Modeling Low Climate Stabilization with E3MG:[1] Towards a 'New Economics' Approach to Simulating Energy-Environment-Economy System Dynamics

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The literature on climate stabilization modeling largely refers to either energy-system or inter-temporal computable general equilibrium/optimal growth models. We contribute with a different perspective by deploying a large-scale macro-econometric hybrid simulation model of the global energy-environment-economy (E3MG) adopting a "New Economics" approach. We use E3MG to assess the implications of a low-stabilization target of 400ppm CO_2 equivalent by 2100, assuming both fiscal instruments and regulation. We assert that if governments adopt more stringent climate targets for rapid and early decarbonization, such actions are likely to induce more investment and increased technological change in favor of low-carbon alternatives. Contrary to the conventional view on the economics of climate change, a transition towards a low-carbon society as modeled with E3MG leads to macroeconomic benefits, especially in conditions of unemployment, with GDP slightly above a reference scenario, depending on use of tax or auction revenues. In addition, more stringent action can lead to higher benefits.

1. INTRODUCTION

The starting point for this paper is that, according to the latest climate change science literature (Hansen et al., 2008, IPCC 2007), deep cuts in global anthropogenic greenhouse gas emissions are necessary over the coming years

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1. E3MG: Energy-Environment-Economy Model at the Global level.

if the risks of dangerous climate change are to be significantly reduced and irreversible catastrophic changes in the earth's climate system avoided. The world's energy system and land use will have to be radically transformed over the next decades, meaning that the energy system will have to switch from its present base of fossil fuels towards low-carbon energy sources. Damaging land-use change, especially in the tropics, will also have to be stopped and reversed.

One critical finding of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2007) was that the economic consequences of stringent stabilization targets and deep cuts have been under-researched in the current literature on the economics of climate change. Furthermore, most model results that are reported so far for the different kind of stabilization targets, have their origin in either energy-system models or inter-temporal Computable General Equilibrium (CGE) / optimal growth models. Energy-system models present the main advantage of a detailed and explicit representation of technological options. However, they ignore the interactions and feedback effects within economic systems across sectors, countries and markets. In the CGE/optimal growth modeling approach, mitigation action is automatically associated with economic costs, e.g. with most optimization models assessing the costs of climate change mitigation at a global scale to be on average around 2-3% of GDP for achieving a 450ppm CO_2-equivalent (CO_2e) stabilization scenario (IPCC 2007).

In this paper, we will add a different perspective on the mitigation problem by putting forward a hybrid approach, combining top-down and bottom-up modeling of energy-environment-economy (E3) systems. We employ a large-scale, non-linear macro-econometric simulation Energy-Environment-Economy Model at the Global level (E3MG) to assess the implications of a low-stabilization target of 400ppm CO_2 equivalent by 2100. In contrast to neoclassical CGE or optimal growth models that are based on normative assumptions and typically one year's data, macro-econometric models incorporate behavior of firms, households and investors based on empirical observations involving many years' data. In addition, through its very large database and high level of disaggregation, E3MG aims to provide a more detailed representation of the economy in comparison to both bottom-up and top-down CGE models. Moreover, the E3MG modeling approach put forward in this paper assesses policies in a non-optimal environment, accounting for the observed under-utilization (for example, via observed trends in labor productivity) and unemployment of resources in many countries.

We argue that mitigation action, if effectively co-ordinated at a global level and depending on the use of tax or auction revenues, may lead to negative costs, i.e. economic benefits in the longer term, with the benefits increasing the more stringent the target. The paper is structured as follows. In the next section, we provide a brief discussion of our modeling approach and how this differs from the conventional view on modeling the economics of climate change. Section 3 comments on scenario formulation, whereas Section 4 extensively discusses the results. Section 5 concludes and summarises the policy implications of our analysis.

2. AN ALTERNATIVE VIEW ON MODELING CLIMATE CHANGE MITIGATION

When investigating the literature modeling the costs of climate change mitigation, two important distinctions may be made (Hoogwijk et al., 2008). The first relates to technology detail, i.e. bottom-up (high technology detail with technologies explicitly and individually modeled) versus top-down (low technology detail where technologies are implicitly modeled through fuel use and are highly aggregated). The second distinction is made more on methodology distinguishing between optimization and simulation. Optimization models aim to describe least-cost energy systems under a set of constraints, where systems are in "equilibrium" and operate at the lowest over-all costs from a centralised perspective. In other words, the crucial assumption of an overarching benevolent centralised social planner is made (normally assuming perfect markets, perfect knowledge and perfect foresight). Simulation models, in contrast, describe the development of the energy-economy systems as they are observed, from a perspective that does not necessarily require optimality, and allowing for different behaviors in different countries and times. Moreover, running a dynamic simulation model implies, on the contrary, limited foresight, and avoids the problem of multiple equilibria, which is a main feature of the literature on endogenous technological change (Köhler et al., 2006, Köhler et al., 2006a).

2.1 The E3MG Hybrid Approach to Modeling the Economics of Mitigation

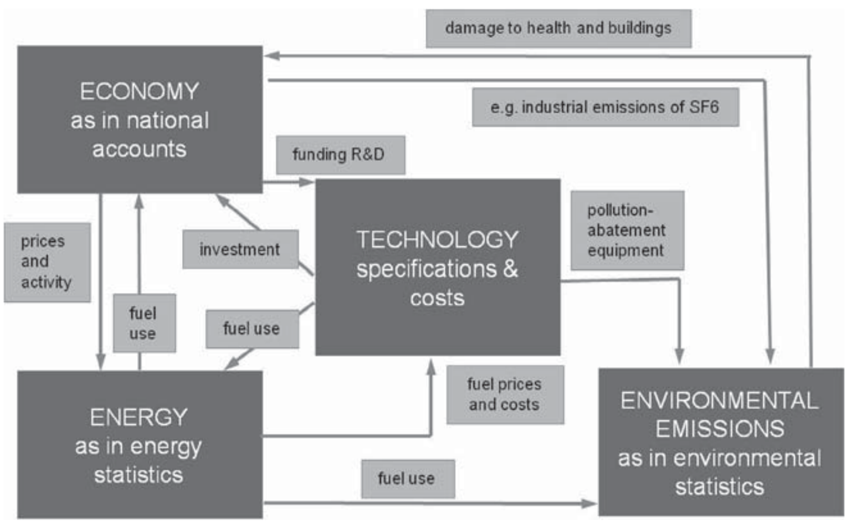
The E3MG model is based on "New Economics"[2] theory as distinct from traditional theory; it is neither an optimization model nor exclusively an energy-systems model. It displays a hybrid simulation approach combining a top-down macro-econometric dynamic overarching framework with a bottom-up energy technology sub-model. In other words, E3MG explicitly accounts for a relatively wide range of low-carbon technologies which are integrated within a top-down dynamic framework involving the use of econometric estimation to capture historical behavior and the effects of endogenous technological change at the macro-level (i.e. E3MG adopts a space-time-economics approach). Simulation models of this type provide information about barriers of implementation for low-carbon technologies (see Barker 2004 for a comparison of general equilibrium and space-time-economics approaches).

