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Assessing the role of energy technology in mitigating GHG emissions

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The problem of mitigating global emissions of GHGs can be addressed by imposing restrictions on emissions, as in Kyoto Protocol, or by encouraging development and diffusion of carbon free technologies or a combination of both. Carbon free technologies exist but are expensive. It is now commonly accepted that learning by doing is a genuine process of cost reduction for newer technologies. Previous studies claim that because of LBD effects, carbon free technologies will grow over time and magnify the effects of carbon tax on emissions reduction. However, these conclusions are drawn from very stylised aggregate models of the global economy. In this paper we re-examine these claims using a multi-sector and multi-country CGE model of global economy with multiple energy technologies and emissions sources. The results generally support the claim with the implication that global agreement on development, diffusion and adoption of carbon-free technologies together with emissions restriction or a tax in earlier periods may hold the key to solving the climate change problem effectively.

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1 Introduction

Climate change is one of the most widely studied and debated topics today. It is multi-disciplinary; it is intergenerational and it is transnational. Many scientists now believe that human induced emissions of greenhouse gases (GHGs) are at the root of the climate change problem. Reduction in GHG emissions in the future is therefore a necessity if we wish to control climate change.

Primarily, GHG emission reductions can be achieved in two different ways: by imposing emissions restrictions (say by levying taxes on emissions, by capping or by capping and trading); or by employing emissions free energy systems and production processes and thereby decoupling human activities – economic growth – and emissions. A combination of the two is also a possible solution.

The main sources of GHG emissions are the use of fossil fuels in the power and transport systems that form the basis of modern societies. There are other sources of emissions, but they are relatively minor and/or diffused.

Imposing emissions restriction therefore means restrictions on the production and use of fossil fuels, fossil fuel based power and transport systems. A series of Kyoto Protocol like arrangements for successive time periods is a possible pathway to emissions reductions. However, the improvement in productivity levels that support continued economic growth is fuelled by the use of energy commodities. A reduction in the use of energy commodities (and transport systems) today would almost certainly lead to a reduction in economic growth and living standards.

Because climate change is intergenerational and transnational, many economic analyses do not take proper account of the free rider problems associated with climate change. Current generations have an incentive to push the cost of climate change onto future generations and regions around the world have an incentive to push the costs onto other nations. The climate change policy problem is a complex one. It is necessary both to decide the level of global emissions for each time period as well as how much each nation should be allowed to emit in each time period. Once that is done there is the difficult question of monitoring emissions and enforcing any agreement if it involves emissions restrictions.

The experience of the past decade in international climate negotiations has illustrated some of the difficulties in organising a successful regime. Any agreement that fails to cover all major emitters will be unsuccessful in limiting climate change as will any agreement that covers a limited time scale. The majority of negotiating time over the past fifteen years has been spent on developing an agreement that attempts to limit emissions directly. An alternative approach would be to concentrate on technologies that have the potential to transform the power generation and transport sectors. If such a transformation could be achieved it would then be possible to decouple economic growth and emissions. For example, the use of renewable energy (or some other emission free technology) to generate electricity and the use of this electricity to produce hydrogen from non-fossil sources for use in the transport sector, is a possibility.[1] Currently this technology is expensive and has some practical problems (Romm 2004).

There are theoretical arguments as well as empirical evidence to suggest that the cost of a given technology declines with the accumulation of experience (Wright, 1936; Arrow, 1962; Grubler and Messner 1998; van der Zwaan et al. 2002; IEA 2000). This has lead to suggestions that particular technologies might be promoted through policy interventions such as tax breaks or subsidies. However, given that there are known technologies on the shelf whose costs decline with experience, then promoting other intermediate technologies through subsidies or tax breaks that could delay the adoption of the best technology could be welfare reducing (Kverndokk, Rosendahl and Rutherford, 2004). The obvious question then is what role carbon free technologies can play in mitigating the emissions of GHGs when technological change are endogenous - how long will it take for carbon free technology to be the major source of primary energy and what form of government intervention, if any, might be considered.

Adopting the learning-by-doing approach to endogenous technical change from bottom-up energy modeling, allowing autonomous energy efficiency to change over time and assuming that the carbon-rich and carbon-free energy sources are good substitutes, van der Zwaan et al. (2002) studied the carbon tax rates required to meet a given atmospheric concentration of GHGs. They found that including endogenous technological change, especially learning by doing, implied earlier emissions reductions and lower carbon tax rates than without endogenous technical change in hitting the given target.

Using a partial equilibrium model of energy demand and supply, Gerlagh et al. (2003) examined the adoption of carbon-free technology and carbon dioxide emissions under endogenous technological change induced by carbon taxes. Endogenous technological change was captured in their model by learning-by-research and learning-by-doing phenomena. They found that with endogenous technical change, the adoption of carbon-free technology and the reduction in emissions caused by the imposition a carbon-tax occurred earlier than without endogenous technical change.

In a further study using a stylised general equilibrium model of the global economy (one region, three sectors of which two are energy technologies - one fossil fuel and the other carbon free – and the third is a final consumer good) Gerlagh et al. (2004) examined the emission pathways under a constant carbon tax when the energy supplied by fossil fuel and the carbon-free sectors are ‘good’ substitutes. They found that with learning-by-doing, which reduces the cost of production of carbon free technologies, a tax of $US50/t of carbon is sufficient to stabilise the global emissions at the 2000 level throughout the 21st century.

[1] http://www.hydrogennow.org/links.html contains links that may provide additional information on various aspects of hydrogen economy.

The required level of carbon tax to stabilise emissions levels or the atmospheric concentration level by 2100, however, depends crucially on the elasticity of substitution between the energy produced by the two technologies. It is also important to note that most of these studies that have modelled endogenous technical change are highly stylised. For example they assume that the consumer good sector is the only user of the energy commodity, energy is supplied by two sources- carbon-rich and carbon free, and that the combustion of fossil fuel (carbon-rich) is the only source of emissions.

As their results are interesting and have important implications for the design of climate change policy, it is useful to examine further whether these results stand qualitatively intact in the context of a multi-country, multi-sector general equilibrium model of the global economy with multiple energy technologies and multiple sources of emissions. In a model with learning-by-doing, would a sufficiently high elasticity of substitution between a new carbon-free technology and existing technologies be enough to eliminate emissions from the power and transport sectors? Would a reasonably modest carbon tax be enough to stabilise emissions throughout the century as found in the aggregate models? What else would be necessary to make the world emissions free? These are the prime questions addressed in this paper. To answer these we modify GTEMLR, the intertemporal version of the Global Trade and Environment Model (Pant 2002; Pant, Tulpule and Fisher 2003) to incorporate learning-by-doing effects in the renewable technology of the technology bundle of the electricity sector. In the spirit of Gerlagh and Liese (2003) we model a variable set of CRESH parameters that allows the niche technology to become competitive with the mature technology and allow all energy users to substitute between the set of energy commodities – coal, oil, gas, petroleum and coal products and electricity – in response to relative price changes using a CES aggregator function with a reasonably high elasticity of substitution.

