and individuals are consuming too much of fossil fuel. And then for R&D sector, the government does the opposite thing: firms are undertaking not enough R&D so the government wants to subsidize them and encourage them to spend more for the purpose of increasing the overall benefits in the whole society. Also, Shiell and Lyssenko (2014) conclude that the contribution of ITC is very sensitive to the research subsidies to internalize inter-firm knowledge spillovers.

Shiell and Lyssenko (2014) consider three types of policy scenarios: first best policy with carbon tax and R&D subsidies; second best policy with carbon tax only; and BAU scenario as the base case. There is a general rule for the policy design: for each market failure, usually we need an instrument that is dedicated to solving that market failure. In this case we have at least two market failures (market imperfection): the pollution damages are one market failure and then the other market imperfection is in the innovation market. Actually within the innovation market, Shiell and Lyssenko (2014) think there are at least two imperfections:

inter-firm imperfection and inter temporal imperfection (knowledge spillover). Nonetheless, using just one instrument for innovation market and one instrument for the pollution market it is able to implement the first best optimal policy with the social planner's problem (Goulder and Schneider 1999, Jaffee, Newell and Stavins 2005, Fischer and Newell 2008, Massetti and Nicita 2010, Acemoglu et al. 2012). Shiell and Lyssenko (2014) find their results strongly support Rezai (2011), which is, if we model the BAU scenario correctly, then with the optimal climate policy there is no major sacrifice for current generation.

Another important issue in the economics of innovation is the phenomenon of duplication. Duplication means that a portion of a firm's knowledge output duplicates what another firm has already discovered, which is inefficient. Duplication externality means that if firms double their R&D expenditures, it will less than double the amount of new knowledge.

Shiell and Lyssenko (2014) argue that most environmental modelers have neglected to treat duplication as an externality in the BAU scenario (Goulder and Schneider 1999, Popp 2004, Gerlagh 2008, and Hart 2008). In the BAU scenario, private firms do not likely take into account the duplication externality, so they will over-estimate the benefits of R&D and spend too much on R&D all else equal. Shiell and Lyssenko (2014) argue that, when the duplication externality is high, there should be a tax on the innovation market since the R&D sector is not really productive and R&D expenditure is a waste of social resources. However when the duplication externality is low, a subsidy is needed because in this case the innovation market is highly productive. Popp (2004) and Gerlagh (2008) both have a scenario where the duplication externality is high, but they do not treat it as an externality in the BAU scenario and that leads to a lower level of R&D expenditure than private firms would actually do. Therefore, these authors come up with some recommendations that R&D is a good thing and we should subsidize it. But these authors should take duplication as an external factor, so firms will end up spending too much on R&D in BAU. In this case, we may not need to subsidize it.

There is a debate from Popp (2004) and Gerlagh (2008) about whether we should have a big tax or small tax on fossil fuel consumption and how much environmental benefits can R&D provide. Gerlagh contends that the cost of reducing the pollution will be essentially zero if government implement a climate policy of high carbon tax. The tax will raise the price of fossil fuel so private firms would face some pressures and then they will become more focused on their R&D sector and generating some new advanced technologies or new carbon free products that will help us to reduce the consumption of fossil fuels. Gerlagh (2008) thinks that ITC would get a zero cost of abatement. He also thinks that because R&D is very effective we can afford a high tax on emissions of the pollution. The tax will stimulate all R&D sectors and society will switch to alternative fuels which are not polluting. So Gerlagh recommends a high carbon tax and the role of R&D is very important.

In contrast, Popp considers that we should not impose a high tax on emissions because a high tax will reduce our standard of living. When we put a tax on consumption of fossil fuels, we benefit from a reduction in the pollution level, but on the other hand the cost is that we have to give up the benefits of using some of the fossil fuels. Popp thinks that R&D has a limited role for solving this problem, as R&D is not going to reduce abatement costs very much. He considers that the level of the carbon tax should be modest, since the only way to reduce the pollution level is to consume less or to switch to more expensive fuel, or solar or wind power, which are going to be very costly. Therefore we should limit the tax to a modest amount, because beyond that the total cost will become too high. To sum up, Popp gets a result which is very pessimistic and Gerlagh gets a result which is very optimistic.

Shiell and Lyssenko (2014) consider that Gerlagh (2008) and Popp (2004) cannot both be right. First of all, they have different models. Instead of one knowledge stock, Gerlagh has three knowledge stocks in his model. So one possible explanation is that having multiple knowledge stocks changes the conclusion. Secondly, both of these models are mistreating the duplication externality in the BAU scenario. Gerlagh internalizes the duplication externality in BAU. Therefore, he shows a lower level of R&D for firms than we would see in reality. As a result, when government taxes pollution emissions, it appears that induced R&D gives a bigger benefit than we would see if firms were overspending on R&D in BAU.

The third error in Gerlagh (2008) is the base year value of energy related R&D expenditure was too high relative to the real case. Gerlagh estimates the share of output allocated to energy related R&D expenditure in the first period (2000-2005) to be 0.73 percent. It is a very high value of share and it is bigger than it should be. The contribution of ITC is very sensitive about energy related R&D. Shiell and Lyssenko (2014) mention that a better estimate of the share of output allocated to energy related R&D is about 0.04 percent. They also point out that Gerlagh uses a conjectural approach to the specification of this value.

The fourth error in Gerlagh (2008) is that he does not fully account for inter-firm knowledge spillovers in the economic model. Firms can only perceive a portion of their total research benefits therefore the appropriation rate “ω” need to be inserted into model FOCs of both expenditure variables and technology stocks. Shiell and Lyssenko (2014) employs a leakage parameter l to capture firm’s knowledge spillovers, they assume that a firm engaged in R&D can only get paid for (1-l) of the resulting benefits. Gerlagh (2008) uses “ω” which is equivalent to (1-l) as the appropriation rate. As a result, by fully considering inter-firm knowledge spillovers, this is going to show that firms will invest too little in R&D.

The current paper modifies Gerlagh’s model in a number of ways. First, it involves the proper handling of the appropriation parameter “ω”. The second modification is about the initial level of energy-related R&D. Thirdly we need to fix the second best results made by Gerlagh in GAMS programming part and the fourth thing is about treating duplication externality in the BAU scenario correctly. Our initial hypothesis is that, with these changes, R&D is not going to generate as much benefits as Gerlagh finds.

III. Model

Gerlagh builds a dynamic model of the global economy and climate with three endogenous knowledge stocks. Gerlagh's model includes structural equations, and behavioral equations. Time proceeds in discrete steps of 5 years each, with periods denoted t=1,…, 60. Our initial period is from year 2000 to 2005 as t=1. The terminal period is from year 2295 to 2300 as t=60. There are 300 years in total.

Final output, Y, is given by the production function:

$$\mathrm{Y_t} = \left(\left(\zeta_{YM}\, A_{YM,t}^{\pi_{YM}}\, M_t\right)^{\frac{\sigma-1}{\sigma}} + \left(\zeta_{YE}\, A_{YE,t}^{\pi_{YE}} E_t\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \qquad (1)$$

As shown, Y is a CES function of a generic intermediate input M and carbon-energy E. Parameter σ is the elasticity of substitution between M and E. A_{YM} and A_{YE} are knowledge stocks and these two variables capture the productivity of M and E. Parameters of π_{YM}, π_{YE} are about the elasticity of productivity to A_{YM} and A_{YE}, respectively. ζ_{YM} and ζ_{YE} are share parameters in the CES output production function.

$$\mathrm{M_t} = \varsigma_M \, \mathrm{A}_{\mathrm{MZ,t}}^{\pi_{\mathrm{MZ}}} \, Z_{M,t} \quad (2)$$

$$\mathrm{E_t} = \varsigma_E \, \mathrm{A}_{\mathrm{EZ,t}}^{\pi_{\mathrm{EZ}}} \, \mathrm{Z_{E,t}} \quad (3)$$

Equation (2) and (3) are production functions for generic intermediate M and carbon energy E, respectively. For producing M, we use the capital-labor composite Z as a production factor, denoted as Z_M. A_{MZ} is the technology stock that control the productivity of Z_M, the parameter π_{MZ} describes the elasticity of productivity to knowledge accumulation, and ς_M is the shift parameter of the production function of M. The same idea applies to the production function E. We have the production factor of Z_E, technology stock A_{EZ}, parameter π_{EZ} and shift parameter ς_E.

$$\left(\mathrm{Z_{M,t}} + \mathrm{Z}_{E,t}\right) = \mathrm{K_t^{\alpha}} L_t^{1-\alpha} \quad (4)$$

Equation (4) shows value-added, Z, as a Cobb-Douglas function of K and L. α is the share parameter.

$$\mathrm{K_{t+1}} = K_t^{1-\delta} I_t^{\delta} \quad (5)$$

Equation (5) represents capital accumulation, which depends on both the current stock of capital K, current investment level I, and the capital depreciation rate δ.

$$A_{YE,t+1} = R_{YE,t}^{\eta}\, A_{YE,t}^{1-\eta} \tag{6}$$

$$A_{MZ,t+1} = R_{MZ,t}^{\eta}\, A_{MZ,t}^{1-\eta} \tag{7}$$

$$A_{EZ,t+1} = R_{EZ,t}^{\eta}\, A_{EZ,t}^{1-\eta} \tag{8}$$

Equation (6)-(8) show knowledge accumulation as a function of the current level of knowledge and current R&D expenditures. The parameter η indicates the duplication factor. The parameter $\eta \in [0,1]$, where η=0 is the case of total duplication. Total duplication means that the R&D has no contribution on the technological level in next period. And η=1 is the opposite extreme case of no duplication. No duplication means that the accumulation of knowledge depends on current R&D expenditure only. In Shiell and Lyssenko (2014), they use 0.7 to represent the modest duplication externality and 0.2 to represent the large duplication externality.