The hybrid modeling approach adopted in E3MG is graphically illustrated in a simplified version in Figure 1 below. Each component of the E3 system as well as the technology sub-model is shown in its own box and utilises its own units of account and sources of data. Exogenous factors coming from

2 "New Economics" is concerned with institutional behaviour, expectations and uncertainty as opposed to traditional economics with its emphasis on equilibrium, mathematical formalism and deterministic solutions. We use the term to include various heterodox approaches including Post Keynesian, evolutionary and institutional economics (see Barker, 2008).

outside the modeling framework are: for the regional economy, population, energy resources and economic activity and prices in outside world areas and economic policy (including tax rates, growth in government expenditures, interest rates and exchange rates); for the energy system, world oil prices and energy policy (including regulation of energy industries); for the environment component, policies such as reduction in non-GHG emissions from large combustion plants.

Figure 1. The Hybrid (Top-down/bottom-up) Structure of the E3MG Model[3]



The linkages between the components of the model are shown explicitly with arrows showing which values are transmitted between components. The economy module provides measures of economic activity and general price levels to the energy module; the energy module provides energy use impacting the economy and the environment depending on the type of energy source being used; the economy module also affects technological change through R&D and the promotion of pollution-abatement equipment which in turn may mitigate environmental emissions. The energy module also provides detailed prices levels for energy carriers distinguished in the economy module and the overall price of energy and energy use.

The hybrid modeling approach has the advantage of explicitly modeling options of different portfolios of electricity technologies (through the bottom-up component – see McFarland et al., 2004), whilst accounting (via the top-down component) for the interactions, feedback and spill-over effects between the required investments and outcomes and the rest of the economy. For instance, the

3. The damages from emissions shown in the figure are not yet formally included in E3MG.

bottom-up Energy Technology Model (ETM) component of our hybrid E3MG approach gives capital and technology an explicit and empirical content which is related to energy in a very specific way (as represented by the interactions between the technology green box and energy-environment-economy systems in Figure 1). This is in contrast with the tradition top-down approach where capital is usually treated as a homogenous input and is related to energy insofar as it is assumed to possess a degree of substitutability with energy inputs/carriers in production (Cambridge Econometrics, 2006). The hybrid modeling approach also has the dual advantage that it tends to avoid the typical optimistic bias often attributed to a bottom-up engineering approach, and unduly pessimistic bias of typical macroeconomic approaches (Köhler et al., 2006). Other advantages of the hybrid approach have been reviewed in Grubb et al. (2002).

2.2 Top-down Features of E3MG

Economic activity undertaken by persons, households, firms and other groups has effects, which transmit to other groups after a lag, and the effects persist to include future generations, although many of the effects soon become so small as to be negligible. But there are many such groups, and the effects, both beneficial and damaging, accumulate in economic and physical stocks. The effects are transmitted through the environment, with externalities such as greenhouse gas emissions leading to global warming, through the economy and the price and money system via the markets for labor and commodities, and through the global transport and information networks. The markets mainly transmit effects through the level of activity creating demand for inputs of materials, fuels and labor, through wages and prices affecting incomes and through incomes in turn leading to further demands for goods and service.

These interdependencies suggest that an E3 model should be comprehensive, including many linkages between different parts of the economic and energy systems. These systems are characterised by economies and diseconomies of scale in both production and consumption, by markets with different degrees of competition, by the prevalence of institutional behavior which may be maximization, but perhaps the satisfaction of more restricted objectives, and by rapid and uneven changes in technology and consumer preferences, certainly within the time scale of climate policy. Labor markets in particular may be characterised by long-term unemployment. The E3MG model aims to represent these features by embodying a variety of behaviors and simulating the dynamics of the system. The approach can be contrasted with that of general equilibrium models, which usually assume constant returns to scale, perfect competition in all markets, maximization of social welfare measured by total discounted private consumption, no involuntary unemployment, and exogenous technical progress following a constant time trend.

E3MG has been designed to assess GHG mitigation policies both for the short-run and for the medium to long-run up to 2100 to include policy measures for influencing technological developments. The model has been developed in the traditions of the Keynesian Cambridge dynamic model of the UK economy (Barker and Peterson, 1987) and the European model E3ME (Barker, 1999). E3MG is a non-equilibrium model in the sense that it represents the economy without assuming equilibrium, as opposed to CGE or optimal growth models which solve for an (assumed) first-best solution through market equilibria. Markets do not necessarily clear and supply does not necessarily match demand; rather economic forces tend to change relative prices and policies to remove imbalances in the long run (Barker et al., 2006, Köhler et al., 2006).

E3MG adopts a different perspective on modeling technological change and economic growth, as opposed to most existing studies on the costs of climate stabilization. The theoretical basis of the approach draws on Post Keynesian theory where economic growth is demand-led and supply-constrained. In modeling long-run economic growth and technological change, the history approach of cumulative causation[4] and demand-led growth has been adopted (Kaldor, 1957, 1972, 1985; Setterfield, 2002; Barker et al., 2006). The demand-led growth in this approach is dependent on Kondratiev waves of investment and as a macroeconomic phenomenon arising out of increasing returns (Young, 1928), which lead to technological change and diffusion. Other features of the model drawing on but not limited to Post Keynesianism include: varying returns to scale (which are derived from estimation), no assumption of full employment, varying degrees of competition, the feature that industries act as social groups and not as a group of individual firms (i.e. bounded rationality is implied), and the grouping of countries and regions based on political criteria.

Three main mechanisms describe the key features of accounting for endogenous technological change in the version of E3MG we used.[5] First, at the macro-level, sectoral energy-demand and export-demand equations include indicators of technological progress in the form of accumulated investment and R&D. Export-demand equations explain the demand for a country's exports in terms of economic activity in the country importing the exports, the relative prices of the exports in relation to the prices of other goods and services, and indicators of technological progress, namely accumulated gross investment. Second, as described below, the ETM incorporates learning-by-doing through regional investment in energy generation technologies that reduce in cost depending on global-scale economies. And third, extra investment in new technologies, in relation to baseline investment induces further output through a Keynesian multiplier effect and therefore more investment, trade, income, consumption and output in the rest of the world economy. However, further changes can be induced

4. "Cumulative causation" refers to a dynamic institutional process in which various factors combine to create a vicious or virtual circle to strengthen an initial effect (Berger, 2008). Kaldor (1957, 1972, 1985) developed the economic theory based on increasing returns and agglomeration economies.

5. For a more detailed explanation, especially of the export and energy demand equations and their associated specifications please see Barker et al. (2006) and Cambridge Econometrics (2006).