The remainder of the paper is divided into four sections. In section two, we give a short overview of GTEMLR and in section three we describe the modifications introduced for this paper. In section four, we simulated the model under two scenarios, with and without a carbon tax, and present the simulation results. In section five we conclude the paper and draw some implications for the design of an effective climate change protocol.

2 An overview of GTEMLR

GTEMLR is the intertemporal version of The Global Trade and Environment Model (GTEM), which is a multisectoral and multiregional dynamic model of the global economy developed at ABARE. The recursive version of GTEM was originally derived from the first version of GTAP model (Hertel 1997) and so at its core GTEM looks very much like the GTAP model; many of the coefficient and variable names and data headers are the same and it is solved using the same software, GEMPACK (Harrison and Pearson 2000). GTEM, however, added the following features to the original GTAP model: a technology-bundle approach to model energy-intensive industries; a population module that generates endogenous changes in population and labor supply; a greenhouse module that tracks emissions from the production of various commodities and from the use of fossil fuels; and accumulation relationships for capital stock, debt and population that made GTEM dynamic.

The intertemporal version of GTEM, which is called GTEMLR, allows agents to be forward-looking. Because of this particular feature, GTEMLR is well suited to study problems with long time horizons, such as climate change. So far, however, GTEMLR does not include the endogenous population module of the standard GTEM and so labor supply and population growth are exogenous. In all other respects GTEMLR is the same as GTEM.

Briefly, the main features of the model can be described as follows. It contains five basic types of agents: a representative consumer, regional production sectors, importers, an international transportation sector, and a global financial center. All agents behave competitively and take prices as given. Supply of natural resources, land, government policies, technology and tastes are exogenous. All factors in each region are owned by the regional household, which receives all factor incomes, all tax revenues and makes and receives transfer payments to and from the rest of the world. A representative consumer decides on the allocation of income of the regional household.

The current gross national income of each region is allocated to savings (units of global bonds) and to the consumption of commodities produced everywhere to maximise the utility of the representative consumer. This is done in three stages: first, a Cobb-Douglas utility function, defined over the private consumption of goods, government consumption of goods and real savings is maximised. This implies that a fixed share of gross national income is allocated to each of the three categories. The budget allocated to private and government consumption is further allocated to individual commodity composites maximizing a Cobb-Douglas utility function for government consumption and a CDE function for private consumption. In the third stage, using the Armington assumption of imperfect substitution between sources of a commodity and assuming rationality both government and private demand of each composite commodity is met from domestic and foreign sources so that the cost of each commodity composite is minimized.

Production sectors use a CES composite of the four types of factors of production, capital, labor, land and the natural resource, and combine it with other energy and non-energy material inputs to produce their output. Production technologies contain nests that allow intra-energy commodity, intra-factor and energy-factor substitution in response to relative price changes and are characterised by constant returns to scale. Each sector minimises cost by choosing inputs optimally; and industry output levels are chosen to maximise profit, given prices. There are two production sectors in GTEM– electricity and iron and steel – whose production functions are different from others. Instead of a single nested production function, each of these sectors has a technology bundle. Electricity is produced by six technologies – coal fired, oil fired, gas fired, hydro, nuclear and renewables; and iron and steel is produced by two different technologies – blast furnace and electric arc. Each technology employs a different Leontief production function. The technology-bundle industries buy CES aggregates of the outputs of corresponding technologies as inputs into their production, which is then sold to the end users. The allocation of output to different technologies is chosen to minimise the average cost of input to the respective technology-bundle industry.

Unlike technologies of the iron and steel sector, which can be considered to produce outputs that are imperfect substitutes, technologies in the electricity sector produce near homogenous output. The CES aggregation of the technologies, which treat them as imperfect substitutes, is indeed an imperfect representation of the capacity constraints faced by each technology in the short run, lumpiness of investment, and different needs of buyers, such as remote location, etc. that support the existence of niche technologies.

Competitive conditions imply price-taking behavior on the part of all agents and satisfaction of zero profit conditions in equilibrium when all markets clear. Input demands for commodities are met from domestic as well as from foreign sources. The Armington assumption of imperfect substitution between sources and the process of cost minimisation again determine the allocation of input demand between sources of supplies.

Aggregation of input and final demand for each commodity identified by source determine a region's imports by commodity and by region. This aggregation also yields a region's export of a commodity by destination and thus bilateral trade. Shipping of commodities from a source to its destination region is done by an international transport sector, which has a Leontief production technology. This sector buys inputs of transports (margin commodities) from various regions minimising the unit cost of the transport aggregate. Importers buy the transport services and the cost of transport creates the wedge between the *fob* and *cif* prices of commodities. Both the transport sector and importers satisfy zero profit conditions in equilibrium because of competition.

The savings of the regional households are pooled by the global financial center and then lent to investors residing in all regions. The allocation responds to the differential of the expected rate of return with the global rate of return that clears the market. The market clearing rate is used to service the debt or pay the savers, which guarantees that the global financial center satisfies its zero-profit condition. Regions may differ in their risk characteristics and policy regimes, therefore it is maintained that different regions may have different expected rates of return in equilibrium. The equilibrium condition simply requires that changes in the expected rate of return be the same across all regions, which equals the changes in the global rate of return. In this sense, the allocation of investment in GTEM is inefficient. There is scope for another allocation of investment (and hence the global capital stock), from a low return region to a high return region, which may raise global income and welfare. However, despite the mobility of investible funds, it is maintained in GTEM that the global capital market does not equalise the expected rates of return on investment.

GTEM is built in the Walrasian tradition. Therefore for each commodity and factor there is a competitive market. It is maintained that with fully flexible prices, markets for all goods and factors clear in each period. Commodities are distinguished by source and sold globally. Thus, they have a global market clearing condition. Capital and labor are region specific, but freely mobile across activities in search of a higher return; land is mobile within agricultural industries and natural resources are specific to each resource based industry such as coal, oil, gas, forestry and fishing. Factors are inelastically supplied and their prices are determined by the respective market demand conditions.