In fact, firms do not perceive knowledge growing in line with (6)-(8) due to inter-firm knowledge spillovers. To account for this, Gerlagh defines a knowledge appropriation parameter $\omega \in [0,1]$ to reflect the share of new knowledge that flows to the firm which undertakes the R&D. The remaining share (1-ω) represents the spillover, i.e. the knowledge that flows to other agents free of charge. Therefore private firms perceive knowledge accumulating according to

$$A_{YE,t+1} = \omega R_{YE,t}^{\eta}\, A_{YE,t}^{1-\eta} \tag{6'}$$

$$A_{MZ,t+1} = \omega R_{MZ,t}^{\eta} A_{MZ,t}^{1-\eta} \quad (7')$$

$$A_{EZ,t+1} = \omega R_{EZ,t}^{\eta} A_{EZ,t}^{1-\eta} \quad (8')$$

These conditions differ from (6)-(8) in that the growth in knowledge is scaled by ω.

$$\mathrm{C_t} + \mathrm{I_t} + \mathrm{R_t} = \mathrm{Y_t} \quad (9)$$

$$\mathrm{R_t} = \mathrm{R_{YE,t}} + R_{MZ,t} + R_{EZ,t} \quad (10)$$

Equation (9) describes the commodity balance for the final good Y. The final output Y can be used as consumptions C, investments I, and research expenditures R. Equation (10) shows that the aggregate research expenditures R would be divided into energy efficient R&D, R_{YE}, materials related R&D, R_{MZ}, and energy production R&D, R_{EZ}.

$$\mathrm{L_t} = \mathrm{h}_t \mathrm{P_t} \quad (11)$$

$$\mathrm{P_t} = P^{LT} \frac{e^{\gamma_p (t-tp0)}}{1+e^{\gamma_p (t-tp0)}} \quad (12)$$

$$\mathrm{h_t} = h_0 \, e^{\gamma_h (t)} \quad (13)$$

Equation (11) shows effective labor supply L is equal to human capital based productivity h times the total population P. From equation (12), the total population level is assumed to follow a logistic growth curve, where γ_p is the population growth rate for low population levels, P^{LT} is the long term population level and t_{p0} is the year at which the population reaches half its maximal size. Equation (13) shows the exponential function of human capital growth, where γ_h is the growth rate for human capital h.

$$\mathrm{ATM_{t+1}} = ATM_0 + (1-\delta_M)(ATM_t - ATM_0) + (1-\delta_E)\left(0.001\left(E_t + \overline{EM_t}\right)\right) \quad (14)$$

$$\mathrm{TEMP_{t+1}} = (1-\delta_T)\, TEMP_t + \delta_T\, TEMP_0 \frac{LOG\left(\frac{ATM_t}{ATM_0}\right)}{LOG(2)} \quad (15)$$

Equations (14) and (15) show the climate change module that describe the connections between energy usage E, CO_2 emissions EM, atmospheric carbon concentration ATM, and the global average surface temperature TEMP. Atmospheric carbon concentration level ATM in the next period of t+1 is determined by the pre-industrial atmospheric CO_2 concentration level ATM_0 plus the current period ATM level after we take account of atmospheric CO_2 depreciation rate δ_M, plus the current period CO_2 emissions EM, which are set equal to the energy usage E and also we take into account of the retention rate ($1-\delta_E$). The variable $\overline{EM}$ represents emissions by other (non-energy) sources. Equation (15) is the global average surface temperature evolution function, where δ_T is the temperature adjustment rate resulting from the atmospheric warmth capacity, and $TEMP_0$ is the long run equilibrium temperature change associated with a doubling of ATM_0.

$$\mathrm{ATM_t} \leq ATM_{TGT} \quad (16)$$

Equation (16) is the quantity constraint for atmospheric carbon concentration level. It is the quantity based emissions control policy and Gerlagh assumes the maximum level of atmospheric CO_2 concentration, ATM_{TGT}, is 450 ppmv.

Gerlagh assumes that there is a strong separability between environmental damages and economic system, and therefore he abstracts from climate damages in his model. In other words, the damage from increase of temperature does not feedback and negatively affect the economy. If we include a damage function into the model, we can see that temperature feeds back and reduces the productivity of industry so the aggregated production function is harmed by those damages. Adding the damage function into this model is part of future work for this project.

In the social planner's problem, the solution is represented as the inter-temporal optimization of a representative agent. The agent's preferences are represented by the social welfare function (17)

$$\sum_{t=1}^{T} \frac{1}{(1+\rho)^{t}} P_t \ln\left(\frac{C_t}{P_t}\right) \tag{17}$$

where ρ is the rate of pure time preference and C_t and P_t are defined previously. In the business-as-usual scenario (BAU) there is no emission control policy, which means that (16) is not applied and the agent ignores the environmental relationships given by (14) and (15). Therefore, the agent's problem in BAU is to maximize (17) subject to equations (1)-(13), subject to given initial values of the stocks K_1, $A_{YM,1}$, $A_{YE,1}$, $A_{MZ,1}$, and $A_{EZ,1}$, as well as a fixed horizon T. In the emissions control scenario, which we label ITC for "induced technical change", the agent's problem is to maximize (17) subject to equations (1)-(16), as well as the initial stock values and the fixed horizon. Note that in both BAU and ITC, the agents substitutes (6'), (7') and (8') for (6)-(8) in the maximization, due to the inter-firm knowledge spillover.

The Lagrangian function for the agent's maximization in the emissions control scenario is

$$\mathrm{L} = \sum_{t=1}^{T} \{\frac{1}{(1+\rho)^t} P_t \ln\left(\frac{C(t)}{P(t)}\right) + P_t^Y \left[\left(\left(\zeta_{YM}\, A_{YM,t}^{\pi_{YM}}\, M_t\right)^{\frac{\sigma-1}{\sigma}} + \left(\zeta_{YE}\, A_{YE,t}^{\pi_{YE}} E_t\right)^{\frac{\sigma}{\sigma-1}}\right)^{\frac{\sigma}{\sigma-1}} - Y_t\right] + \mu_t\left[\varsigma_M\, \mathrm{A}_{\mathrm{MZ,t}}^{\pi_{\mathrm{MZ}}} \mathrm{Z}_{\mathrm{M,t}} - M_t\right] + q_t\left[\varsigma_E\, \mathrm{A}_{\mathrm{EZ,t}}^{\pi_{\mathrm{EZ}}} \mathrm{Z}_{\mathrm{E,t}} - E_t\right] + \xi_t\left[\mathrm{K}_t^{\alpha} L_t^{1-\alpha} - Z_{M,t} - Z_{E,t}\right] + \Psi_t\left[K_t^{1-\delta} I_t^{\delta} - K_{t+1}\right] + \theta_{YM,t}\left[\omega R_{YM,t}^{\eta} A_{YM,t}^{1-\eta} - A_{YM,t+1}\right] + \theta_{YE,t}\left[\omega R_{YE,t}^{\eta} A_{YE,t}^{1-\eta} - A_{YE,t+1}\right] + \theta_{MZ,t}\left[\omega R_{MZ,t}^{\eta} A_{MZ,t}^{1-\eta} - A_{MZ,t+1}\right] + \theta_{EZ,t}\left[\omega R_{EZ,t}^{\eta} A_{EZ,t}^{1-\eta} - A_{EZ,t+1}\right] + P_t^I\left[Y_t - C_t - I_t - R_{YM,t} - R_{YE,t} - R_{MZ,t} - R_{EZ,t}\right] + P_t^{ATM}[(1-\delta_M)(ATM_t - ATM_0) + (1-\delta_E)(E_t + \overline{EM_t}\,) - ATM_{t+1}] + \overline{P}_t[ATM_{TGT} - ATM_t]\}$$

where P^Y is the shadow price of output of final good Y, μ is the shadow price for generic intermediate M, q is the shadow price for energy usage E, ξ is the shadow price for capital-labor composite Z, and Ψ is the shadow price for capital K. θ_{YM}, θ_{YE},

θ_{MZ}, θ_{EZ} are the shadow prices of knowledge stocks A_{YM}, A_{YE}, A_{MZ}, and A_{EZ} respectively[1]. P^{ATM} is the shadow price of ATM, and $\overline{P_t}$ is the shadow price of the atmospheric carbon concentration constraint. Deriving the first-order conditions with respect to the choice and state variables yields the following behavioural equations of the agent:

$$\beta_t = \frac{\frac{P(t+1)}{P(t)}}{(1+\rho)\frac{Y(t+1)}{Y(t)}} \tag{18}$$

$$M_t\text{: } \mu_t^{\sigma} M_t = Y_t \tag{19}$$

$$E_t\text{: } \left(q_t - P_t^{ATM}(1-\delta_E)\right)^{\sigma} E_t = \left[\zeta_{YE}\, A_{YE,t}^{\pi_{YE}}\right]^{\sigma-1} Y_t \tag{20}$$

$$Z_{M,t}\text{: } \xi_t Z_{M,t} = \mu_t\, M_t \tag{21}$$

$$Z_{E,t}\text{: } \xi_t Z_{E,t} = q_t\, E_t \tag{22}$$

$$K_t\text{: } \Psi_t\, K_{t+1} = \alpha Y_{t+1} + (1-\delta)\,\beta_{t+1}\,\Psi_{t+1}\, I_{t+1}^{\delta} K_{t+1}^{1-\delta} \tag{23}$$

$$R_{YE,t}\text{: } R_{YE,t} = \omega\eta\beta_t\,\theta_{YE,t}\, A_{YE\,,t+1} \tag{24}$$