by policy; hence the term *induced* technological change.[6] For example, feed-in tariffs for renewables (as used in Germany) will alter relative prices such that investments in renewable technologies are stimulated and, depending on their learning curve characteristics (and Keynesian multiplier effects at the macro level), they will lead to higher adoption rates. The effects of technological change modeled in 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 version of E3MG used is a 20-region, structural, annual, dynamic, macro-econometric simulation model based on data covering the period from 1970-2001, and projected forward to 2100 (Barker et al., 2005, Barker et al., 2006, Köhler et al., 2006). The top-down structure of the model consists of a dynamic simultaneous system of sets of behavioral time-series equations to explain demand-led growth, as well as prices, energy demand, wages, employment, housing investment and trend output for each industrial sector. Thus, the top-down feature of the model allows for the dynamic representation of the structural variables determining demand, instead of modeling a succession of static equilibria through time, as applied, for instance, in the case of recursive dynamic CGE models. The co-integrating framework is general-to-specific using instrumental variables (see Barker and de-Ramon 2006, for details). In other words, co-integration relations driven by stochastic trends are embodied in the econometric system of the model for the treatment of long-run solutions. A long-term behavioural relationship is identified from the data and embedded into a dynamic relationship allowing for short-term responses and gradual adjustment (with estimated lags) to the long-term outcome. The equations and identities are solved iteratively for each year, assuming adaptive expectations, until a consistent solution is obtained (Barker, et al., 2006, p. 152-3). This presents the main advantage of tying together series that are linked in the end, preventing forecasts from drifting apart and improving simulations and understanding (Clements and Hendry 2008).[7] The emphasis in the modeling is on two sets of estimated equations included in the model: aggregate energy demand by 19 fuel users and 20 world regions and exports of goods and services by 41 industries and 20 regions. The theory and approach behind the energy demand equation, for instance, has been extensively described in Barker, Dagoumas and Rubin (2009). Key parameter estimates and elasticities of the variables influencing energy demand have also been summarised at the global level in table A1 in the Appendix. 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 is invalid. Other real and price

6. The term induced technological change (ITC) refers to further changes in technological progress (i.e. endogenous technological change) that are induced via policy measures (Barker et al, 2006).

7 In other words, trend breaks in the form of structural changes with no historic precedent fostered by a global climate policy are dealt with in the econometric simultaneous system of co-integration equations via the intercept correction technique (and updates). This approach sets the model back on track at the forecast origin and enables the model to account, to some extent, for changes with no historic precedent; "intercept corrections have similar effects to differencing in the face of location shifts, hence their empirical success" (Clements and Hendry 2008).

variables in this version of the E3MG model are treated in a more stylised manner, i.e. real variables are assumed to change with output or real incomes, and price variables change primarily with average consumer prices (Köhler et al., 2006).[8]

2.3 Bottom-up Features of E3MG

Specific technological progress has been included in the model by a bottom-up representation of technologies using energy for electricity generation, and to a limited extent, for road transport, with learning curves and responses to real energy prices. In other words, the energy technologies in the model are reduced to two sets: those for the electricity sector and, in a simpler form, those for road vehicles. The bottom-up Energy Technology Model (ETM) component of E3MG explicitly modeling electricity generation technologies is developed from the notional capacity approach in Anderson and Winne (2003, 2004 and 2007) to represent annual data on generation and capacity by region, and temporal leads for investment planning and lags in equipment coming on stream. 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. Although the original ETM is not specifically regional and is not estimated by formal econometric techniques, it does model, in a simplified way, the switch from carbon-energy sources to non-carbon energy sources over time. It 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 (there are no assumptions on floor costs). A similar approach, although simpler and more stylised, is adopted for the switch from gasoline to battery powered vehicles rechargeable from the electricity grid (the switch to the alternative technology is assumed to be a logistic diffusion process).

The ETM model considers 26 separate energy supply technologies, of which 19 are carbon neutral. A key feature of the ETM is the learning curve which portrays the decrease in technology costs as experience is gained by using a particular technology. With increasing investments in new technologies, innovation and experience, learning takes place, the costs are reduced and the respective technologies are adopted at a faster rate. Learning rate estimates are

8. For the purpose of this paper, no further discussion or detail is provided with regard to the classifications, variables, and econometric specifications used in E3MG. However, detailed explanations of the modeling structure are provided in Barker et al, (2005, 2006) and Barker and de-Ramon (2006) and also on the www.E3MGmodel.com website. Furthermore, the sectoral structure and behavioral equations underpinning E3MG are similar to those of the Cambridge Econometrics European model, E3ME, for which a detailed description is available in Cambridge Econometrics (2006) and in Pollitt et al, (2007). The econometric estimation forms also draw on the equations forming the basis of the Cambridge Multi-sectoral Dynamic Model of the British Economy, presented extensively in Barker and Peterson (1987).

largely taken from McDonald and Schrattenholzer (2001) and shown in Anderson and Winne (2004), and to some extent in the synthesis chapter of this issue (Edenhofer et al., 2010, this Issue). The energy technologies and the equations underpinning the ETM sub-component of E3MG are also extensively discussed in Barker et al. (2005, 2006), Köhler et al. (2006) and Barker et al. (2007) for the E3ME model, the European counterpart of E3MG. The channels of technological learning within the energy sector are represented in the ETM through learning-by-doing and learning-by-R&D. Both ensure that the costs associated with new low-carbon technologies are decreased with global cumulative investments in installations and R&D. Moreover, the substitution process between low and high-carbon technologies is further explained below in section 3.2 detailing the policy scenarios adopted.

Thus, compared to the existing modeling literature targeted at achieving the same goals, we argue that the advantages of the E3MG model lie in four main areas. First, the detailed nature of the model allows the representation of fairly complex scenarios, especially those that are differentiated according to sector and country or region. Similarly, the impact of any policy measure can be represented in a detailed way with the disaggregation of energy and environment industries for which the energy–environment–economy interactions are central. Second, the approach to long-term growth is that this is essentially based on demand-side expectations, that growth is endogenously driven by demand for new products and variety, and is supply constrained, rather than it being based on supply as in the traditional theory. Third, the econometric grounding of the model makes it better able to represent behavior and accounts for under-utilised and unemployed resources (in contrast to traditional computable general equilibrium models that make simplifying assumptions on crucial parameter values across regions and sectors, often not justified by the econometric evidence). Finally, an interaction (two-way feedback) between the economy, energy demand/supply and environmental emissions is an undoubted advantage over other models, which may either ignore the interaction completely or can only assume a one-way causation.[9]

Modeling the costs of mitigation from the type of approach outlined above has been shaping the development of a "New Economics" view of the long-term picture of energy-environment-economy interactions. This new economics approach (see footnote 2) is currently being developed for future research and papers. However, some elements of new economics have already been explored in Barker (2008) and Barker, Scrieciu and Taylor (2008). The key policy messages resulting from adopting the E3MG approach to modeling the economics of climate

9. The two-way feedback is achieved via defining an interface between the bottom-up ETM and the top-down framework of E3MG. For example, ETM calculates investment in energy generation and the shares of the different technologies in new investment, which are part of the overall demand and are also included with gross accumulated sectoral investment in the export equations of the macro-economic model. On the other hand, the top-down component calculates energy demand and fuel prices which are then passed to the ETM for the investment calculations (see Köhler et al. 2006).

change are illustrated in the sections 3 and 4 through assessing the implications of a low-stabilization target of 400ppm CO_2e.

2.4 Limitations of the Model

One of the model's limitations may be that the parameters based on 33-year historical data may not be appropriate for solutions covering a highly uncertain distant future of 100 years. However, the E3MG modeling approach assumes that understanding the future is best done by first understanding the past; hence the econometric basis of the model. A more detailed specification of future technologies may be nevertheless required to improve long-term forecasts.

Increased economic and financial integration is not fully endogenised in E3MG and the financial sector is largely exogenous, incorporating assumptions about exchange rates, interest rates, energy prices. The model is also calibrated to fit likely future projections of particular macro-economic variables, such as GDP by region. This is not to say that economic growth is exogenous in the model; GDP and most of its components are fully endogenised in the model, even though the total is calibrated to match given projected growth paths.

