Decarbonizing the Global Economy with Induced Technological Change: Scenarios to 2100 using E3MG

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This paper reports how endogenous economic growth and technological change have been introduced into a global econometric model. It explains how further technological change might be induced by mitigation policies so as to reduce greenhouse gas emissions and stabilize atmospheric concentrations. These are the first results of a structural econometric approach to modeling the global economy using the model E3MG (energy-environment-economy model of the globe), which in turn constitutes one component in the Community Integrated Assessment System (CIAS) of the UK Tyndall Centre. The model is simplified to provide a post-Keynesian view of the long-run, with an indicator of technological progress affecting each region's exports and energy use. When technological progress is endogenous in this way, long-run growth in global GDP is partly explained by the model. Average permit prices and tax rates about \$430/tC (1995) prices after 2050 are sufficient to stabilize atmospheric concentrations at 450ppm CO_2 after 2100. They also lead to higher economic growth.

1. INTRODUCTION

As part of the research program at the Tyndall Centre, a world macroeconomic model, E3MG, is being developed to investigate policies for climate change mitigation and sustainable development within an Integrated Assessment Modeling system. In coupling economic models with atmosphere-ocean models of climate change, long timescales are necessary because changes in CO_2 concentrations enhance the greenhouse effect over time periods of 50-100 years and more.

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In projecting into the future, the approach of this paper is first to consider the past. Looking back over the last 200 years, the socio-economic system has been characterized by ongoing fundamental change, rather than convergence to any equilibrium state. Maddison (2001) takes a long view of global economic growth over the last millennium. He finds growth rates to be very different across countries and over time, and ascribes the comparatively high rates of growth to technological progress and diffusion. The increase in growth rates that emerged in Europe since 1500, and that became endemic from 1820, were founded on innovations in banking, accounting, transport, military equipment, scientific thinking and engineering. He also finds that inequalities between nations in per capita GDP have increased (in particular since WW2), not diminished over time. These three features of growth (diversity across nations and time periods, technological progress, and increasing inequalities) are evident in the scenarios reported below. These ideas are supported by quantitative studies identifying the causes of economic growth, e.g. Denison (1985) finds that three causal factors associated with technological progress[1] (capital, economies of scale and knowledge) account for 57% of growth. More recently, Wolff (1994a, 1994b) has found strong correlations between investment embodying technological change and growth in OECD economies.

Technology is important for climate change analysis for two reasons: first, technology has allowed anthropogenic climate change to happen; and second, a change to a modern, low-carbon society may well require widespread development and deployment of new, low-carbon technologies. Such large-scale changes have been a feature of ‘advanced’ society in the last 200 years. Widespread use of both coal and oil were part of transformations of economies and societies. In modeling these processes, we have combined an econometric, long-run model with an energy technology model to derive the benefits of moving from a baseline to stabilization targets of 550, 500 and 450 ppmv CO_2, using the instruments of permit trading and carbon taxes, with and without incorporation of endogenous technical change.

2. INCORPORATION OF ENDOGENOUS TECHNICAL CHANGE IN E3MG

In modeling long-run economic growth and technological change, we have followed the “history” approach[2] of cumulative causation and demand-

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[1] Denison’s study of US growth 1929-1982 attributes the average long-run rate of about 3%pa to six factors: about 25% to labour at constant quality, about 16% to improvements in labour quality as from education, 12% to capital, 11% to improved allocation of resources, e.g. labour moving from traditional agriculture to urban manufacturing, 11% to economies of scale and 34% to growth of knowledge.

[2] This is in contrast to the mainstream equilibrium approach (see DeCanio, 2003 for a critique) adopted in most economic models of the costs of climate stabilisation. See (Weyant, 2004) for a discussion of technological change in this approach. Setterfield (1997) explicitly compares the approaches in modeling growth and Barker (2004) compares them in modeling mitigation.

led growth[3] (Kaldor, 1957, 1972, 1985; Setterfield, 2002), which focuses on gross investment (Scott, 1989) and trade (McCombie and Thirwall, 1994, 2004), and in which technological progress is embodied in gross investment. Long-run growth and structural change through socio-technical systems, called 'Kondratiev waves', are described by Freeman and Louçã (2001) and modeled by Köhler (2005). Growth in this approach is dependent on waves of investment in new technologies.