$$R_{MZ,t}\text{: } R_{MZ,t} = \omega\eta\beta_t\,\theta_{MZ,t}\, A_{MZ,t+1} \tag{25}$$

$$R_{EZ,t}\text{: } R_{EZ,t} = \omega\eta\beta_t\,\theta_{EZ,t}\, A_{EZ,t+1} \tag{26}$$

$$I_t\text{: } I_t^{1-\delta} = \delta\,\beta_t\,\Psi_t\, K_{t+1}^{1-\delta} \tag{27}$$

$$A_{YE,t}\text{: } \theta_{YE,t}\, A_{YE,t+1} = \pi_{YE}\,[q_{t+1} - P_{t+1}^{ATM}(1-\delta_E)]E_{t+1} + (1-\eta)\,\beta_{t+1}\omega\,\theta_{YE,t+1}\, R_{YE,t+1}^{\eta} A_{YE,t+1}^{1-\eta} \tag{28}$$

$$A_{MZ,t}\text{: } \theta_{MZ,t}\, A_{MZ,t+1} = \pi_{MZ}\,\mu_{t+1}\, M_{t+1} + (1-\eta)\,\beta_{t+1}\omega\,\theta_{MZ,t+1}\, R_{MZ,t+1}^{\eta} A_{MZ,t+1}^{1-\eta} \tag{29}$$

$$A_{EZ,t}\text{: } \theta_{EZ,t}\, A_{EZ,t+1} = \pi_{EZ}\, q_{t+1}\, E_{t+1} + (1-\eta)\,\beta_{t+1}\omega\,\theta_{EZ,t+1}\, R_{EZ,t+1}^{\eta} A_{EZ,t+1}^{1-\eta} \tag{30}$$

$$ATM_t\text{: } \quad P_{t+1}^{ATM}\,(1-\delta_M) = P_t^{ATM} + \overline{P_{t+1}} \tag{31}$$

$$\overline{P_t}\,[ATM_{TGT} - ATM_t] = 0 \tag{32}$$

[1] For simplicity Gerlagh assumes $\zeta_{YM} = A_{YM,t}$=1 and therefore $R_{YM,t} = \theta_{YM,t}$=0.

In this formulation, Gerlagh normalizes P^Y=1 in all periods by dividing all the behavioural equations by P^Y. This approach is the origin of the β condition in equation (18). In equation (18) we can think β as the price deflator for the final good from period t to period t+1. As a result, β= 1/(1+r) where r is the real interest rate. Thus the β equation represents the Keynes-Ramsey rule. Equation (18) gives the evolution of the price of consumption over time following the Keynes-Ramsey rule.

In addition, the agent's maximization must satisfy the transversality conditions whereby the final values of the co-state variables on the stocks equal zero; i.e. $\Psi_T = \theta_{YM,T} = \theta_{YE,T} = \theta_{MZ,T} = \theta_{EZ,T} = P_T^{ATM} = 0$.

Note that conditions (28)-(30) include the appropriation parameter ω. Gerlagh neglects to include this parameter here, and therefore he does not fully account for the spillover. Later in this paper, we test the impact of including and excluding ω in the conditions.

We can use the behavioural equations to analyze both the BAU and ITC scenarios. In BAU, since there is no emission control policy, $\overline{P_t}$= 0 and it follows from (31) that P_T^{ATM} = 0 as well in all periods. Thus the solution in BAU is characterized by equations (1)-(13), (18)-(30), plus the transversality and initial conditions. In contrast, in ITC, the quantity constraint (16) is imposed, and therefore $\overline{P_t}$ > 0 in some periods, due to the complementary slackness constraint (32). This result feeds into non-zero values of P_t^{ATM} as well, through (31). (In fact, $P_t^{ATM} < 0$.) In condition (20), we see that $[-P_t^{ATM}(1-\delta_E)]$ acts as a carbon tax to discourage consumption of E, thus enforcing the quantity constraint. Thus the solution in ITC is characterized by equations (1)-(32), plus the transversality and initial conditions.

In the ITC scenario, as long as the constraint becomes binding in some future period, it gets transmitted to the present through P_t^{ATM} in (31). So in ITC we have a carbon tax that starts very small and then rises gradually until the constraint (16) becomes binding and then the tax reaches its highest value. This is how a binding constraint is transmitted to early generations as the carbon tax. For every unit of carbon we put into the atmosphere is going to stay up there and that means that in the future people have less freedom to omit carbon, so the user cost will be very high in the future. If you are going to put a carbon pollution right now you have to pay a cost for it and the cost is that there will be less space into the atmosphere to store carbon dioxide in the future. Some future generation is going to suffer since the current generation is putting carbon dioxide in the atmosphere today. So $[-P^{ATM}(1-\delta_E)]$ is the user cost for charging the current generation for filling up that space. It is like a warehouse; if people are putting boxes into the warehouse we better charge them a price because eventually the warehouse is going to get full. In order to manage this rationally we have to charge people even when there is still room in the warehouse, so they do not put so many things there.

IV. Calibration

Gerlagh calibrates his model with a “constant growth model” in which each variable is assumed to grow at its own constant exponential rate. In this approach, Gerlagh (2008) presents certain variables and parameters which are based on empirical data and are used as input in the calibration of the remaining variables and parameters.

The constant growth model is defined as follows.

Structural equations:

$$\mathrm{Y} = \mu\mathrm{M} + \mathrm{qE} \tag{33}$$

$$\mathrm{M} = \varsigma_M \, \mathrm{A}_{\mathrm{MZ}}^{\pi_{\mathrm{MZ}}} \, \mathrm{Z}_{\mathrm{M}} \tag{34}$$

$$\mathrm{E} = \varsigma_E \, \mathrm{A}_{\mathrm{EZ}}^{\pi_{\mathrm{EZ}}} \, \mathrm{Z}_{\mathrm{E}} \tag{35}$$

$$(\mathrm{Z}_{\mathrm{M}} + \mathrm{Z}_{\mathrm{E}}) = \mathrm{K}^{\alpha} L^{1-\alpha} \tag{36}$$

$$\mathrm{e}^{\mathrm{g}_{\mathrm{K}}} = \left(\frac{I}{K}\right)^{\delta} \tag{37}$$

$$\mathrm{e}^{\mathrm{g}_{\mathrm{AYE}}} = \left(\frac{\mathrm{R}_{\mathrm{YE}}}{\mathrm{A}_{\mathrm{YE}}}\right)^{\eta} \tag{38}$$

$$\mathrm{e}^{\mathrm{g}_{\mathrm{AMZ}}} = \left(\frac{\mathrm{R}_{\mathrm{MZ}}}{\mathrm{A}_{\mathrm{MZ}}}\right)^{\eta} \tag{39}$$

$$\mathrm{e}^{\mathrm{g}_{\mathrm{AEZ}}} = \left(\frac{\mathrm{R}_{\mathrm{EZ}}}{\mathrm{A}_{\mathrm{EZ}}}\right)^{\eta} \tag{40}$$

$$\mathrm{C} + \mathrm{I} + \mathrm{R} = \mathrm{Y} \tag{41}$$

$$\mathrm{R} = \mathrm{R}_{\mathrm{YE}} + \mathrm{R}_{\mathrm{MZ}} + \mathrm{R}_{\mathrm{EZ}} \tag{42}$$

$$\mathrm{L} = \mathrm{h}_0 \, \mathrm{P}_0 \tag{43}$$

Behavioral equations:

$$\mu^{\sigma} M = Y \tag{44}$$

$$q^{\sigma} E = \left(\zeta_{YE} A_{YE}^{\pi_{YE}}\right)^{\sigma-1} Y \tag{45}$$

$$\xi Z_M = \mu M \tag{46}$$

$$\xi Z_E = qE \tag{47}$$

$$\Psi K[1-(1-\delta)\,\beta\, e^{g_K}] = \alpha Y \tag{48}$$

$$R_{YE} = \omega\, \eta\, \beta\, \theta_{YE}\, e^{g_{AYE}}\, A_{YE} \tag{49}$$

$$R_{MZ} = \omega\, \eta\, \beta\, \theta_{MZ}\, e^{g_{AMZ}}\, A_{MZ} \tag{50}$$

$$R_{EZ} = \omega\, \eta\, \beta\, \theta_{EZ}\, e^{g_{AEZ}}\, A_{EZ} \tag{51}$$

$$I = \delta\, \beta\, \Psi\, e^{g_K} K \tag{52}$$

$$\theta_{YE} A_{YE} [1-(1-\eta)\,\beta\, e^{g_{AYE}}] = \pi_{YE}\, q\, E \tag{53}$$

$$\theta_{MZ} A_{MZ} [1-(1-\eta)\,\beta\, e^{g_{AMZ}}] = \pi_{MZ}\, \mu\, M \tag{54}$$

$$\theta_{EZ} A_{EZ} [1-(1-\eta)\,\beta\, e^{g_{AEZ}}] = \pi_{EZ}\, q\, E \tag{55}$$

$$\beta = (1+g_{POP})[(1+\rho)(1+g_C)]^{-1} \tag{56}$$

Growth equations:

$$g_Y = \left(\frac{M}{Y}\right)^{\frac{\sigma-1}{\sigma}} (g_M - \pi_{YE}\, g_{AYE} - g_E) + (\pi_{YE}\, g_{AYE} + g_E) \tag{57}$$

$$g_M = \pi_{MZ}\; g_{AMZ} + g_{ZM} \tag{58}$$

$$g_E = \pi_{EZ}\; g_{AEZ} + g_{ZE} \tag{59}$$

$$\left[\frac{Z_M}{Z_M+Z_E}\right] g_{ZM} + \left[\frac{Z_E}{Z_M+Z_E}\right] g_{ZE} = \alpha g_K + (1-\alpha)\, g_L \tag{60}$$

$$g_Y = \left(\frac{C}{Y}\right) g_Y + \left(\frac{I}{Y}\right) g_K + \left(\frac{R_{YE}}{Y}\right) g_{AYE} + \left(\frac{R_{MZ}}{Y}\right) g_{AMZ} + \left(\frac{R_{EZ}}{Y}\right) g_{AEZ} \tag{61}$$

$$\sigma\, g_{\mu} + g_M = g_Y \tag{62}$$

$$g_E = (\sigma-1)\, \pi_{YE}\, g_{AYE} + g_Y \tag{63}$$

$$g_{\xi} + g_{ZM} = g_{\mu} + g_{M} \quad (64)$$

$$g_{\xi} + g_{ZE} = g_{E} \quad (65)$$

The structural equations and behavioral equations are derived from their counterparts in the dynamic model. Most of the variables and parameters were defined in the previous section, with the exception of the growth rates. The notation for growth rates is g_X, where X is the corresponding variable name. The growth equations are derived from the structural and behavioural equations.