The savings of a regional household does not bear any relationship with the amount of regional investment; it is possible for each region to have its capital account in imbalance. A surplus leads to an accumulation of foreign debt, which needs servicing from the next period. This mechanism sets the dynamics of accumulation of net debt in GTEM. As there is a restriction on the amount of investment that a region can undertake in any period via the competition for limited global savings and it cannot borrow for consumption, there is no Ponzi game problem in GTEM.[2] Capital at the start of a period is given by the depreciated stock of the previous period and the gross investment undertaken over the previous period. As long as the amount of gross investment is different from the depreciation requirement, the capital stock of a region continues to change.

In its greenhouse module, GTEM accounts for three gases: carbon dioxide, methane and nitrous oxide. In calculating CO_2 emissions GTEM accounts for combustion, fugitive emissions and industrial processes. In the case of methane and nitrous oxide, it accounts for emissions from livestock and farming activities, fugitive emissions, transport, and chemical industries. The main assumption used in the estimation is that the combustion emissions are proportional to the use of fossil fuels and other emissions are proportional to activity level. The constant of proportionality, the emission intensity is taken as a technological parameter and treated exogenously.

3 Modeling a transition to the hydrogen economy: some modifications in GTEMLR

As mentioned earlier, our main purpose in this paper is to examine whether renewables and renewables based hydrogen can compete with fossil fuels and become the dominant source of primary energy and energy carrier this century. There is no doubt that given the current state of technology hydrogen cannot be a cost effective principal carrier of energy. It is simply too expensive to produce from renewables and the infrastructure, such as refuelling stations, transportation and storage facilities, are too costly to set up. But the question is if the costs decline with the increase in cumulative installed capacity, commonly known as the learning by doing (LBD) effect, will this technology develop, grow and play the lead role in decoupling emissions and economic growth?

[2] In an intertemporally optimising model, if a restriction is not imposed on the accumulation of debt, then it becomes rational for the household to borrow and consume until its marginal utility is zero in each period. It will borrow to service the debt and hence the amount of debt rises 'astronomically', which is called the Ponzi game. As we will see below, in a simplified model of intertemporal choice a no Ponzi game condition has been imposed via a transversality condition in the intertemporal version of GTEM.

In order for a technology to develop three things must happen within a reasonable period of time. First, there must be a niche (or a supported) market to make it exist in the first place when the costs are initially higher. Second, it must be possible to produce the energy commodity or the carrier in large quantities and to distribute it easily. Third, the configuration of other complementary commodities must be such that as the costs of the new technology starts to fall agents have the real option to embrace it. In other words, we must have cars, buses and trucks that run on fuel cells (FCVs); power generators that use renewable sources or use hydrogen produced by emissions free technology.

Hydrogen can be obtained from hydrocarbons, such as coal, oil and gas by a steam reforming process, in which case the by-product CO2 would need to be sequestered if emissions were to be zero, or by electrolysing water. In either case, production of hydrogen requires another source of power. In an ideal state, renewable sources, such as wind, solar, etc. would be used to generate electricity and the electricity would be either used directly or stored in the form of hydrogen. It could then be used in fuel cells in the transport sector or be burned to generate further electricity. How fast a transition to a hydrogen economy would occur will depend on policy settings. It will also depend on the model parameter set that we choose.

In the following sub-sections we outline the modifications we have introduced in GTEMLR to accommodate the mechanisms that are likely to be at work to transform the world energy and transport system totally. To simplify the exercise for the purpose of this paper, we have ignored the development of zero or near zero emission fossil fuel technologies in the intermediate stage. Therefore, the industry specific results are rather biased. The results overstate the decline in the fossil fuel production and refining sectors. The exercise will, nevertheless, illustrate the possibility of the transition to a hydrogen economy within a consistent economic framework.

3.1 Modeling increasing cost of fossil fuels

Although there are counter arguments (Odell, 1999) that cannot be easily rejected, it is generally argued that as continued use of fossil fuels will deplete the existing reserve, the cost of extracting these resources will eventually rise (Gerlagh and Lise, 2003). To model this phenomenon, we associate the productivity of the natural resource factor in the fossil fuel production sectors (coal, oil and gas) negatively with the cumulative quantity of the natural resource used by the industry. Let X_{Njt} be the quantity of natural resource used by the extraction sector j, (we have suppressed the country/region index), A_{Njt} be its productivity index (1 in the base year), P_t be the vector of prices faced by the sector and Q_{jt} be the output produced by the sector at time t, then its cost minimizing input demand function can be written as

(1) $$A_{Njt} X_{Njt} = F_{jt}(P_t; Q_{jt}, A_{Njt})$$

and the productivity index is given by

(2) $A_{Njt} = Z_{Njt}^{-\phi}$ where $Z_{Njt} = \sum_{\tau \le t} X_{Njt}$; $0 < \phi < 1$ and $A_{Nj0} = 1$.

It is clear from (2) that Z_{Njt} is the cumulative quantity of natural resource used by the sector j up to time t since the base year.

The consequence of modeling the productivity factor as given in (2) is that continued use of the resource makes the factor less productive, or expensive in relation to other factors. Therefore, to produce the same quantity of output, more and more labor and capital will have to be employed, depending on the size of the elasticity of factor substitution, which we have maintained slightly greater than unity in GTEMLR, as time goes by. This increases the cost of fossil fuel slowly to the users of fossil fuels – including the power generation sector. As a result, ceteris paribus, renewable technologies will become relatively more attractive compared to fossil fuel technologies. We have chosen 0.05 as the default value for ϕ.

3.2 Modeling learning-by-doing in renewable sector

As mentioned earlier, learning by doing is believed to be a primary reason for the decline in cost of ‘infant’ technologies, such as hydrogen production and distribution. The learning by doing effect is introduced in GTEMLR as an endogenous improvement in input-neutral productivity in the renewable technology of the power generation sector. Recall that the input-output relation in each technology is characterised by a Leontief production function.

Let

(3) $A_{it} X_{it} = Q_t$ for each input i

be the input demand function of the renewable, carbon free technology. (Note that each technology of the technology-bundle industries has a Leontief production function in GTEM.) and A_i represents the productivity factor of the input *i*, which in other words is the inverse of the input-output coefficient. An increase in the value of A_i implies increased productivity as this means that less of X_i is needed, without being substituted for by any other input, to produce a given Q. The subscript t represents time.