A further limitation of the modeling results, also highlighted in the analysis below, is the lack of an uncertainty analysis, exploring the multi-dimensional policy space to determine the most effective way to achieve the targets. In other words, not all combinations of climate policy measures (e.g. carbon prices and regulatory measures) have been tried. A full uncertainty analysis of policy parameters and other exogenous inputs into the model (e.g. oil prices) is to be undertaken in the next stages of research with E3MG. The aim of this paper is to use E3MG to provide a proof of concept, to demonstrate the macroeconomic costs and benefits of a global transition towards a low-carbon society and the effects of more stringent climate stabilization targets on these costs and benefits.

3. SCENARIOS EXPLORED

The E3MG model is used to derive a cost-effective emission pathway which keeps cumulative emissions within the limits prescribed by the IMAGE/TIMER model, corresponding to the stabilization levels of CO_2e being targeted.[10] Although IMAGE/TIMER 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. It is important to reiterate that we explicitly model the energy sector with a focus on electricity generation technologies and simple treatment of vehicles. CO_2 emissions from land use changes are incorporated into the model but only as an exogenous input with projections taken from the IMAGE/TIMER model used in the ADAM scenario work (van Vuuren et al., 2009).

10. The cumulative CO_2 emission targets (all anthropogenic sources) by 2100 from the IMAGE/TIMER model are 1923.3 GtC for the 550ppm CO_2e case, and 799.3 GtC for the 400ppm CO_2e target.

3.1 Baseline

The common ADAM baseline has been taken as a starting point. In other words, to run forward in time, a baseline time path of GDP is assumed. A sophisticated method has been developed to calibrate the baseline GDP components (on the demand side) of E3MG over the projection period. The growth rates of the totals for gross output, net output, private consumption, government consumption, investment, exports and imports have been projected based on past trends (i.e. econometric work on time-series) and inter-linkages between the respective variables, their lags, the growth in global GDP, the growth in country/regional GDP, and time and country dummies. This panel-data analysis has been used to make projections of several key macroeconomic variables conditional on the regional and global GDP projections being adopted by the ADAM project. These totals for each region have then been matched with the model's projections at a sectoral level, maintaining adding-up constraints. The projections have been made subject to two further constraints. First the growth rates of global exports and imports have been matched at a 41 sectoral level, assuming that any imbalances remain constant at the levels in the historical data. Second, the GDP identity has been imposed, such that GDP (expenditure basis) equals consumption plus investment plus exports minus imports, at a regional level. These methods are intended to ensure that the structural projections of E3MG in the baseline scenario will reproduce, more or less, the changes in structure shown in the data period (1970-2002), with the Social Accounting Matrix identities (Input-Output structure) maintained. An endogenous version of the baseline is then generated, reproducing the calibrated solution to allow for full interaction between the main economic and energy variables. Policies are then applied, which alter relative prices and hence change demand away from the baseline (see also Köhler et al., 2006 and Barker et al., 2006 for more discussion on how E3MG is run). Thus, in a policy scenario, GDP is endogenous, compared to the endogenous GDP in the baseline. Sectoral output, relative prices, employment, the level of investment in power generation and the choice of energy technologies, and hence emissions are also endogenous.

3.2 Policy Scenarios

Two climate policy stabilization scenarios are simulated in order to compare the economic implications of more stringent targets. These refer to a "550ppm" and a "400ppm" CO_2e stabilization levels.

3.2.1 On Carbon Pricing

Carbon prices are dependent on the stringency of stabilization targets and are set in both stabilization scenarios through a global cap-and-trade scheme applied to the energy sectors only (electricity supply, the fossil fuel and energy-intensive sectors covering metals, chemicals, mineral products and ore extraction). All carbon permits are auctioned. For the rest of the economy a carbon tax is applied at the rate implied by the carbon prices reached in the cap-and-trade scheme. The emission permit scheme and the carbon taxes have their effects in raising prices of energy products in proportion to their carbon content, wherever they are imposed. The emission scenarios are also subject to exogenously defined dates (based on ongoing political/policy developments) at which countries together impose permit and carbon tax schemes. In both climate policy stabilization scenarios the rates for carbon prices/taxes start from small values in 2011 and escalate rapidly until 2020, afterwards staying constant in real terms until 2100.

3.2.2 On Revenue Recycling

Other mitigation policies apply in the model, in addition to setting a carbon price through emissions permit trading and carbon taxation. These are associated with fiscal policies which recycle the revenue raised from auctioning permits and implementing carbon taxes, and regulatory measures promoting low-carbon technologies in power generation and transport (electric vehicles). The recycling of revenue is achieved via lowering indirect taxes, incentivising low-carbon technologies on the electricity supply side, and supporting low-carbon production methods and energy efficiency on the end-user side (for both industry and households). The carbon tax revenues are assumed to be recycled in each region independently. The different stabilization scenarios comprise different policy portfolios depending on the stringency of the target. In other words, the policy scenarios implemented in the model partly differ in their assumptions on revenue recycling / fiscal incentives, and the introduction of the extra climate policy regulatory measures (in addition to the resulting differences in carbon prices). However, both stabilization scenarios assume the same proportion of the revenue (collected at the country/regional level) to be recycled to lower indirect taxes (i.e. employers' contribution to social security) in order to maintain fiscal neutrality and price stability. They also assume the same proportion of revenues to be recycled via subsidies for low-carbon technologies (on the energy-supply side) in the form of energy-saving R&D (the corresponding shares are presented in Table 1). Nevertheless, the stabilization scenarios differ in their assumptions on the strength of regulation promoting electric vehicles and the extent of fiscal policies supporting energy efficiency and low-carbon production methods for industry and household end-users.

In other words, at the macroeconomic level, inflation / price stability is assumed by the recycling of permit-auction and tax revenues through the reductions in the respective indirect taxes. This translates in effect into a shift of indirect taxation towards products in proportion to their carbon intensity (the increase in the costs of carbon-based products is offset by a decrease in the costs of non-carbon-based products). That is to say that 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. On the monetary policy side, independent central banks are also assumed to contribute towards holding the rate of consumer price inflation constant. Interest rates and exchange rates are thus assumed to remain more or less at baseline levels in both policy scenarios.

The revenue recycling via offering subsidies to low-carbon electricity-generation technologies is implemented in the energy-technology sub-component of the model. These are incentives in addition to those offered via the carbon price that increases the cost of fossil-fuel intensive based technologies. In other words, the subsidy (a negative G_t in Equation 1 below) alters the relative price of a marker/conventional technology[11] in favor of its clean alternative.

Equation 1. The Price Ratio of Technology *i* to a Marker Technology

$$P_{it} = \frac{C_t^N (1 - T_t)}{C_{it} (1 - Gt)}$$

where P_{it} denotes the price of the marker technology relative to that of the alternative i; $C^N{}_t$ and C_{it} denote the present worth of the (total capital and operating) costs of using the technologies per unit of output, the superscript N in the former referring to the fuel of choice; T_t represents taxes (carbon taxes say) on the former and G_t taxes on the latter (either may be negative if the energy source is subsidised). The price ratio P_{it} in turns affects the investment shares in energy generation technologies (see Barker et al., 2007, Köhler et al., 2006, and Anderson and Winne, 2003 and 2004 for detailed descriptions of the equations underpinning the energy technology sub-model of E3MG). The subsidy (in terms of $ per kwh) is evenly spread across new technologies, i.e. renewables and CCS (excluding nuclear and hydro). In other words, the learning rates for different technologies in different regions (leading to a reduction in costs with their cumulative deployment) correspond to measures to stimulate the deployment of the new low-carbon technologies. The share of revenue recycled that is used for subsidising the new technologies starts at a level of 40% from 2011 to 2030, dropping to 20% by 2040 and to 0% by 2050 (as per Table 1).