In this part we are proposing some modifications to Gerlagh's calibration method. First, we constrain the initial value of energy related R&D expenditure. As mentioned in section I and II, we need a share of output allocated in energy related R&D around 0.04 percent (Shiell and Lyssenko (2014)).

$$R_{YE} + R_{EZ} = 0.0004\, Y \quad (66)$$

The second modification is about the insertion of "ω" into FOCs of technological variables to fully account inter-firm knowledge spillover effects. Therefore equation (53) (54) (55) becomes (53') (54') (55'):

$$\theta_{YE}\, A_{YE}\, [1 - (1-\eta)\, \omega\beta\, e^{g_{AYE}}\,] = \pi_{YE}\, q\, E \quad (53')$$

$$\theta_{MZ}\, A_{MZ}\, [1 - (1-\eta)\, \omega\beta\, e^{g_{AMZ}}\,] = \pi_{MZ}\, \mu\, M \quad (54')$$

$$\theta_{EZ}\, A_{EZ}\, [1-(1-\eta)\, \omega\beta\, e^{g_{AEZ}}\,] \;=\; \pi_{EZ}\; q\, E \qquad (55')$$

Table 4.1

Knowns	Unknowns
σ , δ , η , h_0 , P_0 , β , ρ , ω , Y , E , I , R , q , g_Y , g_E , g_{POP} .	ζ_{YE} , π_{YE} , π_{MZ} , π_{EZ} , ς_M , ς_E , α , M , A_{YE} , A_{MZ} , A_{EZ} , Z_M , Z_E , K , L , R_{YE} , R_{MZ} , R_{EZ} , C , μ , ξ , ψ , θ_{YE} , θ_{MZ} , θ_{EZ} , g_M , g_{AYE} , g_{AMZ} , g_{AEZ} , g_{ZM} , g_{ZE} , g_K , g_L , g_C , g_μ , g_ξ .

Table 4.1 lists the known and unknown values in the calibration. Gerlagh (2008) solves the model for the unknown values (parameters and some endogenous variables and growth rates). However, when we follow his approach we actually have the problem of the incomplete control of the unknowns, i.e. more unknowns (36 unknowns) than equations (33 equations). As a result, there are multiple solutions to the calibration. It appears that Gerlagh addresses this problem with his second phase of the calibration, therefore we still need to put more effort into the modeling of the second phase of the calibration. In the meantime, we rely on solutions to the calibration which appear to be reasonably close to Gerlagh's values.[2]

V. Results.

To test the robustness of Gerlagh's results, we carry out four experiments.

[2] All computation work in the paper has been done with the GAMS software. Consult www.gams.com for details.

Experiment 1 is our base case which generates results from Gerlagh's approach directly; experiment 2 shows results that if we put the missing "ω" parameter into conditions (28)-(30); experiment 3 shows our findings if we constrain the initial level of energy related R&D expenditures in the calibration process to equal 0.04 percent of initial output Y_1; experiment 4 combines 2 and 3, i.e. constraining the initial level of energy related R&D expenditures and putting "ω" parameter into conditions (28) to (30).

Table 5.1

EXP1	Gerlagh's approach
EXP2	Adding "ω" parameter into FOCs of A_{YE} A_{MZ} A_{EZ}
EXP3	Putting the constraint of initial level of energy related R&D
EXP4	Combination of EXP2 and EXP3

In our case, we have three experiments (EXP1 EXP2 EXP4)[3] and our target is to see if we make the correction of Gerlagh's model whether we can get a different conclusion or a similar conclusion as Gerlagh did in his paper. The general approach is, firstly in each experiment we compare main variables' paths of two policy scenarios

[3] For EXP3's results, there are some difficulties in GAMS programming and this part needs to be done in the future.

and therefore we can get a conclusion of how ITC‘s contribution towards abatement cost. Secondly, if we make the cross comparisons of different experiments, like EXP2 BAU and EXP1 BAU, EXP 4 BAU and EXP1 BAU, and EXP4 ITC and EXP1 ITC, we can see that how the model structure changes will affect the main variables' paths under two different experiments.

Figure 1 describes BAU in EXP1 of Y and C variables. Both Y and C follows the same increasing pattern with time. The path for Y is above the path of C from year 2005 to 2150.

Figure 2 describes BAU in EXP1 of R, R_{YE}, R_{MZ} and R_{EZ} variables. We can see that R, R_{YE} and R_{MZ} continue to increase over time while R_{EZ} stays in a relatively low value (from 0.1 to 0.5, measured in trillion US$1995).

In Figure 3, we show the ITC values of Y, C, M and K in EXP1 relative to their BAU values. All these variables in relative value follow the same trend that increases over time. That means under EXP1, ITC would generate a higher value for these variables in each period. The result shows that under the ITC scenario, the economy becomes more productive than BAU, the induced technological change has a positive impact on the economy. The results could be explained as follows.

Rezai's (2011) and Shiell and Lyssenko (2014) support Gerlagh's conclusion:

with optimal climate policy there is no major sacrifice for current generation. Under BAU, when we got these externalities that will cause the economy is so distorted that agents are not making their optimal choices even from today's perspective. For instance, agents are over investing in physical capital which marginal product is low and they are under investing in environmental capital or human capital which marginal product is high. So when we put some signals in places (ITC, carbon tax as the user cost) private agents internalize these externalities, and we are giving financial incentives for the private agents to start taking into account making investments on human capital and environmental capital. Then agents immediately rearrange their investment decisions to invest in assets that have the highest rates of return like human capital and environmental capital. In fact they do not have to invest much in human capital or environmental capital since these investments have a higher return than the physical capital investments. It follows that under ITC we can get immediate benefits now. The economy become more efficient as a result we have more money left over for consumption in the current period and so on.

Figure 4 shows the ITC values of M and E in EXP1, relative to BAU. We can find that there is a very small change in input M between the ITC and BAU scenarios under EXP1 but there is a decrease in the usage of E in the ITC scenario of EXP1. The graph shows that the use of energy E diminishes significantly and the use of generic intermediate M increases a very small amount. Under ITC, carbon tax stimulates substitution effect when we produce output Y. Firms use more generic intermediate

M as an input, substituting for energy E, compared with the BAU case. As we will show below, under the ITC scenario, the knowledge accumulation shifts from energy production to energy saving technology. Therefore energy usage E has decreased in the ITC scenario and at the same time output Y still keeps increasing overtime since there is more knowledge stock in A_{YE}.

Figure 5 shows the ITC values relative to BAU values of R, R_{YE}, R_{MZ} and R_{EZ} under EXP1. The relative values of knowledge variables A_{YE}, A_{MZ}, A_{EZ} are not shown in this graph since they follow the same pattern as the relative values for the R&D variables. We got a jump down in R_{EZ} and an increase in R_{YE}, while R_{MZ} increased a little bit over time. R_{MZ}'s path for two scenarios are almost identical except that it is a slightly higher in ITC. This is because under ITC the economy is more productive, and therefore the output firm has a higher demand for M. As a consequence, A_{MZ} and R_{MZ} increase correspondingly. The R relative value seems gradually increases over time but not very much. As a result, the ITC case helps this economy switch from investment in carbon energy production technology R_{EZ} to carbon energy efficiency technology R_{YE}, but there is a very little impact on the materials R_{MZ}.

Figure 6 shows the BAU values of EXP2 relative to BAU values from EXP1 of Y, C, M, E and K. We got a significant drop in E and significant increases of Y, C, M and K in relative values. In fact, Y, C, M and K are essentially growing at the same rate. Explanations are as follows.

In EXP 2 BAU, there is a reduction in E, A_{YE}, A_{EZ}, Z_E, R_{YE}, R_{EZ}, and ATM. There is an increase in Y, I, R, C, K, M, A_{MZ}, Z_M, R_{MZ} compared with EXP1 BAU. Besides that, there is a shift in their investments from energy related variables to generic intermediate related variables and output also increased. Therefore EXP2 BAU appears to be more efficient and has a higher social welfare impact. In our case, by putting ω in the model we are saying that firm is less optimistic of how much of R&D they are going to be paid for. The coherent explanation of why agents will cut back in the energy usage E and increase generic intermediate M if we put ω in (EXP2 BAU) are as follows.