Assume further that one source of productivity growth is learning-by-doing, which means that the cost of production declines with accumulated experience, measured by the cumulative change in the productive capacity. It is commonly believed that a doubling of the cumulative capacity leads to about a 20 per cent fall in the cost of production. In this paper we make the explicit assumption that doubling cumulative capacity, measured by output level, implies a 10 per cent fall in the requirements of all inputs, which means A_i will be about 10 per cent higher as a result of doubling of cumulative capacity. This process can be modelled as

(4) $$A_{it} = BZ_t^{\theta}$$

where Z is the cumulative experience, measured by the cumulative output of the new technology, B is a scaling constant and $0 \le \theta \le 1$ is a learning parameter. As equation (3) holds for all t, we can write[3]

(5) $$A_{it} / A_{it-1} = (Z_t / Z_{t-1})^{\theta}.$$

If productivity rises by the rate l_r, (i.e., costs fall, ceteris paribus, by the rate l_r) for a doubling of the experience, we must have

(6) $$l_r = 2^{\theta} - 1.$$

Expressing (4) in linearised form, we get a relationship between annual growth rates of factor productivity that depends on annual growth rates of cumulative experience as follows

(7) $$a_{it} = \theta z_t.$$

We have chosen θ=0.10, which gives a conservative learning rate of around 7 per cent, the rate claimed in the literature is about 20 per cent (van der Zwaan et al. 2002). We initialize $a_{i0} = 0; A_{i0} = 1$. (ie setting $A_{it} = 1$ initially for all t and then updating with the cumulative change in the As).

3.3 Modeling variable elasticity of substitution between alternative energy sources

Even in studies based on simplified models of the economy with two sources of energy supply and a single user there is a problem in modeling the substitution possibility between alternative sources of energy supply. Should the carbon free and carbon-rich sources be treated as perfect substitutes, imperfect substitutes or complements has remained an unresolved question. For example, Peck and Teisberg (1992) treat the two as perfect substitutes but impose a capacity constraint and higher costs for the carbon

[3] By making θ different for different inputs, the learning effects on demand for each input can be made different.

free technology. Goulder and Schneider (1999) treat them as poor substitutes and set the elasticity of substitution very low, as is done in standard GTEM in which the default value is 0.75. Using a CRESH aggregator (Hanoch, 1971), TIGEM-D sets the values of the CRESH parameter differently for different technologies between 0.1 and 1.5 (Li, et al. 2003). Similarly, van der Zwaan et al. (2002) assume the value to be 3. An interesting approach has been followed in Kverndokk et al. (2004), however. They have assumed the elasticity of substitution between existing fossil fuel and carbon free technology to be unity and between their aggregates and the backstop technology to be infinity. No matter what value we choose for the elasticity of substitution between the technologies, the estimate really matters.

Gerlagh, et al. (2004) argue that since under a CES aggregation rule, the ratio of cost minimizing demand for carbon free energy, Y_t^N, to fossil-fuel, Y_t^F, is related to the ratio of respective prices P_t^N and P_t^F according to

$$(8) \qquad (Y_t^F / Y_t^N) \approx (P_t^N / P_t^F)^{\sigma}$$

where σ is the elasticity of substitution between the two energy sources, the choice of base year prices, quantities and the elasticity of substitution should agree and satisfy (8). This means, we must have

$$(9) \qquad \sigma = \log(Y_t^F / Y_t^N) / \log(P_t^N / P_t^F) .$$

When the literature based of Y and P for both fossil fuel and carbon-free technologies for the base year were used to calibrate the value of the elasticity of substitution, σ, they found that the value is nearly 3.

In fact, the demand system derived from a CES function would be of the form

$$(10) \qquad (Y_t^F / Y_t^N) = \beta (P_t^N / P_t^F)^{\sigma}$$

where β is a function of distribution parameters. Hence the above approach to calibrating the elasticity of substitution ignores the presence of this scaling factor. We have one equation and two parameters to estimate, thus we cannot find a solution. In the absence of explicit assignment of the value of β prior to calibrating σ, one is free to choose any value for σ. The value of β will adjust continually to satisfy the above equation and the base year data. Hence, Gerlagh, et al.'s claim that σ=3 accords well with the data is not generally correct.

In an earlier paper Gerlagh and Lise (2003) used a different approach to tackle the calibration problem. They argued that the elasticity of substitution depends on the market share of the technology. In the case with two technologies, the elasticity of substitution will be low if one technology dominates and highest when both technologies have equal market shares. To model this they adopted the variable elasticity of substitution (VES) aggregator function proposed in Kadiyala (1972) and treated both technologies symmetrically. They calibrated the VES function in such a way that the resulting elasticity of substitution fell between 1 and 4.

In Gerlagh et al. (2004) it is shown (via simulations) that the required carbon tax to attain a given emission trajectory or target critically depends on the elasticity of substitution between alternative sources of energy supply. If the elasticity of substitution between the conventional carbon-rich and new carbon-free sources of energy supply is sufficiently large then the required carbon tax that can deliver the same outcome could be substantially lower compared to the case with low or no possibility of such substitution. It is also demonstrated in Gerlagh et al. (2004) that, under the assumptions of the paper, that is, with a sufficiently high elasticity of substitution, carbon free sources will almost dominate within this century as the sole provider of energy. In this case the critical question is whether the atmospheric load of the GHG produced over this century is within the tolerance limit of the climatic system. If not, then carbon taxes could be used to bring it under control. Therefore, the size of the elasticity of substitution and the precise mechanism supporting the propagation of carbon free technologies in these models remain the subject for further examination.

3.3.1 Substitution between power generation technologies

GTEMLR contains multiple technologies of power generation – one of them is 'other renewables' (which excludes hydro).[4] The base year share of this technology to total power generation is very small in almost all regions and has been chosen to represent the hydrogen technology in this paper. If we use a CES function to aggregate the power generation technologies, as is done in many other studies and we assign a single value for the elasticity of substitution between all possible pairs, then for a reasonable change in relative prices it is quite clear that the output of the renewables can not rise to any significant number. This is simply because even if the relative price of renewables falls by say 10 per cent, keeping everything else constant, with a elasticity of substitution of 3, the output of renewables will rise nearly by a 30 per cent. Since 30 per cent of a small number is also small, there would be an extremely long time needed for this technology to capture a substantial market share. On the other hand, a small increment in the existing capacity of renewables may mean a large percentage increase because of the small base. For example, an addition of two solar panels when there was one is a 200 per cent increase in the production capacity and output. Hence, in order to represent the behavior of technologies with very small shares correctly, use of a CRESH function with different CRESH parameters appears more suitable than a CES function.