Besides recycling the revenue resulting from carbon pricing for maintaining fiscal neutrality and directly supporting primary energy demand for low-carbon sources, no further additional climate policy measures are pursued in the 550ppm CO_2e stabilization scenario.[12] However, in the 400ppm CO_2e stabilization case, extra policy incentives are assumed to accelerate the development and deployment of low-carbon and energy efficiency improvement methods. In

11. A ‘marker’ technology is a technology or fuel of choice that usually applies for each type of energy demanded and against which the alternatives will have to compete.

12 Electric vehicles penetrate by only 5% of total vehicles by 2020 in the 550ppm CO_2e case.

Table 1. Climate Policy Assumptions in Addition to Carbon Pricing Related to the 550ppm and 400ppm Stabilization Scenarios Implemented in E3MG

	Fiscal neutrality and price stability	Energy supply	Transport	End-use (extractive) industrial sectors	End-use (manufacturing) industrial sectors & commercial buildings	End-use households
Type of climate policy measure (in addition to carbon pricing & taxation)	**Revenue recycling / fiscal measures**: Lowering indirect taxes (employers' contribution to social security) and maintaining fiscal neutrality	**Revenue recycling / fiscal measures**: Subsidising (via an increase in energy-saving R&D) low-C electricity-generation technologies (renewables & CCS but not hydro & nuclear) **regulatory measures**: Carbon intensity standards imposed	**Technological agreement / regulatory measures**: Global accelerated diffusion of electric plug-in vehicles (energy use from road vehicles decreases according to the share of electric vehicles)	**Revenue recycling / fiscal measures**: Proportion of revenue (from auctioning) returned for R&D expenditures to stimulate low-C production methods	**Revenue recycling / fiscal measures**: Incentives for investments in energy efficiency (shares of total ETS revenues)	**Revenue recycling / fiscal measures**: Incentives for investments in energy efficiency (shares of total ETS revenues)

Table 1. Climate Policy Assumptions in Addition to Carbon Pricing Related to the 550ppm and 400ppm Stabilization Scenarios Implemented in E3MG (continued)

	Fiscal neutrality and price stability	**Energy supply**	**Transport**	**End-use (extractive) industrial sectors**	**End-use (manufacturing) industrial sectors & commercial buildings**	**End-use households**
550ppm CO_2e stabilization	Share of emission permit / tax revenue for each region for maintaining fiscal neutrality and price stability: 60% from 2011 to 2030 increasing to 80%: 2031- 2040; increasing to 100%: 2041-2050 100%: 2051-2100	Share of emission permit / tax revenue for each region for additionally incentivising low-C technologies: 40% from 2011 to 2030 dropping to 20%: 2031 to 2040; dropping to 0%: 2041 to 2050 0%: 2051-2100 Regulation prevents coal-based power without CCS being re-introduced. All new coal-based power to be fitted with CCS after 2020.	Share of electric vehicles is forced up gradually to 5% by 2020	Not applied	Not applied	Not applied
400ppm CO_2e stabilization			Share of electric vehicles is forced up gradually to 30% by 2020	Sectors targeted & shares: other mining, basic metals and non-metallic mineral products: 100%	Sectors targeted & shares: food, drink & tobacco: 2% textiles, clothing & leather: 1% wood & paper: 1% manufactured fuels: 2% electronics: 3% other manufactures: 2% commercial buildings: 4%	Sectors targeted & shares: households: 15%

other words, in order to achieve the more stringent target, additional regulatory measures and fiscal incentives are pursued to target specific end-use sectors, i.e. transport, energy-intensive industries, manufacturing, commercial buildings, and households. On the transport side, a global penetration of electric vehicles reaching a share of 30% (of the total vehicle fleet) by 2020 is implemented.[13] On the industry and household side, further incentives are provided (recycling some of the revenue raised via increased investments and R&D expenditures) to stimulate energy efficiency and low-C production methods (see Table 1 above for a list of the corresponding shares and sectors targeted).

Moreover, with regard to the 400ppm CO_2e climate stabilization scenario, two further sub-scenarios are considered that help highlight the type of mitigation portfolio required. First, the option of accelerated electrification of the vehicle fleet through regulatory policies is excluded from the mitigation package ("400noecars" – the penetration rate is limited to only 5 percent). Second, the option of using the revenue raised from auctioning permits for providing extra sector-targeted fiscal incentives for stimulating low-C production and energy efficiency improvement methods on the end-user side (for both industry and households) is switched off ("400norev").

3.2.3 Additional Remarks on Policy Variables

The dramatic rise in carbon prices in 2011 to 2020 coupled with the onus of additional climate policy actions on the same period up to 2020 are intended to reflect the urgency of the climate change problem. They are argued to be necessary in order to achieve the rapid and early decarbonization of the world economy and avoid catastrophic anthropogenic climate change. Though we fully acknowledge that a global well-coordinated environmental fiscal/regulatory reform as outlined above is a strong assumption and may be difficult to achieve in practice, our aim is to illustrate an effective and efficient policy of implementing emission reduction measures that cover at least all major sectors and all major regions. The urgent need for a massive programme of investment to resolve the 2007-9 financial crisis supports this assumption.

The time profile of energy-related emissions across 2000-2100 is endogenously determined in E3MG. The model iteratively varies carbon prices (keeping to the time profile mentioned below) and other climate policy measures so that the corresponding carbon budgets are approximated. In this sense, therefore, the carbon price is endogenous in these runs, though not automated in the model. In other words, if the CO_2 emission pathway does not result in stabilization in the full integrated analysis, policy parameters are adjusted in E3MG until a consistent solution is achieved. These and other reported results are

13 Electric vehicles are assumed to be roughly 20 percent more expensive (including infrastructure) than petrol-based vehicles. Electric vehicles are also assumed to be more efficient via a simple rule that reduces energy use from road transport with the increase in the share of electric vehicles as a response to climate policy measures.

uncertain, as the highly-dimensional policy space has not yet been explored in a systematic manner. A major exercise is planned to assess the uncertainties in the projections, but was not possible for this paper. Having said this, one may note that the weaker the extra mitigation incentives and regulations are, the greater the carbon price will be for a given stabilization target. Moreover, the projections are expected to become less reliable the further they are in the future.

4. MODEL RESULTS

E3MG outputs a large array of variables across the projection period. For the purpose of this paper, we provide a summary of results with a focus on the time profile for GDP, investments, carbon prices and changes in the energy mix projected at the global level over the period 2000-2100 (reported on a ten-by-ten year basis).