Firstly, in EXP 2 BAU, for the company producing Y, they use M and E as their production inputs. If we add ω into the model, according to the FOC of M: $\mathrm{P}_t^{\mathrm{Y}}\, Y_t^{\frac{1}{\sigma}} \left(\zeta_{YM} A_{YM,t}^{\pi_{YM}}\, M_t\right)^{\frac{\sigma-1}{\sigma}} = \mu_t M_t$, which gives us the production firm's demand for M as the marginal product of M equals the marginal cost of M. The marginal product of M is not affected by insertion of ω. In contrast, for the FOC of E: $\mathrm{P}_t^{\mathrm{Y}}\, Y_t^{\frac{1}{\sigma}} \left(\zeta_{YE} A_{YE,t}^{\pi_{YE}}\, E_t\right)^{\frac{\sigma-1}{\sigma}} = [q_t - P_t^{ATM}(1-\delta_E)]E_t$, A_{YE} falls then efficiency of energy use falls which means the marginal product of energy falls. Therefore, in the market of M the demand curve shifts out because the marginal product of M is affected by increases in Y and the marginal product of M increases, output company needs more M as their production input and there is a higher price of M (μ) and higher demand of M in equilibrium. In the market of E the demand curve shifts in and there is a fixed price of E (q) and an even lower demand of E in equilibrium. So the output production becomes dominated by materials M.

Secondly, since there is a higher demand for M and μ has increased, it is going to be more profitable to accumulate A_{MZ}. Therefore A_{MZ} will accumulate faster and R_{MZ} will increase as well, despite the inter-firm knowledge spillover.

Thirdly, since there is a lower demand for E and the price of E is fixed (q), energy companies would produce less. Therefore there is less accumulation of A_{EZ}. If there is less A_{EZ} in each period so R_{EZ} decreases as well.

Figure 7 shows BAU values of EXP2 relative to BAU values from EXP1 for R_{YE}, R_{MZ}, R_{EZ} and R in each period. Firstly, we got a big increases in R_{MZ} and R and a decrease in R_{EZ} and R_{YE}. (The paths of relative values for R_{YE} and R_{EZ} are very similar; they both follow the identical downward trend.) The relative value of R is increasing over time, reflecting the increase in R_{MZ}. In EXP2 BAU agents are switching out of energy related R&D into materials related R&D, for the reasons given above for figure 6. The significant reduction in the use of energy in EXP 2, under BAU, has the unexpected result that the total atmospheric concentration of carbon (ATM) never exceeds the target level of 450 ppmv. As a result, the carbon constraint (16) under the ITC scenario is never binding and therefore ITC and BAU yield identical results.

Figure 8 shows that the ITC values of Y, C, M and K in EXP 4 are increasing relative to their BAU values of EXP4. The gap between the two scenarios is increasing over time (same explanation as made in figure 3 about EXP 1 ITC values relative to EXP1 BAU values). The result shows that under the ITC scenario the economy becomes more productive. The effect of ITC on economy's output level is very positive.

Figure 9 shows the ITC values of EXP4 relative to BAU values from EXP4 for M and E in each period. In EXP4 ITC's scenario, M is slightly greater than its BAU level for every period but E is significantly lower than its BAU level. In Fact, the ITC level of E is less than 1/5 of the BAU level of E under EXP4 for every period. (Same explanations as made in figure 4 of EXP1 ITC values relative to EXP1 BAU values). ITC leads the economy to invest more in M and less in E because of the constraint on atmospheric carbon concentration level ($ATM \leq 450\, ppmv$) in this scenario. According to Gerlagh and Lise (2003), they show that ITC accelerates the substitution of carbon-free energy for fossil fuel substantially. Similarly, our experiment 4 shows that ITC contributes very much to the reduction of abatement cost.

Figure 10 shows the ITC values of R_{YE}, R_{MZ}, R_{EZ} and R in EXP4 relative to EXP4 BAU values in each period. There is a big increase of R_{YE} investment in energy use efficiency. For example, in 2005, R_{YE} is almost 16 times larger in ITC case than the BAU case under EXP4. There is also a higher value of R_{MZ} in every period, since under

ITC the economy becomes more productive and there is a higher demand for generic intermediate M (which has been shown in figure 9). Consequently the firm that produces M has a higher demand for A_{MZ}. In contrast, R_{EZ} is much smaller in the ITC scenario compared with BAU (relative value of R_{EZ} is less than 1). For example, in 2005, the relative value of R_{EZ} is less than 1/5. Knowledge stocks follow the similar paths of R&D variables in the relative terms. The value for R increased a little in the ITC case (the relative value of R is around 1.2 to 1.4), reflecting the large increase in R_{YE}. Within EXP4, ITC case has a lower value of R_{EZ} compared with R_{EZ} from BAU. Eventually within EXP4, if we compare ITC with BAU, the relative value of R_{EZ} would go to 0.15.

This finding supports Gerlagh's results: 1. There is a shift from carbon energy production R&D to carbon energy efficiency R&D. 2. Consumption in ITC is not negatively affected. In fact, the C level of ITC case under EXP4 goes up compared with its BAU case for each period. Thus ITC brings benefits to our economy rather than costs.

Figure 11 shows the BAU values of EXP4 relative to BAU values from EXP1 of R_{YE}, R_{MZ}, R_{EZ} and R in each period. As time goes on, agents relying on more investment in material knowledge R_{MZ} and much less investment in energy related knowledge (R_{EZ} and R_{YE}). The main story here is the shift in arrangement of R&D from energy related to material related R&D due to the change in the calibration of the initial value of energy related R&D.

Figure 12 shows the BAU values of Y, C, M, E and K in EXP 4 relative to EXP1 BAU in each period. The problem for K path is due to our first phase calibration process errors[4]. When we calibrate the model in the right way, it should produce the same value of Y and K in the first period for both EXP4 BAU and EXP1 BAU. Different from EXP2 BAU to EXP1 BAU's case, our case shows that in EXP4 BAU both E and M decreases initially and then starts to rise compared with EXP1 BAU. Conditional on lower Y and higher C over time, agents rely more on energy and materials and less on energy related R&D (R_{EZ} and R_{YE}) in the long run. These trends make sense since (i) firms will be investing less in energy related R&D because of "ω" in EXP 4 and (ii) in EXP 4 the model is calibrated so that energy-related R&D is less productive. Therefore firms increase their consumption of raw energy E and materials M.

Figure 13 shows the ITC values of Y, C, M, E and K in EXP4 relative to EXP1. At a certain point, the economy becomes richer and agents start spending more in Y, C, M, and K. And we have the relative value of C immediately above 1 which means that in EXP4 ITC has an even higher value of aggregate consumption for each period. Also in this case we have a reduction in energy usage E and an increase in generic intermediate M same as the figure 6, but both relative values of M and E start to rise in later periods. Gerlagh's conclusion still works in this case and we can see that EXP4

[4] Note: There is a problem in our first stage calibration, because we have more unknowns than equations in our system of equations and therefore we need to put more work on this part.

ITC even brings more benefits to us. Actually, in the ITC case we have already shown that the cost of abatement is negative; i.e. there is no sacrifice for the current generation. Rezai (2011) argues that there is no sacrifice of consumption of current generation under the optimal policy.

Figure 14 shows the ITC values of R_{YE}, R_{MZ}, R_{EZ} and R in EXP4 relative to EXP1 ITC in each period. R_{YE} is not affected as much as R_{EZ} in first several periods. R_{EZ} is affected the most, while R_{YE} falls at first (relative to EXP 1 ITC) and then it starts to increase (same explanation as figure 11). By design, EXP1 has a very large initial value in energy related R&D compared with EXP 4 so we could see that both R_{YE} and R_{EZ} are significantly lower in EXP4. However, even though values of R_{YE} and R_{EZ} are lower in EXP4 than in EXP1 but within EXP4 at least R_{YE} is much higher in ITC than the BAU value (Figure 10). Since within EXP4 ITC case there are lot of investments in energy efficiency R_{YE} sector.

VI. Conclusion

In this paper, we made a comprehensive analysis about Gerlagh (2008). First of all, we have indicated that there are four major problems in Gerlagh (2008): the initial value of energy related R&D, the appropriation rate "ω", the second best result, and the duplication externality. In the present paper, we have fixed the first three problems and leave the last one for future work. Secondly, we established three different experiments and showed how model structure changes affected firms' choices of inputs with particular focus on technology R&D.

Our major conclusions are as follows; Firstly, we concluded that the induced technological change had a significant impact on the reduction of greenhouse gas abatement cost since our Y increased and even aggregate consumption increased. Therefore the economy becomes much more efficient. Secondly, we find that agents switch out of energy-related R&D into materials-related R&D since inserting the inter-firm knowledge spillover parameter into our model affects the marginal productivity of carbon energy which results in a cut in the usage of energy E. Thirdly, in EXP4 we have a much lower value for our energy related R&D compared with EXP1 since we calibrate a constraint of initial level of energy related R&D.

For this project there are three major things need to be done in the future: The first job is to improve the calibration to provide a unique solution for unknown parameters. The second thing is to correct the duplication externality in the BAU scenario. And our third job is continue to find and correct other potential errors in Gerlagh (2008), like adding the damage function into the Gerlagh's model.