[4] Hydroelectric technology is considered as a mature technology with severe limitations to grow.

A cost minimizing input demand for the output of technology k, in percentage change form, subject to a CRESH aggregator can be written as[5]

$$(11) \qquad x_k = q - \rho_k (p_k - \hat{p})$$

where q is the percentage change in the output (or aggregate input of the technology bundle) of the technology-bundle industry, x_k is the percentage change in the output allocated to technology k, p_k is the percentage change in the price of technology k, $\hat{p}$ is the modified share weighted (see equation (12) below) average price of all technologies and ρ_k is the CRESH parameter associated with the technology k. The average price, $\hat{p}$, is given by

$$(12) \qquad \hat{p} = \sum_k \frac{\rho_k S_k}{\sum_r \rho_r S_r} p_k$$ where both r and k range over the set of technologies.

The pair wise Allen-Uzawa partial elasticity of substitution is given by

$$(13) \qquad \sigma_{ik} = \frac{\rho_i \rho_k}{\sum_r \rho_r S_r}$$ with $i \pi k$.

The special feature of the CRESH function is shown by equation (13). The ratio of pair wise elasticity of substitution parameters, $(\sigma_{ik} / \sigma_{ij}) = (\rho_k / \rho_j)$ for all $i \pi k, j$ and thus the ratio remains constant for any pair k, j and hence the name. If, however, $\rho_k = \rho_j$, for all k and j, then the CRESH function becomes identical to a CES function with $\rho_k = \rho_j = \sigma$.

For a niche technology, we can see from equation (12) that changes in its price will not affect the average price in a significant way even if the price change was large. From equation (11) we can see that the percentage change in demand for its output will not be dramatically high unless the corresponding CRESH parameter is very large. But, we know that in the beginning, when the base quantity is small, a small absolute increase means a very large change in percentage terms. Hence a reasonably large value for the CRESH parameter of the niche technology is warranted. But as its market share grows to a significant number, maintaining a large value for the CRESH parameter would give undue sensitivity to this technology. The elasticity of substitution between the carbon free technology vis a vis any other technology will remain high while that between other fossil fuel technologies will remain low. This is especially important in models

[5] See Dixon et al. (1982, pp 76-90) for the derivation.

with learning by doing, as the cost of the niche technology would be falling with the increase in cumulative capacity, other things the same, and the demand for the output of the niche technology will be growing disproportionately. Therefore the CRESH parameters associated with the niche technology should have higher values in the beginning and decline subsequently. This also means that the CRESH parameters should be modelled as time dependent quantities.

To address this problem we specify the time path of CRESH parameters as

(14) $$\rho_{kt} = \rho_{kt-1} - \omega_{kt}(\rho_{kt-1} - \rho_k^{*})$$

where

(15) $\omega_{kt} = \theta * (Q_{kt} / \sum_s Q_{st})$, and $\theta \geq 0$ is a calibration parameter, ρ_k^* is the target value ('steady state') of the technology specific CRESH parameter. This is arbitrary, but is in line with previous studies. The initial value for ρ_{kt} is 0.75 for all conventional (fossil fuel as well as hydro and nuclear) technologies, and 25, 10, 15 and 10 for the other renewables (hydrogen technology) in OCED90, REF, ASIA and ALM regions respectively.[6] We have set $\rho_k^* = 1$ for all technologies so that as technologies mature the CRESH aggregator function converges to the CES function. The default value of θ is set at 2 which means that the CRESH parameter of the new technology, ρ_{kt}, declines with its market share and converges to ρ_k^* as soon the market share reaches 50 per cent. If the market share of a technology is falling over time, and the initial market share is less than 0.5, then the CRESH parameter for this technology will be increasing from 0.75 toward 1 and will remain less than 1. By doing so, we have increased the elasticity of substitution between the hydrogen technology and other existing technologies to some value up to 20 initially and declining to unity, while keeping the elasticity of substitution between the existing technologies themselves equal and rising very slowly with market share to unity. The resulting initial boost in the demand for the output of the new technology is partly, as mentioned above, to capture the asymmetric behavior of small numbers, and partly taken to be supported by biased policies in favor of the new technology.

3.3.2 Use of energy commodities by firms

It was mentioned in section 2, production technologies contain nests that allow intra-energy commodity, intra-factor and energy-factor substitution in response to relative price changes and are characterised by constant returns of scale CES aggregator functions in each stage. The default elasticity of substitution between energy

[6] The regions have been taken to match the aggregate regions used to report in the Special Report on Emission Scenarios of IPCC (Nakicenovic, 2000).

commodities in standard GTEM for short run simulations is 0.2. For the purpose of this paper it is set to 2. This keeps the value of the elasticity of substitution within the range used by previous studies. This increase also presupposes at the same time that machines and equipments that operate on fuel cells/electricity are available to compete with the ones that operate on coal, oil or gas (for example gas heating system versus fuel cell/hydrogen heating). In particular, it assumes that FCVs are available if there is a demand in the market to replace internal combustion engines.

3.3.3 Use of energy commodities by households

The other important user of energy commodities is the household sector. In standard GTEM, household consumption demand is modelled by minimising a CDE expenditure function. It does allow substitution between the energy commodities, but the size of the substitution within the energy group may not be comparable to the level of substitution possibilities required by a transition to a hydrogen economy. The important point here is to allow households to be able to substitute between all energy commodities including fuel cells/electricity and allow the introduction of FCVs, should that become cost competitive. Hence for the purpose of this paper the consumer demand system has been modified and one more nest has been added. The energy commodities form a group, and a Cobb-Douglas utility function has been maximised to allocate the budget to different commodities and the energy composite. The energy composite has been aggregated by a CES function with the elasticity of substitution equal to 2. Once the demand for each energy commodity has been sorted out from this nest, the standard GTEM allocation of demand for each commodity to the sources of supply using an Armington process has been maintained. We are aware of the limitation of using a Cobb-Douglas utility function at the top. It implies that the budget share of each commodity composite and its income elasticity remains fixed for all income levels. This projects a very distorted demand pattern as the economies become richer over time. In particular the demand for food would be over estimated and hence the output of that sector and thus the emissions from the agricultural sector would be biased upwards. Work is underway to improve the consumer demand system in GTEM and the results reported here should be treated with caution.