The study reported below is the first to use a large-scale econometric model with a dynamic structure, which is both sector and region specific, to model these processes. It involves the use of econometric estimation to identify the effects of endogenous technological change (ETC) on energy and export demand and embed these in a large post-Keynesian non-linear simulation model. In addition, a treatment of substitution between fossil and non-fossil fuel technologies is employed, accounting for non-linearities resulting from investment in new technology, learning-by-doing, and innovation. This treatment allows policy measures for induced technological change[4] (ITC) to be modeled. The model has been developed in the traditions of the Cambridge dynamic model of the UK economy (Barker and Peterson, 1987) and the European model E3ME (Barker, 1999). The effects of technological change modeled this way may turn out to be sufficiently large in a closed global model to account for a substantial proportion of the long-run growth of the system. The approach has been developed to include the bottom-up energy technology model (ETM) within the top-down highly disaggregated macroeconomic model, E3MG. Thus, like the studies (Nakicenovic and Riahi, 2003; and McFarland, et al., 2004) which are also based on the linkage of top-down and bottom-up models, our modeling approach avoids the typical optimistic bias often attributed to a bottom-up engineering approach, and unduly pessimistic bias of typical macroeconomic

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[3] The theoretical basis of the approach is that economic growth is demand-led and supply-constrained. Growth is seen as a macroeconomic phenomenon arising out of increasing returns (Young, 1928), which engender technological change and diffusion, and which proceeds unevenly and indefinitely unless checked by imbalances. Clearly growth can increase only if labour and other resources in the world economy can be utilised in more productive ways, e.g. with new technologies and/or if they are otherwise underemployed in subsistence agriculture or unemployed. One implication of the theory is that investment induces the requisite voluntary saving, i.e. "Mr Meade's Relation" holds (Dalziel and Harcourt, 1997). Palley (2003) discusses how long-run supply is affected by actual growth. In contrast, the modern theory of supply-side economic growth assumes full employment and representative agents, and optimises an intergenerational social welfare function (see Aghion and Howitt, 1998). It goes back to Solow (1956, 1957), with endogenous growth theory developed by Romer (1986, 1990).

[4] In the models, exogenous or autonomous technological change is that which is imposed from outside the model, usually in the form of a time trend affecting energy demand or the growth of world output. If, however, the choice of technologies is included within the models and affects energy demand and/or economic growth, then the model includes endogenous technological change (ETC). With ETC, further changes can generally be induced by economic policies, hence the term induced technological change (ITC); thus ITC implies ETC throughout the rest of this paper.

approaches. The advantages[5] of using this combined approach have recently been reviewed (Grubb et al., 2002).

The version of E3MG used in this study includes a partial treatment[6] of endogenous technological change in 3 ways:

i. the sectoral energy demand equations include indicators of technological progress in the form of accumulated investment and R&D, such that extra investment in new technologies induces energy saving
ii. the sectoral export demand equations include the same indicators, such that the extra investment induces more exports and therefore investment, trade, income, consumption and output in the rest of the world and
iii. the ETM incorporates learning curves through regional investment in energy generation technologies that depend on global scale economies.

These long-run energy and export demand equations are of the form given in equation (1), where X is the demand, Y is an indicator of activity, P represents relative prices (relative to GDP deflators for energy and to sectoral competitors' prices for exports), TPI is the Technological Progress Indicator, the β are parameters and the ε errors. TPI is measured by accumulating past gross investment enhanced by R&D expenditures (Lee, Pesaran and Pierce, 1990),[7] with declining weights for older investment. The indicators are included in many equations in the model, but only those for energy and exports are analyzed here. All the variables and parameters are defined for sector i and region j.

$$X_{i,j} = \beta_{o,i,j} + \beta_{1,i,j}\mathrm{Y}_{i,j} + \beta_{2,i,j}P_{ij} + \beta_{3,i,j}\,(TPI)_{i,j} + \varepsilon_{i,j} \tag{1}$$

In both sets of equations, $\beta_{2,i,j}$ are restricted to be non-positive, i.e. increases in prices reduce the demand (for energy demand, see surveys in Atkinson and Manning, 1995 and Graham and Glaister, 2002; for export demand, price elasticities are reported in the literature cited below). In the energy equations $\beta_{3,i,j}$ are estimated

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[5] There are also disadvantages. The coupled model is highly non-linear with the possibility of instabilities, multiple solutions and discontinuities. The solution is simplified by adopting the smooth transitions assumed by Anderson and Winne (2004), but local instabilities remain. We are intending to tackle this problem by using the multiple solution techniques of a Bayesian uncertainty analysis.

[6] A full treatment will include the effects of increasing returns and technological progress on many other variables in the model, including imports, consumption, employment and prices.

[7] This is an indirect measure assuming that new techniques are embodied in gross investment including R&D, so that the stock of techniques is found by accumulating this investment, allowing for their obsolescence by the declining weights. Arrow (1962, p.157) used cumulative gross investment as a measure of experience in learning by doing, and the measure also finds empirical support in Schmookler's (1966) correlations between patents and gross investment 1873-1940 in several sectors. Increases in R&D unaccompanied by new investment (i.e. pure, unapplied knowledge) has no special effect on supply in the model.

to be negative, i.e. more TPI is associated with energy saving;[8] and in the export equations $\beta_{3,i,j}$ are estimated to be positive, i.e. more TPI is associated with higher exports. These parameters are constant across all scenarios.