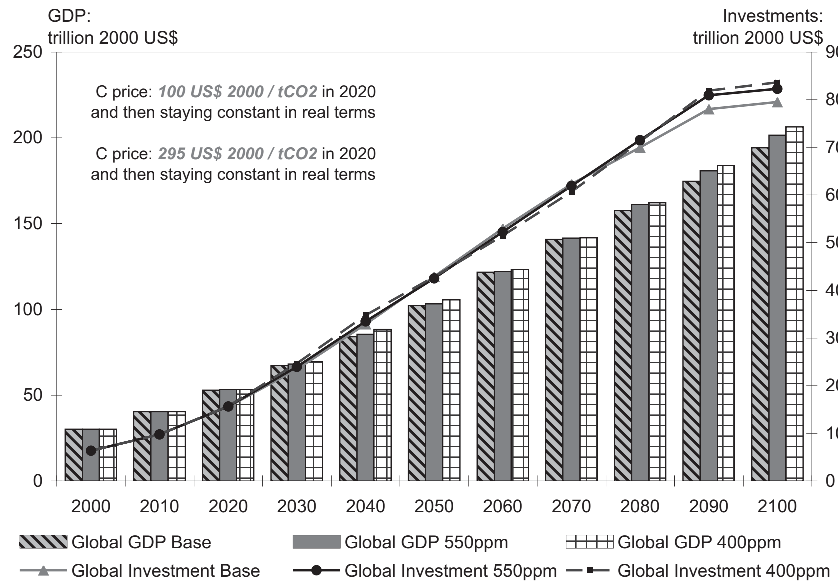
4.1 The Macro-economic Implications of Stringent Stabilization

There are two key outcomes of the E3MG model with respect to the macroeconomic implications of mitigation. First, mitigation action results in higher economic growth (relative to a business-as-usual scenario), as we argue that a decarbonization of the economy via induced technological change does not impede but may in fact stimulate long-term economic growth rates. And second, setting more stringent climate stabilization targets may lead to greater growth. In other words, as opposed to many findings in the literature,[14] a less carbonised economy may not cost more than a more carbonised one. In addition, low-carbon pathways have much less air pollution, so that the damages to human health and welfare are much less (though the latter are not modeled in the current version of E3MG). The potential GDP gains from mitigation, particularly for the low stabilization scenario are illustrated in Figures 2 and 3, and in Table 2.

GDP at the global level in constant 2000 prices for the year 2100 is projected to be US$194 trillion in the base case, US$201 trillion in the 550ppm CO_2e scenario (3.7% above base) and almost US$207 in the more stringent 400ppm CO_2e scenario (6.3% above base). Stringent mitigation may induce faster growth and lift "business-as-usual" real output growth rates, in the long term, by around 0.2 percentage points, for example, from 1.03% to 1.27% annual real global GDP growth rates in 2090 (in the 400ppm case). However, it is crucial to observe the non-linearities in energy-economy systems simulated by E3MG. The growth rates in GDP for the projections are shown in Table 2 as % annual

14. However, the IPCC AR4 states (2007, SPM WG3 p.16) "Although most models show GDP losses, some show GDP gains because they assume that baselines are non-optimal and mitigation policies improve market efficiencies, or they assume that more technological change may be induced by mitigation policies. Examples of market inefficiencies include unemployed resources, distortionary taxes and/or subsidies." At least 14 of the models considered in the AR4 have shown GDP above base for GHG mitigation at the global and national levels over different periods and under some combination of assumptions.

Figure 2. Global GDP and Investment Projections in Absolute Values Across 2000-2100 (Every Ten Years): Baseline, 550ppm and 400ppm CO_2e



Source: E3MG modeling results

averages for 10-year periods to 2100. The growth rates are very similar across scenarios and slow down through the century as population grows more slowly and full employment is reached in most countries.

The time profiles for differences between mitigation scenarios' GDP and that of the baseline for each 10-year period are displayed in Figure 3. They show that the mitigation costs or benefits vary across the projected period and tend to specifically follow investment cycles revealed in the model's solutions. Two main findings may be inferred from Figure 3. First, the more stringent stabilization target (400ppm CO_2e) appears to result in mitigation benefits that are larger than those simulated for the 550ppm CO_2e case, across the entire projected period. In other words, benefits (relative to the baseline) from climate policy may increase with the stringency of the target.[15] The relatively lower GDP benefits towards the middle of the century are due to the deceleration of investments below the baseline, as the first investment cycle in low-carbon technologies reaches its trough. The second modeling result relates to the dynamic aspects of the

15. More stringent targets will require much higher carbon prices and/or stronger regulation, and seems likely to lead to even higher investment and GDP growth. The world economy will be decarbonised long before any limit to this process is observed in the model.

Table 2. Global Real GDP Growth Rate Projections (Annual %)

	Base	550ppm	400ppm
2000-2010	3.0	3.0	3.0
2010-2020	2.7	2.8	2.8
2020-2030	2.4	2.5	2.7
2030-2040	2.3	2.3	2.4
2040-2050	2.0	1.9	1.8
2050-2060	1.7	1.7	1.6
2060-2070	1.5	1.5	1.4
2070-2080	1.1	1.3	1.4
2080-2090	1.0	1.2	1.3
2090-2100	1.1	1.1	1.2

Source: E3MG modeling results

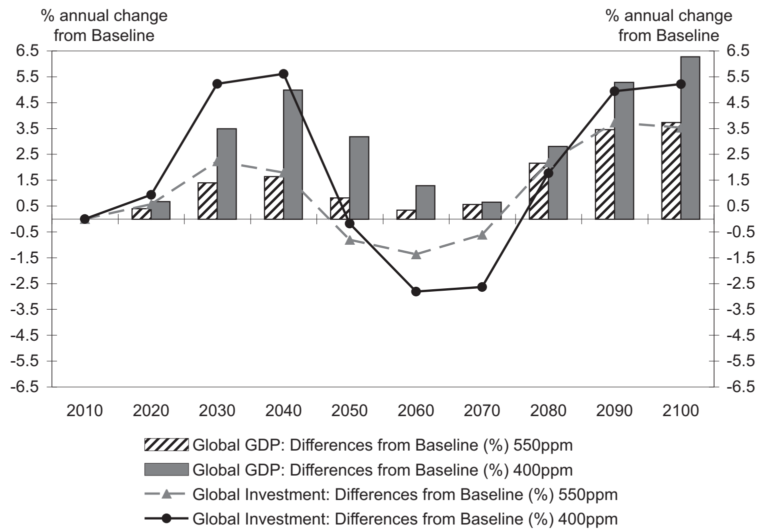
simulation, i.e. a significant part of mitigation benefits are achieved not only in the long term (by 2100), but also at an early stage during the next 20 to 40 years (i.e. 2030-2050). That is to say, the extra investments in low-carbon technologies induced by the increase in carbon prices and fossil fuel costs (due to stringent targets) and through the adoption of other regulatory and fiscal policy incentives are overall larger and earlier than investments in conventional fossil technologies in the baseline. The latter argument reflects at least the economic feasibility of rapid and early decarbonization and is also portrayed by the dramatic early decline in emissions during 2020-2030 (see Figure 4).[16]

It is interesting to observe that the low stabilization target may not necessarily imply negative emissions at the global level when emissions reductions are not delayed and are strongly implemented at an early stage, starting from 2010.[17] Moreover, the long-term mitigation benefits are argued to be the greatest as any perceived additional cost premium associated with higher than "normal" economic and technical risk is overcome in the long run with learning-by-doing

16. With regard to the implications for early decarbonization of energy systems in developing countries, we assume that the capital costs associated with coal-fired power plants in China (and India) are half of the world levels due to the existence of a specialist market and large economies of scale in these countries. This implies that the conventional energy system in China (and India) faces lower investment costs than otherwise with the introduction of high carbon prices. In other words, it implies a smoother transition to low-carbon energy technologies. The GDP loss can be avoided if the investment resources could be planned in advance to be diverted from coal plant to additional renewable or other low-carbon plant. Nevertheless, a smoother transition in these countries would also require the building of a low-carbon technology capacity and an institutional framework to support this, which is in part dependent on international cooperation and effective technology transfer.