4 Model Simulation

4.1 Base case without emission restrictions or carbon tax

For the purpose of this paper, the GTEM database has been aggregated to four regions (members of the OECD at 1990 (OECD90), reforming economies of Eastern Europe and the Former Soviet Union (REF), other countries of Asia (ASIA), and countries in Africa, Latin America and Middle-East (ALM)), 13 commodities (coal, oil, gas, petroleum and coal products, electricity, Iron and steel, non-ferrous metal, other minerals, manufacturing and food, agriculture, forestry and fishing, services and capital goods) and four factors of production (land, labour, capital and natural resources). The model is calibrated to the 1997 database. In the base case the regional economies were assumed to have the following exogenous growth pattern per year from 1989 to 2100 for the following variables: Labour and population in ASIA and ALM were assumed to grow at 1 per cent and average factor productivity is assumed to grow by 2.5 per cent. Labour and population in OECD90 and REF were assumed to grow at 0.5 per cent and average factor productivity in REF is assumed to grow at 2 per cent per annum and in OECD90 the productivity growth rate was assumed to be 1.5 per cent. These numbers are arbitrary. Naturally, the endogenous process would be accumulating capital and foreign debt/assets of the regions respectively. In addition to that, the renewable based hydrogen sector is assumed to have the learning by doing process. In addition to these growth shocks, we also assumed that energy intensity declines uniformly by 0.5 per cent per year; emission intensity of fuel inputs (combustion emissions) as well as of output (non-combustion emissions) falls by 2.5 per cent in all industries in all region until 2005, and continues to do so for the emission intensities of outputs of agriculture and manufacturing and food processing sector until 2025 (this is to correct for the inadequacy of the demand system and reduce excessive emission intensities of some sectors in developing countries).

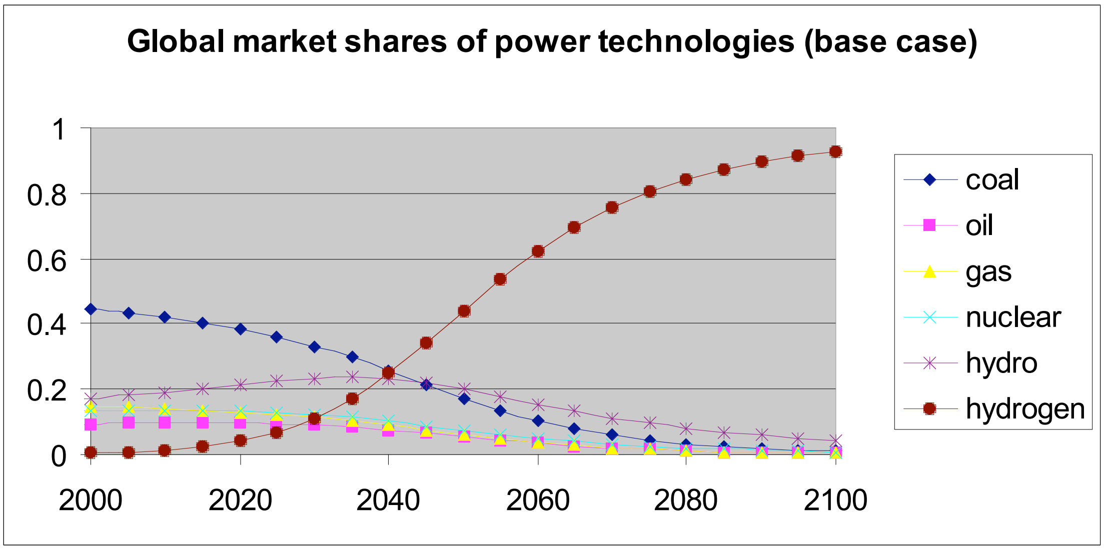

Figure 1: Global market share of power generating technologies (base case)

Figure 1 show the influence of including learning by doing in the base case scenario. The hydrogen technology, which did not have any significant market share before 2000, has gradually picked up and by 2040 has a market share equal to coal. Existing technologies had the benefit of average factor productivity growth; but they did not have the advantage of the learning by doing effects as they are considered mature technologies. This assumption may be questioned. But as long as we are prepared to accept this, the growth of the carbon-free hydrogen technology is strong. By 2100, without any carbon taxes the market share increases to about 85 per cent. There are regional variations on how the market share grows with time, but the difference is not significant enough to nullify the over all picture.

4.2 Model simulation with gradually increasing carbon tax

Now we introduce a small carbon tax on OECD90 and REF regions from the first year of the simulation (1998), and for ASIA and ALM only after 2005. The initial rate is about 20cents per ton of carbon and increases by the same amount every year. By 2050 the carbon tax rate is about $14 in all regions, all measured in local currency units. The carbon tax rates after 2050 are held fixed at 2050 level. In addition to the leverage obtained from the learning by doing effects, the impact of the imposition of the carbon tax is to increase the market share of the carbon free technology as shown in figure 2.

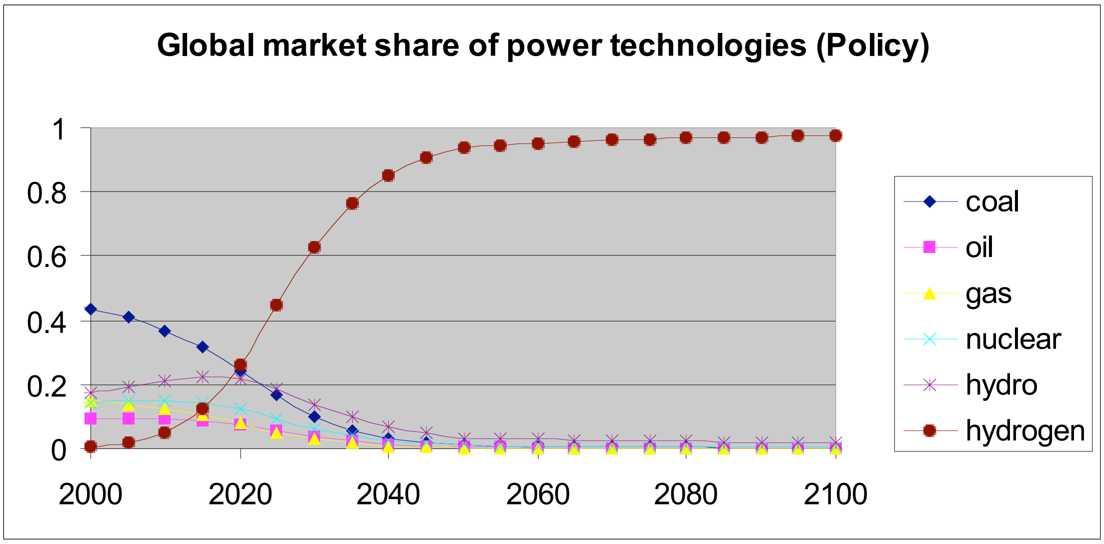

Figure 2: Global market shares of power generation technologies with small but increasing carbon tax that stabilises at 2050.