VII. Figures

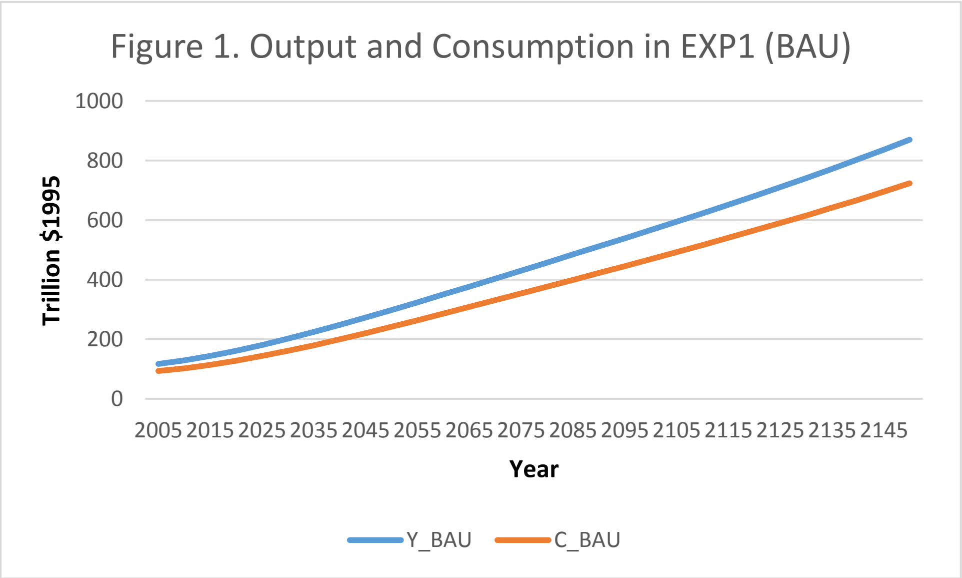


Figure 1. Output and Consumption in EXP1 (BAU)
1000
800
600
400
200
0
Trillion $1995
2005 2015 2025 2035 2045 2055 2065 2075 2085 2095 2105 2115 2125 2135 2145
Year
Y_BAU
C_BAU

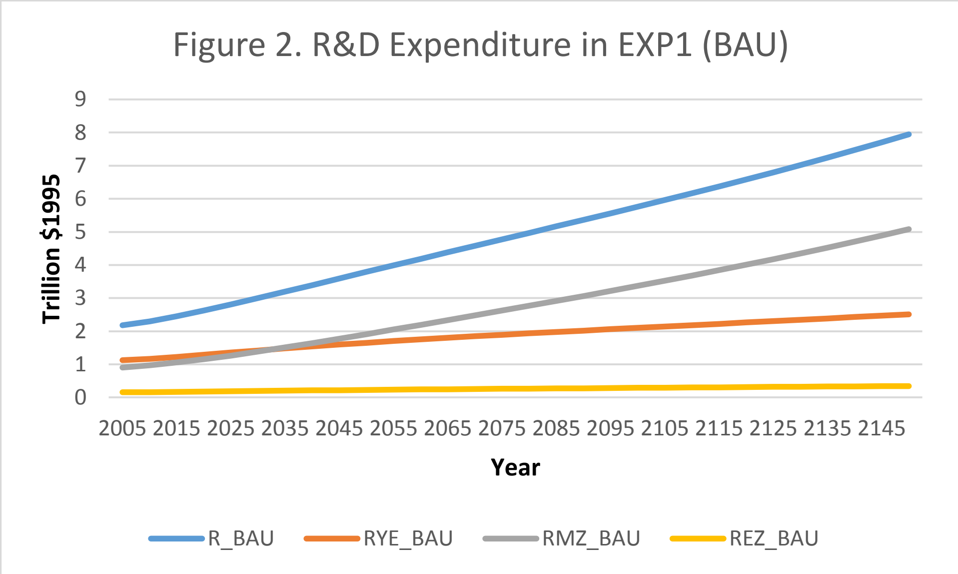


Figure 2. R&D Expenditure in EXP1 (BAU)
Trillion $1995
9
8
7
6
5
4
3
2
1
0
2005 2015 2025 2035 2045 2055 2065 2075 2085 2095 2105 2115 2125 2135 2145
Year
R_BAU
RYE_BAU
RMZ_BAU
REZ_BAU

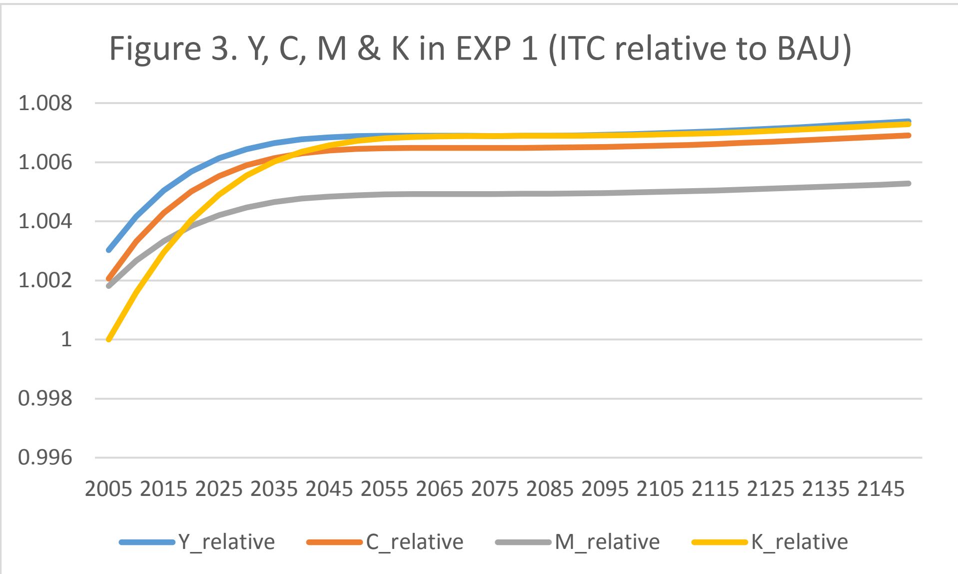


Figure 3. Y, C, M & K in EXP 1 (ITC relative to BAU)
1.008
1.006
1.004
1.002
1
0.998
0.996
2005 2015 2025 2035 2045 2055 2065 2075 2085 2095 2105 2115 2125 2135 2145
Y_relative
C_relative
M_relative
K_relative

Figure 4. Comparison of M and E in EXP1 (ITC relative to BAU)

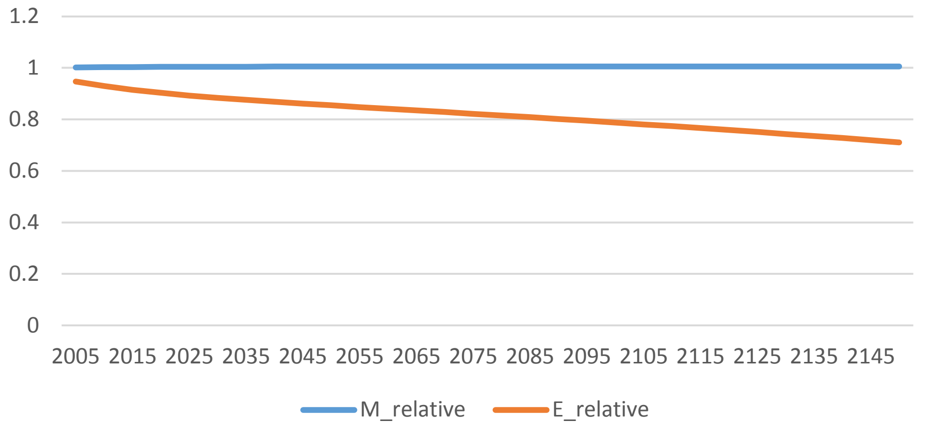


Figure 5: R&D in EXP1 (ITC relative to BAU)

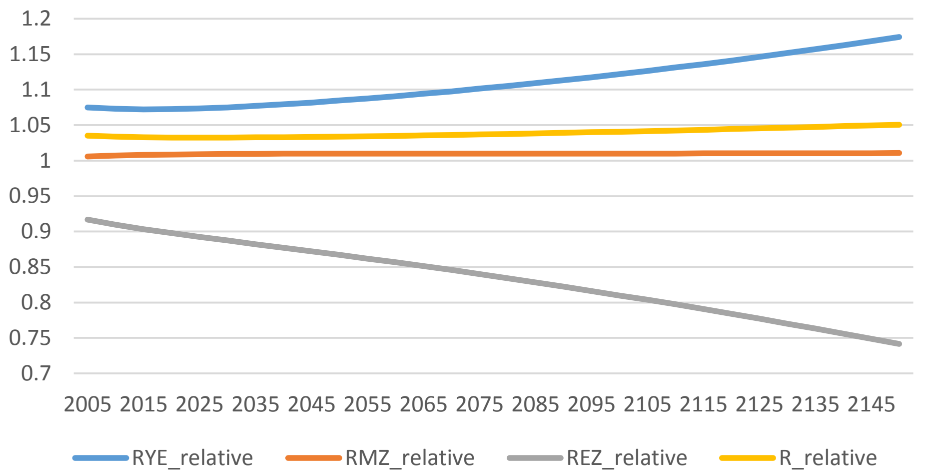
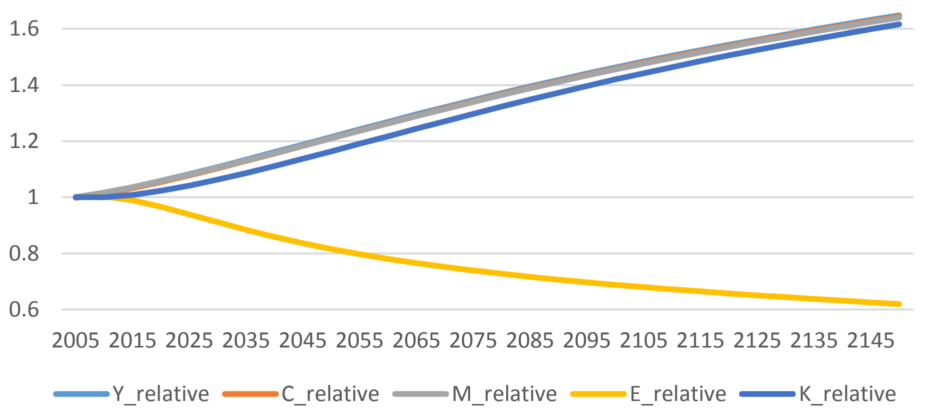