The effect of investment and R&D on export performance, which drives our long-run results, goes back to Posner's technological gap theory (1961). Since the 1990s they have been the topic of substantial empirical research, and the effects have been found for different countries and regions at the individual plant, industrial sector and macro economy levels. Roper and Love (2001) use micro-level data to compare export performance for UK and German manufacturing plants and find "strong and consistent evidence that innovation, however measured, has a systematic effect on both the probability and propensity to export." Greenhalgh (1990) and Greenhalgh et al (1994) find significantly positive effects of R&D for over 30 UK industries' net exports. Wakelin (1998) in a study of 22 industries in nine OECD countries finds effects of different technological indicators on trade, suggesting that the choice of index is important. Magnier and Toujas-Bernate (1994) find evidence of the innovation effects on exports for nine EU countries. Fagerberg (1988) and León-Ledesma (2000) both find support for a positive effect of OECD trading partners' R&D on their exports. There is a potential two-way causation between exports and investment, but the estimations of the E3MG export equations protect against both spurious correlations (by using cointegration techniques) and the simultaneity between the dependent and the explanatory variables (by using instrumental variables or some other means).[9]

The explanation of growth being explored in E3MG is that higher investment and/or R&D is associated with higher quality and innovatory products and therefore exports, and that the extra demand for exports in world markets is matched by extra demand for imports, which are normally constrained by the balance of payments (McCombie and Thirlwall, 2004), i.e. the extra exports weaken the constraints. For the extra demand for exports to be effective in the long run, there must also be an increase in supply, which in the model is realized by economies of specialization and scale in production and higher employment and labor productivity. This study assumes that the drivers of prices and wages

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[8] There is an ongoing debate on how to include the effects of technological change in energy demand equations, with the main contenders being asymmetric price elasticities, time trends and (as in E3MG) direct measures in the form of the TPI. It seems clear that it will be difficult to distinguish between the explanations in the time-series analysis. See (Gately and Huntington, 2002; Griffin and Schulman, 2005; and Huntington 2005).

[9] The literature on the effect is clear on the direction of causation: R&D and R&D-inspired investment in the exporting country leads to higher exports. Causation is very difficult to prove in macroeconomic behaviour, but there are convincing results at the micro level. Two independent, explicit and thorough studies of the direction of causation from innovation to export performance using German microeconomic data come to the unambiguous conclusion that the direction of causation is from R&D innovation to export volumes (Ebling and Janz, 1999; Lachenmaier and Wößmann, 2004). However these studies are concerned with R&D expenditure and other measures of innovation rather than R&D-enhanced gross accumulated investment, the indicator of technological progress adopted in E3MG. There is a close relationship between market R&D expenditures and gross investment so it is very difficult to distinguish separate effects in empirical work.

are largely exogenous (except for energy and technology prices) and that capacity utilization remains at "normal" levels. The modeling explains how low-carbon technologies are adopted as the real cost of carbon rises in the system, with learning by doing reducing capital costs as the scale of adoption increases. A rise in the costs of fossil fuels resulting from increases in CO_2 permit prices and carbon taxes thus induces extra investment in low-carbon technologies, and this is larger and earlier than the investment in conventional fossil technologies in the baseline. The carbon tax revenues and 50% of the permit revenues are assumed to be recycled in the form of lower indirect taxes. The outcome is that the extra investment and implied accelerated technological change in the stabilization scenarios leads to extra exports and investment more generally, and higher economic growth.

The bottom-up annual, dynamic energy technology model ETM (Anderson and Winne, 2004), has been extended to cover lags between orders for plant and the year when the new plant comes on stream and a rolling 7-year-ahead cost-benefit analysis of system requirements for each region. It is based on the concept of a price effect on the elasticity of substitution between competing technologies. Existing economic models usually assume constant elasticities of substitution between competing technologies. ETM is designed to account for the fact that a large array of non-carbon options is emerging, though their costs are generally high relative to those of fossil fuels. However, costs are declining relatively with innovation, investment and learning-by-doing. The process of substitution is also argued to be highly non-linear, involving threshold effects. The ETM simulates the process of substitution, allowing for non-carbon energy sources to meet a larger part of global energy demand as the price of these sources decrease with investment, learning-by-doing, and innovation. The model considers 26 separate energy supply technologies, of which 19 are carbon neutral. Investment shares in energy generation technologies are based on the following equation:

$$S_{it} = S_{it-1} + a_i S_{it-1} \left(\hat{S}_{it-1} \left(1 + S_{it-1} - \textstyle\sum_i S_{it-1}\right) - S_{it-1}\right)\left(P_{it} - P_{it-1}\right) \tag{2}$$

where S is market shares in new investment in technology i, $\hat{S}_{it}$ is a maximum share attainable by any given technology and P is the price ratio of technology i to a marker technology (typically CCGT) . A similar representation, although simpler and more stylized, is adopted for the switch from gasoline to battery-powered vehicles rechargeable from the electricity grid. Thus ETM provides a simple model of the process of switching from a marker technology to the possible substitutes. This substitution process may be accelerated if an emission permit scheme is implemented, so that technological change leads to reductions in the use of fossil fuels by power generation, with associated reductions in emissions of greenhouse gases.

Cumulative emissions of CO_2 to 2100 are derived from the MAGICC model as used by the IPCC (Watson et al., 2001). It is a set of linked reduced form models emulating the behavior of a GCM, comprising coupled gas-cycle, radiative forcing, climate and ice-melt models integrated into a single package.

It calculates the annual-mean global surface air temperature and sea-level implications of emission scenarios for greenhouse gases and sulphur dioxide. The E3MG model is used to derive a cost-effective emission pathway which keeps cumulative emissions within the limits prescribed by the MAGICC model. Costs of stabilization are then calculated relative to the baseline. The emission pathways that come from E3MG are then put back into MAGICC to check that, with the new profile, the same concentrations are achieved. Many other studies of stabilization costs (e.g. Nakicenovic and Riahi, 2003; Van Vuuren et al., 2004) also use the MAGICC climate model to represent the relationship between emissions and concentrations. Although MAGICC and E3MG both model emissions scenarios detailing non-CO_2 greenhouse gases, we do not consider the costs of reducing these gases and their effects in this analysis.[10]

The analysis requires a set of assumptions, in addition to the usual ones for an econometric model, e.g. that a long-run solution exists, to reduce the complexity of the problem. The main ones adopted for the results reported below are as follows:

1) Population growth and migration are exogenous at baseline levels, and the assumption is adopted of sufficient labor being available from productivity growth or structural change to meet the demand for products. After 2050, the economic growth rate in all the scenarios slows down to match a slower growth in population. Throughout the century it is assumed that the workforce in developing countries will move from traditional, rural sectors, to urban and modern sectors.
2) Monetary and fiscal policy. Independent central banks are assumed to hold the rate of consumer price inflation constant. Ministries of Finance maintain a long-run fiscal balance by combining lower-non-carbon prices and reductions in costs from new technologies, sufficient to prevent any extra long-run inflation from the change in the tax regime. The increase in the costs of carbon-based products is offset by a decrease in the costs of non-carbon-based products. This implies that interest rates and exchange rates remain more or less at baseline levels in all the scenarios
3) The econometric equations in the model are reduced to two sets: energy and export demand. The energy technologies in the model are also reduced to two sets: those for the electricity sector and, in a simpler form, those for road vehicles. Except for investment by the electricity and vehicles industries, other behavioral equations are treated as being in fixed proportions to their main determinants.
4) The emission permit scheme and the carbon taxes have their effects in raising prices of energy products in proportion to their carbon content where ever they are imposed, and revenues are recycled as

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[10] If the CO_2 emission pathway does not result in stabilisation in the full integrated analysis, policy parameters are adjusted in E3MG until a consistent solution is achieved.

reductions in indirect taxes to maintain fiscal neutrality. The high rates required, especially for 450ppm, may prove impractical, if not politically impossible. Thus the scenarios show how high the emission prices and tax rates have to rise to achieve the targets.

4. ESTIMATION, CALIBRATION AND CRITICAL VARIABLES

The industrial and energy/emissions database[11] covering the years 1971-2001 is drawn from OECD, IEA, GTAP, RIVM, and other national and international sources and processed to provide comprehensive and consistent time-series of varying quality and reliability across regions and sectors. It contains information about the historic changes by region and sector in emissions, energy use, energy prices and taxes, input-output coefficients, and industries' output, trade, investment and employment. This is supplemented by data on macroeconomic behavior from the IMF and the World Bank. These data are used to estimate a set of econometric equations using cointegration techniques proposed originally by Engel and Granger (1987) and discussed by Abadir (2004) as appropriate for post-Keynesian modeling of non-clearing markets in which a long-run solution is not necessarily in equilibrium. E3MG requires as inputs dynamic profiles of population, energy supplies, baseline GDP, government expenditures, tax and interest and exchange rates; and it derives outputs of carbon dioxide and other greenhouse gas emissions, SO_2 emissions, energy use and GDP and its expenditure and industrial components.