We can see from figure 2 that imposition of a small carbon tax is enough to virtually eliminate the conventional technologies from the market, their market share combined falls to less than 1 per cent by 2100; their importance declines to a trivial level by 2060. Figure 3 compares the growth path of the hydrogen technology under the base case and under policy with an increasing carbon tax. The figure shows that imposition of a carbon tax brings the adoption of cleaner technology forward. Although there results, at this stage, are mainly generated by the chosen numbers and functions and hence can be considered as arbitrary, they nevertheless, illustrate an important point. It is that if carbon-free technologies are supported with biased policies of say initial subsidies at an earlier stage and continued Pigouvian taxes then the carbon-free technology could become competitive because of the learning by doing effects.

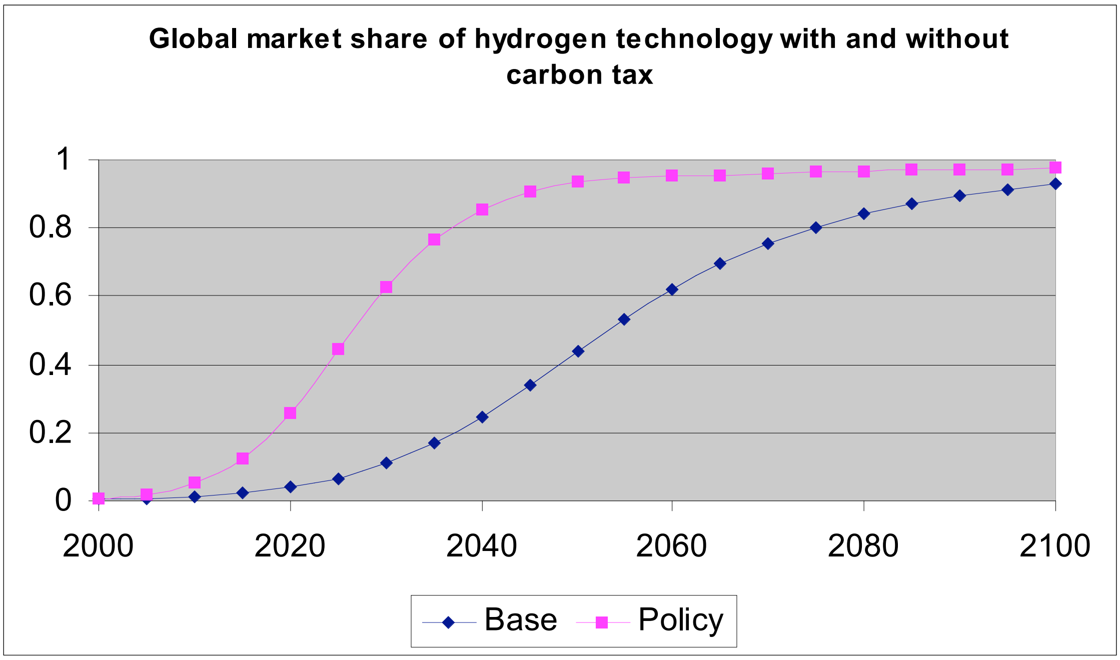

Figure 3: The global market share of hydrogen technology with and without carbon tax

The results presented in figures 1, 2 and 3 together confirm the results obtained by previous authors (for example, Gerlagh and Lise, 2003; Gerlagh, et al. 2004) on the behavior of a niche carbon-free technology. It is that the adoption rate follows an S-shaped curve and the imposition of a carbon tax hastens the adoption of the carbon free technology.

4.3 Discussion of the results

The results obtained by simulating GTEMLR have confirmed the possibility that emissions produced by the transport and power-generation sectors can be eliminated by moving toward the hydrogen economy. This leaves emissions from other non-combustion sources, which will grow with economic growth over time. Therefore, an effective policy also needs to include a strategy for controlling emissions from other sources, such as fugitive emissions and emissions from industrial processes and the agricultural sector using methods such as carbon capture and storage and changes in farming practices. In the following discussion we will ignore this aspect of an effective emission control strategy and focus on combustion emissions from the power and transport sectors.

The key result that the renewable based hydrogen economy will evolve and dominate the power generation and transport sector is driven by the following assumptions: (i) the size of CRESH parameter chosen; (ii) the elasticity of substitution within fuel commodities assumed for the household sector and for the production sectors, (iii) the learning by doing effect in the hydrogen production and distribution sector and (iv) the rate at which productivity of natural resources decline in the fossil fuel production sectors (the resource exhaustion effect).

All of these assumptions have made some contribution to the result obtained but the main driver has been the size of the CRESH parameter. Although not reported, we have observed that the speed of adoption of the new technology and the impact of a carbon tax on accelerating the adoption rate critically depends on the size of the CRESH parameter associated with the new technology. So what does the higher value of this parameter mean in the real world and how can we best estimate this number are important questions.

It can be seen from equation (13) that when the cost share of the new technology is very small and the CRESH parameters of other technologies are equal and close to unity, the elasticities of substitution between the new clean technology and each of the existing mature technologies are roughly equal to the value chosen for the CRESH parameter for the new technology. The elasticity of substitution between possible pairs of other technologies remains close to the common value of their CRESH parameter, which is 0.75 in the base year and slowly increases toward one as their combined market share gradually falls from unity. So the choice of large values for the CRESH parameter for the new technology effectively magnified the relative price responsiveness of the niche technology several times. Is this a reasonable depiction of reality?

We argue that a higher value of the CRESH parameter at the initial stage for the new technology can be a stylisation of any of the following situations:

(i) A large value of the parameter captures the behavior of the quantities in terms of proportional changes better than a uniform and small value for all technologies when the base is initially very small. In this case a small change in the levels means a substantial change in percentage terms.

(ii) A reflection of possible policy interventions, such as a subsidy on the development and diffusion of the cleaner technology or simply a regulatory requirement to increase the uptake of the new technology by some users such as power generators.

(iii) A growing provision of complementary goods and networks, such as the availability of higher quality equipment and spare parts that take fuel cells, increased provision of refuelling stations, etc. make the technology more attractive and improve the substitutability between old technologies and new technology. The CRESH parameter for the new technology would be very large if the substitution is near perfect. It is not uncommon to find models that treat back-stop technologies as perfect substitutes for conventional ones (for example, Kverndokk et al. 2004).