17. It is important to note here, that CO_2 emissions from land use turn negative by 2100, though these are exogenously inputted into E3MG. In some cases, e.g. Brazil, it turns out that negative CO_2 emissions from land use are greater than energy-related emissions by 2100 in the 400ppm CO_2e case. Other non-CO_2 greenhouse gases are not explicitly modeled and costed but are assumed to be mitigated with no-cost options in line with the reductions corresponding to the stabilization target. Furthermore, from the technology side, biomass with CCS would allow for negative emissions. However, this option is not available as yet in E3MG.

Figure 3. Annual Changes in Global GDP and Investment Cycles, 2000-2100 (Every Ten Years) for the 550ppm and 400ppm CO_2e Stabilization Scenarios



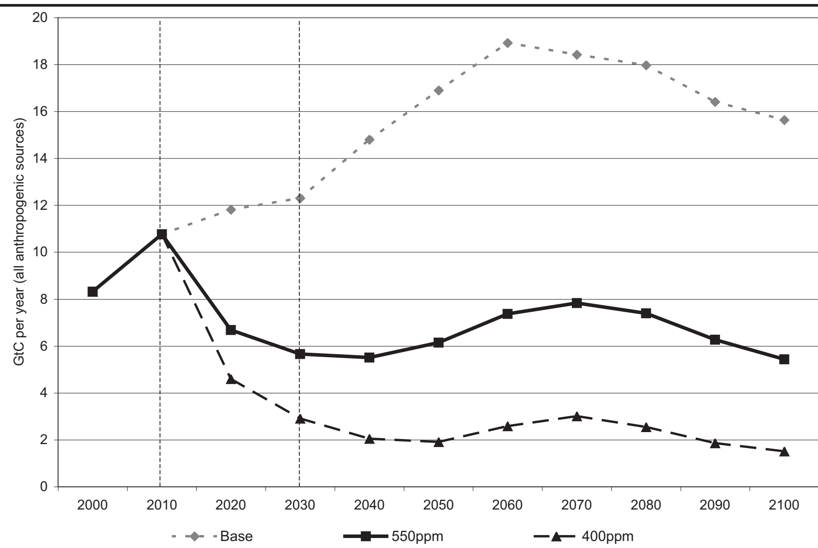
Source: E3MG modeling results

and the diffusion and wide-spread adoption of low-carbon technologies. Portfolio analysis of risk also suggests, for instance, that the optimum mix of technologies favors renewables, because of the volatility of fossil-fuel prices (Awerbuch, 2006). This is confirmed in our analysis and modeling results, with the dramatic drop in emissions being largely induced via the accelerated use of renewables (for electricity generation).[18]

A further salient feature of the E3MG modeling approach, as previously mentioned is that the model assesses policies in a non-optimal environment, accounting for the observed under-utilization of resources (via changes and past trends in labor productivity) across the globe and not allowing for (e.g. labor) market closure. For the demand to be effective in the long run there must also be an increase in supply which is realized in the model through economies of specialization and increasing returns to scale implying higher and better employment opportunities. The assumption adopted here is that sufficient labor is available from productivity growth or structural change to meet the extra demand for products (i.e. the model does not reach full utilization of resources in any of

18. E3MG projects that in the stringent stabilization case of 400ppm CO_2e in the year 2100, the energy mix is dramatically dominated by renewables, with fossil energy playing only a minor role. For example, the share of coal, gas, oil, nuclear, and renewables, in total energy use in 2100 are 0.4%, 3.5%, 5.4%, 5.7%, and respectively, 85%.

Figure 4. Emission Reductions Pathways: Baseline, 550ppm and 400ppm to 2100



Source: E3MG modeling results

the stabilization scenarios). This partly explains why the benefits of mitigation appear to increase with the stringency of the stabilization target. The solution has a much higher carbon price in the low stabilization scenario reflecting the stringency and the challenges of meeting the target. E3MG simulations show that the real (in 2000 US$) carbon price by 2020 associated with the 550ppm CO_2e target is US$100 / tCO_2 (assumed to be constant in real terms afterwards until 2100), whereas in the 400ppm scenario the carbon price increases to 295 US$ / tCO_2 by 2020 (also assumed to be constant in real terms thereafter until 2100).[19] The role of (fiscal) policy incentives and regulation in addition to setting up a global carbon price for the economics of low stabilization are further explored in the remainder of this section.

4.2 The Role Of Regulation And Additional Fiscal Incentives for Achieving Rapid and Early Decarbonization

All the sets of policies and measures described in section 3 above are required to achieve the corresponding mitigation targets. The relative contribution of each set of measures forming the mitigation policy portfolio may be partly assessed by removing a specific subset from the target/policy scenario and

19. The model also calculates a real carbon price for the 450ppm CO_2e stabilization target of approximately US$130/$tCO_2$ to apply by 2020.

comparing the outcomes with and without (the respective subset). This method is necessary because there are strong non-linearities and interactions in the solution, especially when regulations or fiscal incentives force early technologies so that they achieve substantial economies of specialization and scale. However note that the portfolios are designed specifically to achieve each mitigation target and the individual sets of sectoral policies and measures cannot be simply aggregated to find a total, since the interactions between the sectors and within the model can be substantial. Furthermore, a more systematic exploration of the uncertainties surrounding policy space scenario is left for future research analysis. The mitigation consequences for excluding the regulatory options stimulating electric cars (“400”noecars) and energy efficiency improvements and low-carbon methods in the end-use industry and household sectors (“400”norev) are illustrated in Figure 5.

In the scenario where the penetration of electric cars in the transport system (“400”noecars) is strictly limited, the 400ppm CO_2e stabilization target is under-achieved by a wider margin relative to the scenario with no additional incentives for the industry and household end-users (“400”norev). Cumulative emissions in the year 2100 are, in the “400”noecars, around 20% higher than those required to achieve the 400ppm stabilization target, and around 12% greater than those resulting in the “400”norev scenario. The 550ppm CO_2e target continues to be met (i.e over-achieved), nevertheless, in both additional subsets of policy scenarios.