Figure 6. Y, C, M, E & K in EXP2 relative to EXP1 (BAU)



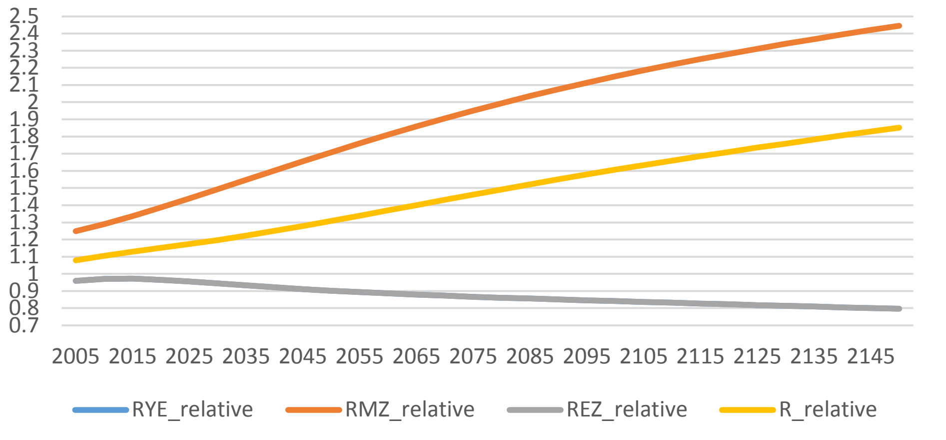


Figure 7: R&D Expenditure in EXP2 relative to EXP1 (BAU)

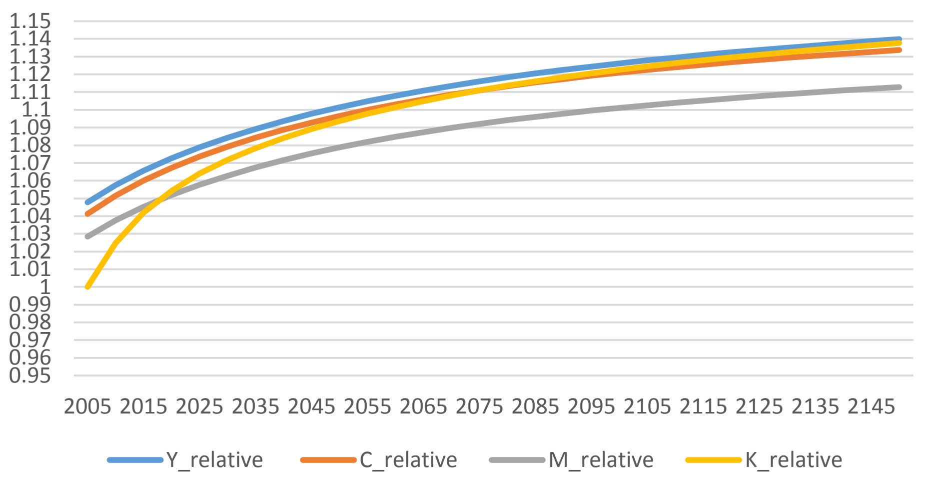


Figure 8: Y, C, M & K in EXP 4 (ITC relative to BAU)

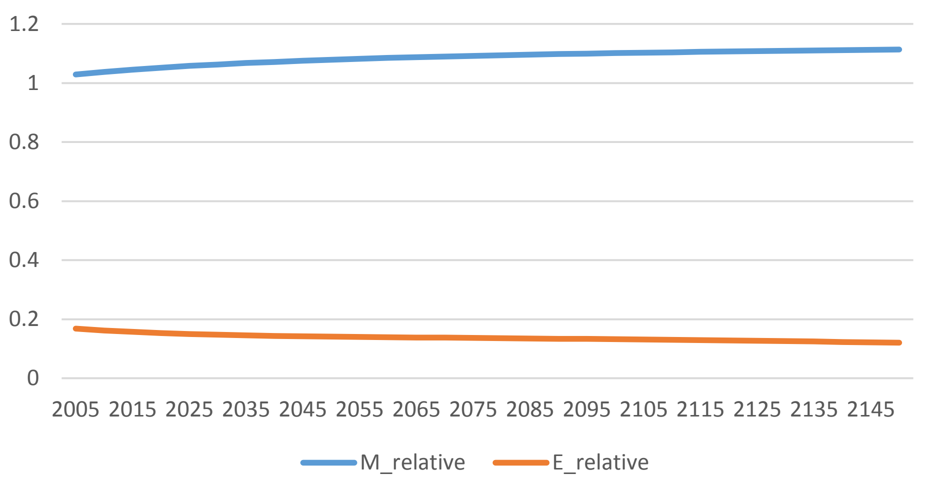


Figure 9: M & E in EXP 4 (ITC relative to BAU)

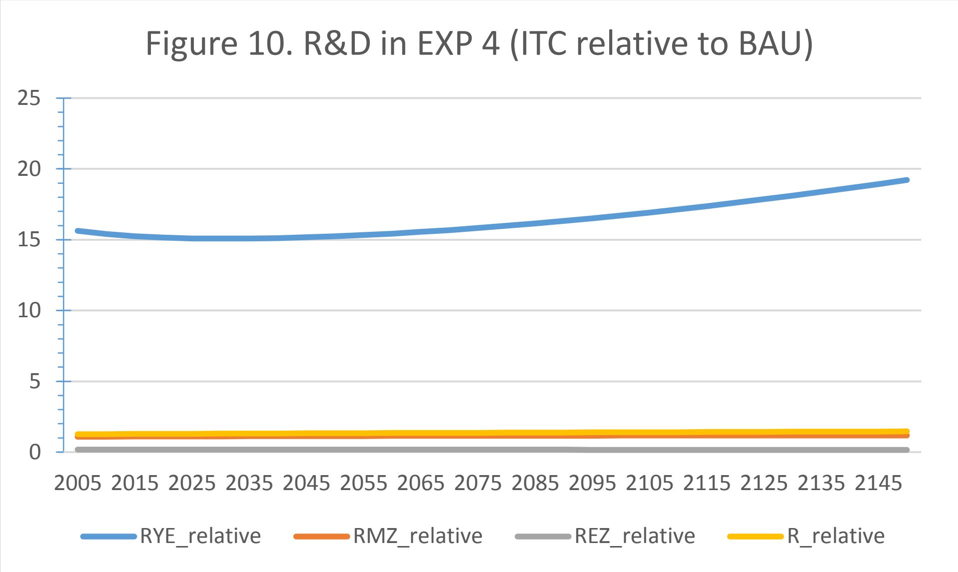


Figure 10. R&D in EXP 4 (ITC relative to BAU)
25
20
15
10
5
0
2005 2015 2025 2035 2045 2055 2065 2075 2085 2095 2105 2115 2125 2135 2145
RYE_relative
RMZ_relative
REZ_relative
R_relative

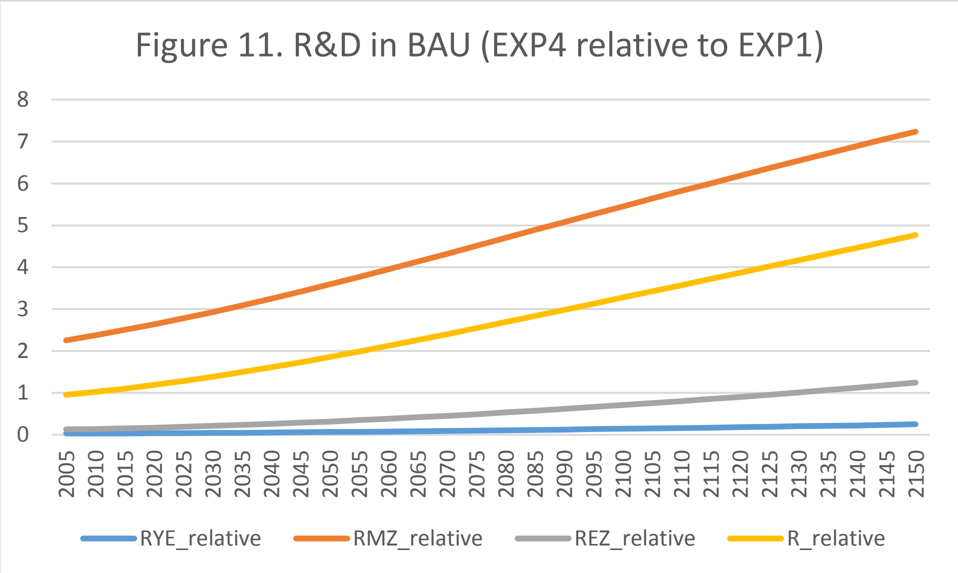


Figure 11. R&D in BAU (EXP4 relative to EXP1)
8
7
6
5
4
3
2
1
0
2005 2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060 2065 2070 2075 2080 2085 2090 2095 2100 2105 2110 2115 2120 2125 2130 2135 2140 2145 2150
RYE_relative
RMZ_relative
REZ_relative
R_relative