5 Concluding remarks: summary and implications to climate policy design

Using aggregate models previous authors have observed that because of the learning by doing effects and assuming a reasonably large elasticity of substitution between carbon-rich and carbon free energy the carbon-free niche technology could dominate the energy market within this century. If a modest carbon tax is imposed, the adoption rate could be accelerated (Gerlagh et al. 2004). Moreover, models with learning by doing predict significantly lower costs arising from emission restrictions (van der Zwaan et al. 2002) than those without this effect. Recently claims have also been made that learning by doing reduces the extent of carbon leakage in the case of partial agreement on climate regimes (Glombek and Hoel, 2004). This paper re-examined the main claim using a dynamic multi-sectoral general equilibrium model of the global economy with multiple energy technologies and multiple emission sources.

The simulation results confirmed the claims of previous authors that, if the elasticity of substitution can be taken as sufficiently large, then carbon-free technologies (or back-stop technologies) could dominate the energy market. The speed of uptake depends on various factors, including the extent of substitutability with conventional energy sources as summarised by the size of the elasticity of substitution. This means that by increasing the elasticity of substitution between electric and non-electric (fossil fuels) energy sources for industries and for households together with the substitutability between conventional and back-stop renewable power generation technologies, the growth in emissions from the power generation and transport sectors can be arrested quickly and then reduced significantly. Previous studies with learning by doing have been able to demonstrate stabilised emissions at the 2000 level for the whole century by imposing a modest carbon tax because they either ignored emission from non-combustion sources (van der Zwaan et al. 2002) or they assumed that non-combustion emissions remain constant at the base year level (Gerlagh, et al. 2004). This not the case with GTEMLR which has multiple sources of emissions that change with economic growth.

Nevertheles, it is quite clear that promotion of carbon-free technologies, such as electricity from renewables or other zero emission technologies and development and diffusion of hydrogen as a primary energy carrier for the transport sector and other specific industrial uses is a possible pathway for tackling the problem of climate change. This conclusion leads to an important implication for the design of climate policy.

As outlined in the introduction, because of its inherent nature, climate change is a global and intergenerational problem; it needs to be tackled globally with a long time horizon. It has been well recognised that agreements like the Kyoto Protocol, though an important advancement in recognising the problem and finding a first order solution, has serious limitations (for example, Fisher et al. 2003, 2004). It has been argued that it lacks environmental effectiveness and most importantly, that it lacks self-enforceability – countries may not do what they agreed to do. To correct this deficiency several proposals have been made (Barrett, 2001, 2002; Benedick, 2001; Buchner and Carraro, 2004; Fisher et al. 2003, 2004). Although stated in different words, all of these proposals emphasise environmental effectiveness, individual rationality and self-enforceability as the basic requirement of an effective climate agreement.[7]

Recognising that technological progress is necessary to address the climate change problem effectively and knowledge obtained from basic research is in part a public good, Barrett (2002 p.5) states that 'A (similar) collaborative effort, incorporated in a new protocol, is needed to fund research into new energy technologies, particularly technologies that produce energy without emitting carbon or that capture and store carbon safely'.

He further adds, 'A complimentary pull incentive is also needed – one that, in contrast to the Kyoto approach, eases the constraint on compliance and participation. The most attractive approach is to agree on common standards for technologies identified by collective R&D effort. These standards should be established in complimentary protocols. As examples, energy efficiency standards could be established for automobiles, requiring, say, the use of a new hybrid engines or fuel cells. Standards for fossil fuel power plants might require carbon capture and storage.' (p.6)

The usefulness of Barrett's proposal was examined by Buchner and Carraro (2004) using the FEEM-RICE model, which is a modified version of the RICE model (Nordhaus and Yang, 1996). In particular, they examined whether a climate regime based on cooperation on technological innovation and diffusion, without any binding abatement commitments, such as the one outlined by Barrett (2002), would satisfy the above three principles. If they do, then it would provide a strong basis to argue for a technology based climate protocol because it would guarantee a given environmental outcome, and it would be economically efficient that is, it would be self-enforceable, and it would not be based on coercion and satisfy individual rationality, meaning that everyone would have joined voluntarily and happily.

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[7] It can be argued that the principle of economic efficiency and equity emphasised in Fisher et al. (2003, 2004) is the same as self-enforceability and individual rationality outlined in Buchner and Carraro (2004). Self-enforceability requires that the agreement be most profitable to each participant and the coalition be stable, which means that the signatories do not defect and there be no incentive for people to come in if they are already not in. Given perfect foresight, a protocol must be economically efficient to each party means, it must maximize the outcome for each individual; and conversely, a protocol maximizes the pay off to each individual means it is economically efficient. Similarly, if a protocol is a pay off maximizer to an agent, then every agent who has an opportunity to sign in will sign by rationality and once signed will not leave the coalition and hence it is stable. Moreover, the principle of equity outlined in Fisher et al requires no coercion to any party, that they sign with their own will which is the same as the requirement that the protocol be individually rational. Hence we view that the three principles of 5Es (environmental effectiveness, economic efficiency and equity) outlined in Fisher et al (2003) and the game-theoretic conditions outlined in Buchner and Carraro (2004) are equivalent.

They have found that a climate-based agreement replacing the Kyoto Protocol would be self-enforcing and individually rational, because it increases growth, but also produces more emissions relative to the Kyoto Protocol. The reason was that the R&D that was devoted to technological development in the technology based cooperation not only reduced the emissions intensity of output but also increased productivity of the factors and thus increased the overall output level. The output effect dominated the intensity effects and as a result the technology-based cooperation was environmentally deemed ineffective. Their model, however, had only one sector in each region, and therefore emissions reducing R&D also had a productivity enhancing effect. But in general, there is no reason to believe for example that someone driving a FCV would be more productive than someone who drives a similar car with an internal combustion engine. Contrary to Buchner and Carraro's arguments, Goulder and Schneider (1999) have found that increased climate related R&D effort might 'crowd out' R&D expenditures in the non-energy and carbon based energy sectors. Therefore, we still do not have a conclusive argument that a technology based protocol would necessarily be environmentally ineffective, as claimed by Buchner and Carraro (2004).

The upshot of all this is that a technology based protocol for global R&D effort complemented by a standards protocol as suggested Barrett (2002) is an approach worthy of further consideration for dealing with reducing emissions from the power and the transport sectors. This still leaves the question of dealing with emissions from non-combustion sources which will continue to grow with economic growth. To address this issue as well as to hasten technology development other instruments would be necessary.

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