The emphasis in the modeling for this paper is on two sets of estimated demand equations as in equation (1) above: aggregate energy demand by 19 fuel users and 20 regions and exports of goods and services by 41 industries and 20 regions. These sets of equations have been estimated by instrumental variables in a co-integrating general-to-specific framework, assuming a long-run relationship that can be projected over the next 100 years. Each sector in each region is assumed to follow a different pattern of behavior within an overall theoretical structure, implying that the representative agent assumption[12] is invalid.

Two sets of critical parameters, one from each set of equations are shown in Figures 1 and 2 as probability plots (see Barker and De Ramon, 2006, for an explanation of the tests and graphics) of the short- and long-run responses of energy demand to relative prices, and the long-run responses of export demand to the technological progress indicator for Annex I and non-Annex I regions. There are in principle 380 parameter estimates for energy and 820 for exports, and the estimated ones are shown with bubbles representing their standard

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[11] The database was constructed, and the equations estimated, by teams in Cambridge Econometrics headed by Rachel Beaven and Sebastian De-Ramon, including Dijon Antony, Ole Lofsnaes, Michele Pacillo and Hector Pollitt.

[12] The assumption of the representative agent, commonly adopted in equilibrium models, is that the behaviour of an economic group is adequately represented by that of a group, each of whose members have the identical characteristics of the average of the group.

Figure 1. Probability Plots for Short- and Long-run Response of Fuel Use to Relative Price

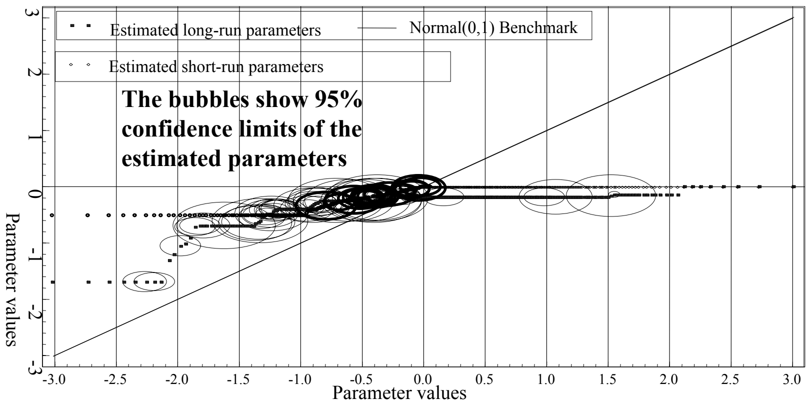
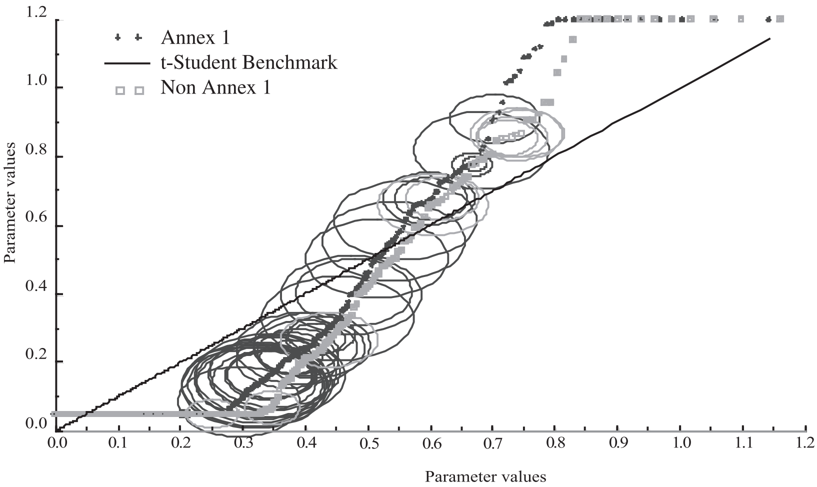


Figure 2. Probability Plots for Annex I and Non-annex I Long-run Responses of Exports to the Technological Progress Indicator



errors. If a parameter is significantly different from a unique estimate using the whole dataset, then the bubble will intersect with the 45 degree line, showing the expected values of the average assuming normality. Both plots show a number of departures from the benchmark t-Student distribution. Figure 1 shows that the short-run responses are small compared with the long-run ones, which have a maximum of -1.8; Figure 2 shows that the long-run responses for Annex I regions are more reliable (many more bubbles shown), more concentrated (most of them near the origin) and lower (clustered around 0.2) than those for non-Annex I regions, which is not a surprise, given the quality of the data for the latter regions.