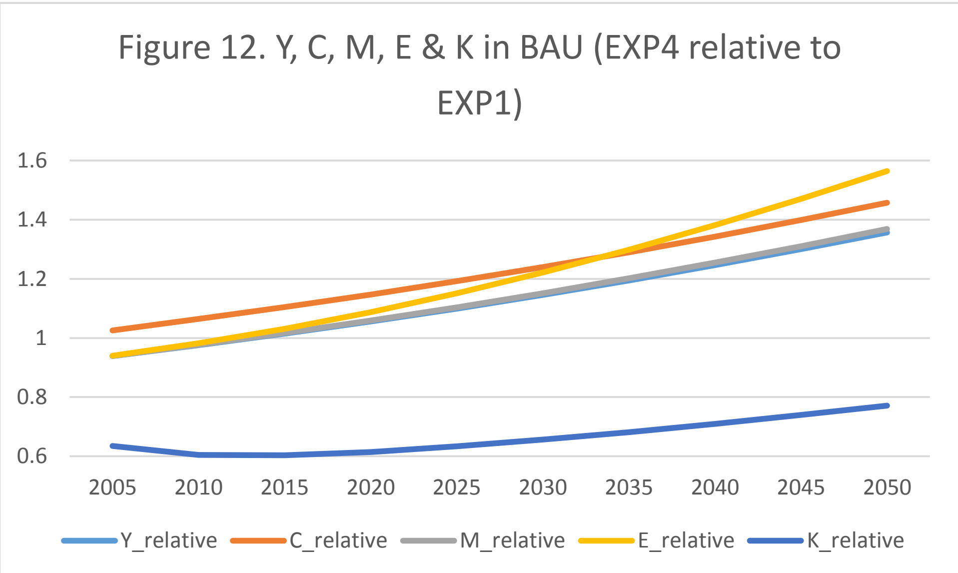


Figure 12. Y, C, M, E & K in BAU (EXP4 relative to EXP1)
1.6
1.4
1.2
1
0.8
0.6
2005 2010 2015 2020 2025 2030 2035 2040 2045 2050
Y_relative
C_relative
M_relative
E_relative
K_relative

Figure 13. Y, C, M, E & K under ITC (EXP4 relative to EXP1)

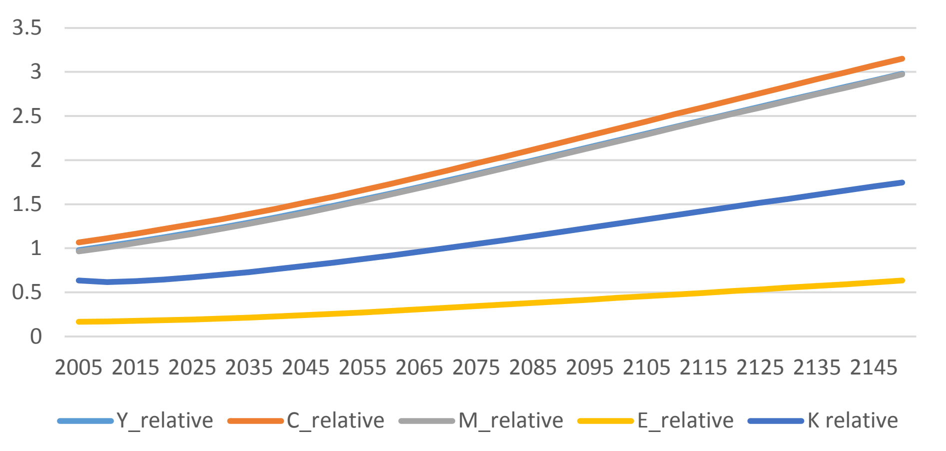
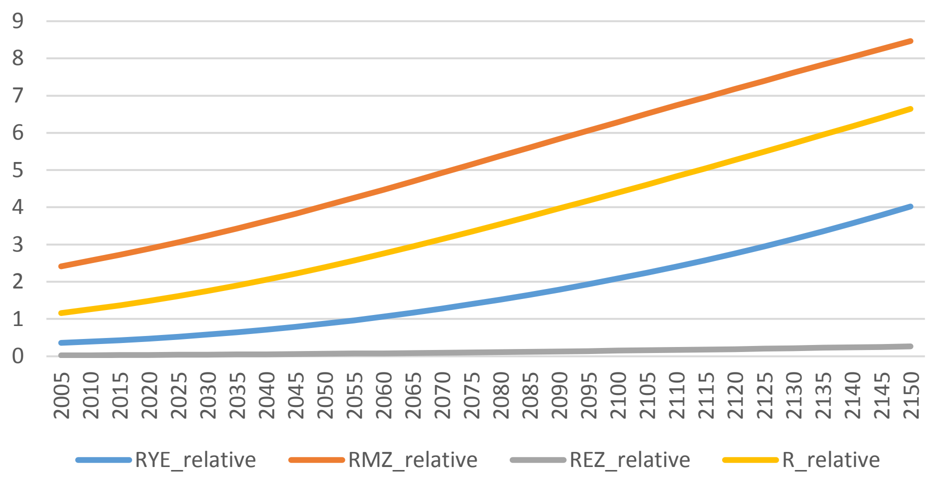


Figure 14. R&D under ITC (EXP4 relative to EXP1)



VIII. Calibration results

Table 1. Calibration results from EXP1

ζ_{YE} = 95.01076	K = 28.70000
π_{YE} = 1.3329090768	L = 14.71200
π_{MZ} = 0.05685	R_{YE} = 1.2575423496
π_{EZ} = 0.2569885643	R_{MZ} = 2.58000
ς_M = 12.52060	R_{EZ} = 0.2424576504
ς_E = 89.74025	C = 0.01595
α = 0.25925	μ = 0.94554
M = 0.02090	ξ = 11.68352
A_{YE} = 0.7365039352	ψ = 3.97874

A_{MZ} = 0.79278 A_{EZ} = 0.1420000000 Z_M = 16.91673 Z_E = 0.57801	θ_{YE} = 0.39540878 θ_{MZ} = 66.24335 θ_{EZ} = 39.54088

Table 2. Calibration results from EXP2

ζ_{YE} = 0.01882 π_{YE} = 3.5674971128 π_{MZ} = 0.21349 π_{EZ} = 0.6878233310 ς_M = 12.98441 ς_E = 0.02081 α = 0.25925 M = 0.02090 A_{YE} = 0.7365039352 A_{MZ} = 0.79278 A_{EZ} = 0.1420000000 Z_M = 16.91673 Z_E = 0.57801	K = 28.70000 L = 14.71200 R_{YE} = 1.2575423496 R_{MZ} = 2.58000 R_{EZ} = 0.2424576504 C = 0.01595 μ = 0.94554 ξ = 11.68352 ψ = 3.97874 θ_{YE} = 0.39540878 θ_{MZ} = 66.24335 θ_{EZ} = 39.54088

Table 3. Calibration results from EXP4

ζ_{YE} = 99.59289 π_{YE} = 0.1189156684 π_{MZ} = 0.33085 π_{EZ} = 0.0990108389 ς_M = 11.54285 ς_E = 82.14921 α = 0.25925 M = 0.02090 A_{YE} = 0.0218356948 A_{MZ} = 1.22857 A_{EZ} = 0.0153952602 Z_M = 16.91673 Z_E = 0.57801	K = 28.70000 L = 14.71200 R_{YE} = 0.0435203121 R_{MZ} = 3.99824 R_{EZ} = 0.0382396879 C = 0.01595 μ = 0.94554 ξ = 11.68352 ψ = 3.97874 θ_{YE} = 0.44749508 θ_{MZ} = 66.24335 θ_{EZ} = 53.36667

IX.References

Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn, and David Hemous (2012), "The Environment and Directed Technical Change" *American Economic Review* 102(1), 131-166.

Fischer, Carolyn and Richard G. Newell (2008), "Environmental and Technology

Policies for Climate Mitigation," *Journal of Environmental Economics and Management* 55, 142-162.

Gerlagh, Reyer (2008), "A Climate-Change Policy Induced Shift from Innovations in Carbon-Energy Production to Carbon-Energy Savings," *Energy Economics* 30, pp. 425-448.

Gerlagh, Reyer and Lise Wietze, 2003. "Induced Technological Change Under Carbon Taxes," Working Papers 2003.84, Fondazione Eni Enrico Mattei.

Goulder, Lawrence H., and Stephen H. Schneider (1999), "Induced Technological Change and the Attractiveness of CO2 Abatement Policies," *Resource and Energy Economics* 21, 211-253.

Hart, R. (2008), "The Timing of Taxes on CO2 Emissions When Technological Change is Endogenous," *Journal of Environmental Economics and Management* 55(2), 194-212.

Jaffee, Adam, Richard Newell, and Robert Stavins (2005), "A Tale of Two Market Failures: Technology and Environmental Policy," *Ecological Economics* 54, 164-174.

Jones, Charles I. (1995), "R&D-Based Models of Economic Growth," *Journal of*

Political Economy 103(4), 759-84.

Jones, C.I., and J.C. Williams (2000), “Too Much of a Good Thing? The Economics of Investment in R&D,” *Journal of Economic Growth* 5, 65-85.

Massetti, Emanuele, and Lea Nicita (2010), “The Optimal Climate Policy Portfolio When Knowledge Spills Across Sectors,” *FEEM Working Paper* 96.2010.

Popp, David (2006), “ENTICE-BR: The Effects of Backstop Technology R&D on Climate Policy Models,” *Energy Economics* 28, 188-222.

Popp, David (2004), “ENTICE: Endogenous Technological Change in the DICE Model of Global Warming,” *Journal of Environmental Economics and Management* 48, 742-768.

Popp, David (June 2003), “ENTICE: Endogenous Technological Change in the DICE Model of Global Warming,” *NBER Working Paper*, No. 9762.

Rezai, Armon (2011), “The Opportunity Cost of Climate Policy: A Question of Reference,” *Scandinavian Journal of Economics* 113(4), 885-903.

Shiell, Leslie and Nikita Lyssenko, 2014. “Climate Policy and Induced R&D: How great is the Effect?" University of Ottawa, Department of Economics, Working Paper #1405E.