For the ETM, a database was developed by Anderson and Winne (2004), using learning rates reported in McDonald and Schrattenholzer (2001). Regional differences in the costs of fuels were taken into account and the model was fitted to IEA data on electricity capacity and generation by region and technology. However it should be noted that for many technologies, no past data on capacities exist, so the projections rely on assumed initial shares.

The Common POLES-IMAGE (CPI) baseline has been derived from the IMAGE IPCC SRES A1B and B2 baselines. CPI assumes continued globalization, medium technology, continued development, and strong dependence on fossil fuels. Population follows the UN medium projections for 2030 and the UN long-term medium projection between 2030 and 2100. Further details may be found in Criqui et al. (2003). This baseline is used for the population assumptions of E3MG and projections are made for government expenditures and per capita household consumption for each region assuming the average growth rate will slow after 2050. With other components of GDP endogenous in the model, GDP (in $ at year 1995 prices and market exchange rates) is calculated. Economic growth is near the historic average at 2.3%pa 2000-2100, with higher rates to 2050 and lower rates thereafter. The assumption that baseline growth with ITC is given makes it clear that the model is essentially explaining relative effects, and that the effects on the relative level of GDP and the relative costs of carbon of GHG reductions or of removing ITC may be more reliable than the absolute numbers of GDP and carbon costs in the baseline.

The solution process is complicated. There are three baseline solutions, each yielding closely similar results. The first is the calibrated solution of the model, in which consumers' expenditures are exogenous. A second endogenous, but calibrated, solution is derived by including equations explaining these expenditures, and calculating and storing the residuals between the equation solution and the exogenous values. A third endogenous un-calibrated solution then solves the equations with the residuals and so reproduces the calibrated solution. This endogenous solution includes, for each sector and region: sectoral output, employment, energy use and prices and emissions. It is the basis for two baseline sets of CO_2 emissions, one in which E3MG and ETM allow for endogenous technological change, and another in which they do not. In these baseline solutions technological change still occurs and is modeled as a projection of the estimated effects and through learning by doing.

The emission scenarios are also subject to exogenously defined dates at which countries together impose permit and carbon tax schemes. By default the permit scheme covers the energy sectors only (electricity supply, the fossil fuel and energy-intensive sectors covering metals, chemicals, mineral products and ore extraction) while carbon taxes at the same rates are imposed on the non-energy sectors. The rates start from small values in 2011 and are assumed to escalate in real terms until 2050, then stay constant in real terms until 2100. 50% of the permits are allocated freely to the energy users on the basis of their past emissions (grandfathering) and the rest are auctioned (this rule is adopted to prevent excessive profits in the energy sectors from the sale of permits under conditions in which the industries have market power).[13] The carbon tax revenues are assumed to be recycled in each region independently. The auction revenues are used along with the revenues from carbon taxes to reduce indirect taxes in general (such as the USA's sales taxes or the EU's VAT) as the instrument to help maintain macroeconomic price stability.

5. RESULTS

The results obtained use policies (carbon taxes and/or carbon permit trading) to induce technological change in sectoral energy use in general and electricity generation and motor vehicles to achieve stabilization levels of 450, 500 and 550 ppmv CO_2 by 2100. Table 1 shows the tax levels and trading prices necessary to achieve these targets and Figure 3 shows the resulting CO_2 emissions pathways.

Table 1. Global Carbon Tax Rates and CO_2 Permit Prices[14] (\$(1995)/tC)

	With no ITC				With ITC			
Scenario	**2020**	**2030**	**2040**	**2050-2100**	**2020**	**2030**	**2040**	**2050-2100**
550ppmv	37	74	110	147	16	32	49	65
500ppmv	59	119	178	238	27	54	81	108
450ppmv	184	368	551	735	108	216	324	432

Source: E3MG2.1sp2

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[13] Barker and Rosendahl (2000) in a study of ancillary benefits of GHG mitigation in the EU find that free allocation of permits leads to large profits in the energy industries, compared to the baseline, and that profits can be maintained in the long run if only 50% of the permits are allocated freely (p. 21). Goulder has also addressed this issue, using a general equilibrium approach. A recent paper concludes: "Under a wide range of parameter values, profits can be maintained in both "upstream" (fossil-fuel-supplying) and "downstream" (fossil-fuel-using) industries by freely allocating less (and sometimes considerably less) than 50 percent of pollution permits." (Goulder et al. forthcoming, p 4).

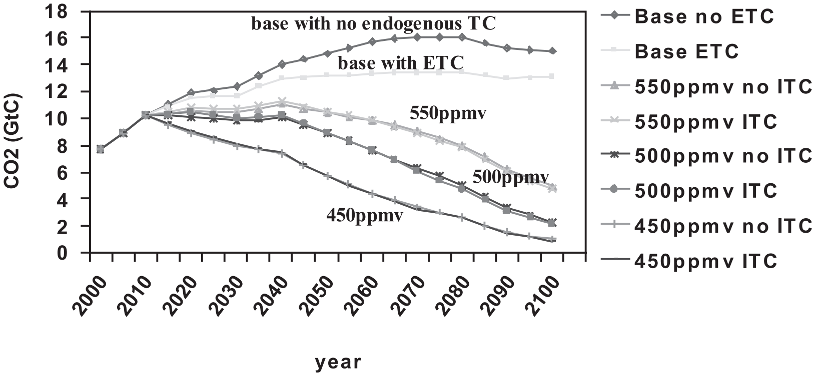
[14] These and other reported results are uncertain. A major exercise is planned to assess the uncertainties in the projections, but was not possible for this paper. However the projections are expected to become less reliable the further they are in the future.

There are four features worth mentioning about the rates. First the rates with ITC are about half those without. Second, there are the modest levels required for the 550ppmv target with ITC, with rates starting at \$1.6/tC in 2011 and rising to \$16tC by 2020. These rates are sufficient to increase energy efficiency appreciably and shift the electricity system to a mixture of low-carbon options including renewables, coal and gas with sequestration, and nuclear depending on region and local conditions. Third, the rates for the 500ppmv target are not quite double those for the 550ppmv target. The increase is a sufficient incentive to cause the conversion from gasoline to electric vehicles largely over the years to 2050. The modeling of the conversion is highly non-linear, since it requires a system change, and the permit/tax rates required are very uncertain. As the transport sector decarbonises, it requires more electricity, and this further accelerates the move to low-carbon technologies in the electricity sector. Third, the 450ppmv target is much more difficult to achieve. Rates with ITC start at \$11/tC in 2011 and rise to \$108tC by 2020 and \$432 by 2050. The easier, lower cost options for reducing emissions have been exhausted, and the extra growth stimulated by the higher investment is also encouraging the demand for energy in general.

Figure 3 shows the emission pathways, both with and without induced technological change. The baseline with no ETC or ITC is substantially higher than that with ETC and, since there are no tax changes, no ITC. The striking feature of the stabilized scenarios is that the treatment of technological change makes very little difference to the use of carbon. Taking the system as a whole, the effects of technological change as modeled are simultaneously to reduce energy demand directly through improvements in efficiency but increase economic growth and so increase energy demand indirectly, offsetting the effects of the improvements in energy efficiency. This relates to the "rebound effect" found in studies of energy efficiency (Herring, 2004; Frondel, 2004) in which the expected reductions in energy use do not occur because the extra real income provided by the improvement in efficiency leads to more energy use. At the global, long-run scale, technology drives energy efficiency, but it also, more significantly, drives economic growth and offsets the efficiency gains so that energy use and CO_2 emissions remain high. The scenarios show that these can be curtailed by increases in real carbon prices.

Both energy and carbon intensities fall after 2010, with energy intensities falling earlier, partly because low-carbon transportation requires a longer time to develop but mainly because technological change affects energy use in general, rather than carbon use in particular. The carbon taxes and permits also have their main effect on energy use rather than CO_2 because of the difficulties of substituting away from carbon outside the power sector. In power generation, fossil fuel shares fall and renewable shares rise in both the base and the scenarios. The higher real costs of carbon in the scenarios have their main effect in accelerating this shift. Within the renewable group, there is a wide diversity of technologies adopted, depending on local conditions and niche markets.

Figure 3. Global CO_2 Emission Pathways and Endogenous Technological Change



Source: E3MG2.0sp1r1, model solutions annually to 2020 and every 10 years to 2100.

Table 2. Global GDP Projections in the Scenarios

	$(1995) trillion			Difference from base %	%pa	
Scenario	**2000**	**2050**	**2100**	**2100**	**2000-2050**	**2050-2100**
Baselines:						
no ITC	33.2	133.5	289.2		2.8	1.6
ITC	33.2	141.9	330.1		3.0	1.7
550ppmv:						
no ITC	33.2	134.8	292.5	1.11	2.8	1.6
ITC	33.2	143.3	334.2	1.15	3.0	1.7
500ppmv:						
no ITC	33.2	135.9	294.8	1.85	2.9	1.6
ITC	33.2	144.1	336.4	1.75	3.0	1.7
450ppmv:						
no ITC	33.2	166.2	298.6	3.09	3.3	1.2
ITC	33.2	180.6	342.0	3.37	3.4	1.3

Source: E3MG2.1sp2

Table 2 shows the outcomes for GDP, also with and without induced technological change. The effects of including endogenous technological change in the baseline are apparent, with appreciable effects on global economic growth as employment shifts more rapidly from traditional to modern sectors, especially in developing countries. This is not a surprise. Technological change is led by improvements e.g. in the use of machinery and information technology, which allow long-run growth to proceed by restructuring and saving on scarce resources such as labor and energy. The growth itself ultimately comes from the demand by consumers for goods and services, through increasing returns exploiting technological and marketing innovations. The growth rates are hardly affected by decarbonisation of the global economy, partly because energy demand and supply is very small in relation to the rest of the economy, around 3-4% of value added. These results appear to confirm those of Gritsevskyi and Nakicenovic (2000) using the MESSAGE model which suggest that a decarbonised economy may not cost any more than a carbonised one and that there is a large diversity across alternative energy technology strategies.

Table 2 also shows the extent to which higher growth is induced by the extra investment as a result of the increases in real carbon prices. At 550ppmv, the overall effects are very small, with the growth rates unchanged. When the stabilization targets are more demanding, the extra investment required leads to a small increase in the growth rate before 2050, and GDP is about 3-4% higher by 2100.

Table 3. Sensitivity Tests on Inclusion of ITC in E3MG

	Base		**450ppmv**	
	CCO2	**GDP**	**CCO2**	**GDP**
Effects of ITC as % difference from non-ITC base by 2100:				
sectoral energy equations	-9.4	0.1	-0.9	-0.8
sectoral export equations	3.2	13.6	0.7	12.3
ETM	-1.6	0.4	0.1	2.7
Total	-8.0	14.1	-0.1	14.5

Source: E3MG2.1sp2
Note: CCO2 is accumulated global CO_2 emissions to 2100.

The sensitivity[15] of the results to the inclusion of endogenous technological change (ETC) in the different sets of equations in the model is reported in Table 3. Starting with a solution without ITC, the model has then been run with the ITC effects included in the sectoral energy equations, and the differences calculated for accumulated CO_2 (CCO_2) and GDP for 2100: the main effect is to reduce CO_2 emissions in the base by 9.4%, while the small emissions in the 450ppmv stabilized scenario are almost unchanged. The effects of ITC in the export equations are to increase CO_2 by 3.2% in the base, and GDP by over 10% in both scenarios. The effect of the ITC in the ETM is to reduce emissions slightly in the base, but increase GDP by 2.7% in the 450ppmv scenario. The extra investment induced by the switch to low-carbon technologies then leads to higher exports and hence higher world growth.

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[15] A sensitivity analysis of E3MG parameters in principle requires repeated re-estimation of parameters under different assumptions, with associated projections. This major exercise was not possible for this paper.

6. CONCLUSIONS

Under a set of plausible assumptions, economic growth has been made endogenous in a large-scale econometric model, with sets of export and energy demand equations estimated on 20-region annual data 1971-2001. General technological progress at the macroeconomic level has been measured by indicators chosen as accumulated gross fixed investment enhanced by R&D expenditures, and its effects estimated by inclusion of the indicators in these equations. However, improvements in energy efficiency are offset in their effects on emissions by the effects of higher growth in exports, incomes and therefore the demand for energy. This phenomenon is a global, macroeconomic counterpart to the rebound effect found in microeconomic studies of energy policies. The main conclusion is that general technological change alone seems unlikely to lead to decarbonisation.

Specific technological progress has been included in the model by a bottom-up representation of technologies using energy in the electricity and vehicle industries, with learning curves and responses to real energy prices. When technological change is induced by allowing the technologies to respond to increase in the costs of carbon through costs of permits and taxes, the outcome is a wave of extra investment, initiated in the electricity and vehicle industries, but diffusing rapidly to all investing and other industries in all regions. The extra investment raises economic growth, with demands being stimulated by higher incomes and supplies made available by economies of scale and specialization as well as a more rapid shift of employment from traditional to modern sectors in developing countries. At the 450ppmv stabilizations level, the permit price and the carbon tax rates are much higher than at the 500ppmv and 550ppmv levels, but the increase in economic growth is only slightly higher.

The conclusions are conditional on model uncertainties and assumptions, and on specific fiscal polices. Macroeconomic inflation stability is assumed by the recycling of permit-auction and tax revenues through reductions in indirect taxes, e.g. VAT, holding consumer inflation at baseline values. In effect indirect taxation is shifted towards products in proportion to their carbon intensity. Energy-industry profits are assumed to remain at baseline values by half the permits being freely allocated. The long-run public sector finances are assumed to be kept in balance by the increases in tax revenues from the higher growth. Under these conditions, if policies raise real carbon prices, then the extra investment from the induced technological change is expected to lead to slightly more economic growth.

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