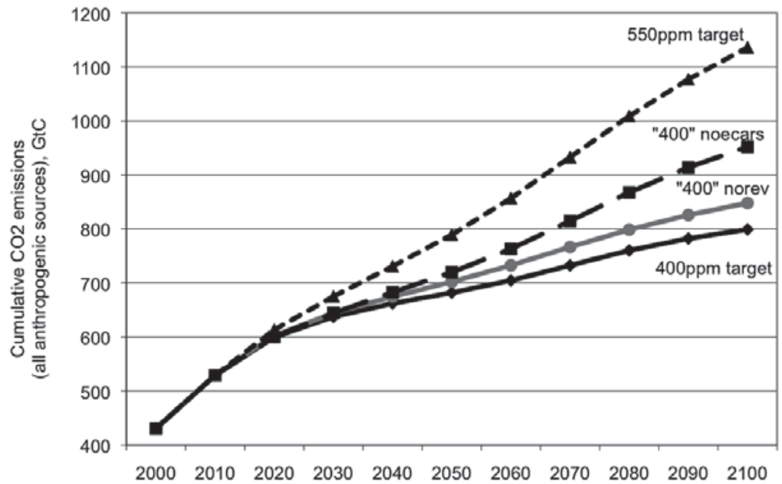
4.3 Policy Implications

Essentially we find that a mix of (efficient) regulation and revenue recycling is required to support the low-cost achievement of the targets and that the more stringent targets can only be achieved at low costs by stronger regulation forcing an early penetration of key technologies, e.g. the all-electric vehicle, and thereby allowing for substantial economies of scale and reductions in unit costs.[20] In other words, mitigation policies in addition to carbon pricing and/or carbon taxation would need to be pursued if stringent stabilization targets are to be met at lower costs. Direct climate policy support supplements the effects of the increases in carbon prices, so that the *accelerated* adoption of new technologies leads to lower unit costs and strengthens the price signal (see Barker, Scrieciu and Foxon 2008 for a more detailed discussion on mitigation policy portfolios)

Overall, the direction of causation of growth modeled in E3MG that results in GDP gains due to climate policy is mainly explained through the following:

20. It was also found that, in order to achieve the 400ppm CO_2e target within the “400”norev scenario, (2000) real carbon prices would need to escalate from 295 to 512 US\$/tCO_2. However, if the electric vehicle option is not implemented in the policy scenario, the 400ppm target may not be achieved at all (the model is not able to reach this low stabilization target without the additional policy measures stimulating the penetration rate of electric vehicles on the global market).

Figure 5. Under-achieving the 400ppm CO_2e Target by Excluding Electric Cars and Extra Incentives for Low-carbon Technology Deployment



Source: E3MG modeling results

- Climate policies lead to more efficient and higher productive investment. Energy efficiency improvements and the pace and scope of substitution between low-carbon and fossil-fuel intensive technologies are determined in the business investment decision by the real price of carbon and the additional incentives pushed forward via mitigation measures. Furthermore, it is argued that low-carbon production of energy in the global system is more capital-intensive than high-carbon production, hence the higher the carbon price (and the greater the policy inducement), the higher the global investment (Köhler et al., 2006). The potential for learning-by-doing and learning-by-R&D is also higher for new low-carbon capital, and this results in faster adoption rates of clean technologies and in a potentially faster economic growth. Additionally, as the transport sector decarbonises (vehicles tend to have a rapid turnover and a low inertia), it requires more electricity, and this further accelerates the shift to low-carbon technologies in the electricity sector.[21]
- The higher investment results in higher output and growth in the short-term, partly via a Keynesian multiplier effect applied at the global level. The global economy being closed, the leakage into imports from extra domestic investments leads to an increase in world exports, and a rise in output, investment, and consumption in exporting countries. In other words, a shift from fossil to low-

21. The assumption here is that road transport may switch away from oil quickly as the transport infrastructure (even though long-lived) does not require major changes.

carbon energy results in an increasing overall amount of investment in the global economy. The underlying hypothesis here is that higher investment and/or R&D is associated with higher quality and innovatory products (implying better utilization of under-utilized resources via productivity increases) and therefore greater exports and higher demand for exports.[22]

- The short-term growth further translates into a higher long-term growth via the diffusion of extra demand from the engineering industries across all industries. Higher long-term growth is also explained by the acceleration of endogenous technological change and increasing returns to scale effects via the mechanisms modeled in E3MG, explained above in section 2 (also see Köhler et al., 2006 for details).[23]

As a result of these simulated effects, the policy implications are to support a portfolio or mix of market-based instruments, regulatory and technology climate-policy measures that induce and diffuse the change towards low-carbon technologies and achieve the required stabilization target with an overall benefit to the global economy. The types of policy mechanisms assumed to be pursued at a worldwide level, for which international policy coordination is essential, are crucial for both achieving low stabilization and rendering mitigation action as an investment project with significant returns. The policy interpretation of our results is that carbon price signals need to be loud, long and lasting, and introduced at a very early stage for a rapid decarbonization of the global energy-economy system.

5. CONCLUDING REMARKS

There are two crucial messages stemming from our modeling approach that are contrary to the conventional view on the effects of mitigation policies on the macroeconomic costs (or more positively the benefits) of mitigation since we find that the overall costs can be negative.

1. Climate change mitigation policies may not induce economic costs but on the contrary bring benefits in terms of higher, accelerated economic growth, especially in times of unemployment.
2. The benefits of climate change mitigation increase with the stringency of the stabilization target.

The reasons for these key findings are twofold. The first relates to our modeling approach and the way we represent the dynamics of economic and energy systems and endogenous technological change in E3MG. The second relates to

22. This assumption is based on the variety hypothesis, i.e. the desire for variety (including more innovatory and higher quality products associated with higher productivity rates and better employment perspectives) explains international trade (Barker, 1976, Barker and Peterson, 1987). Furthermore, investment multipliers differ across sectors and technologies, the net effect being an overall increase in total investments in the global economy.

23. Further discussions of the E3MG approach and assumptions (and results) in comparison with those of other studies may be found in Strachan et al. (2008) and in the IMCP study in Edenhofer et al. (2006).

how climate change mitigation policies are being designed and implemented in the model.

The insights from the theory and modeling suggest that setting more stringent targets and the rapid and early decarbonization of society is likely to induce more investment and increased technological change towards low-carbon alternatives at lower costs. Contrary to the conventional view on the economics of climate change, a transition towards a low-carbon society may very well lead to macroeconomic costs being positive, so that GDP can be slightly above a business-as-usual scenario, partly depending on use of tax or auction revenues. However, model results are dependent on the relatively smooth implementation of the climate policy measures being modeled here. We implicitly assume efficient regulation, credible carbon prices and effective international cooperation and technological transfer. The reported model results only provide an approximation for reality and need to be viewed with these caveats in mind.

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APPENDIX

The Energy Demand Econometric Specification used in E3MG

The following text and table draws on Barker, Dagoumas and Rubin (2009) and describes the estimation of the energy demand equation in the E3MG model. A 2-level hierarchy is being adopted when estimating the aggregate demand equations on annual data covering 19 fuel users/sectors and 20 regions is estimated and then sharing it out among main fuel types (coal, heavy fuel oil, natural gas and electricity). The fuel choice for electricity first for "premium" use (e.g. lighting, motive power) is assumed, and then non-electric energy demand is shared out between coal, oil products and gas. The energy demand for the rest of the 12 energy carriers is estimated based on historical relations with the main 4 energy carriers. All energy demand equations use co-integrating techniques, which allow the long-term relationship to be identified in addition to the short term, dynamic one. These long-run energy demand equations are of the general form given in the equation below, where X is the demand, Y is an indicator of activity (sectoral output), P represents relative prices (relative to GDP deflators for energy), 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 with declining weights for older investment. All the variables and parameters are defined for sector i and region j. In the equations, β2,i,j are restricted to be non-positive, i.e. increases in prices reduce the demand. In the energy equations β3,i,j are estimated to be negative, i.e. more TPI is associated with energy saving. These parameters are constant across all scenarios.

$$X_{i,j} = \beta_{0,i,j} + \beta_{1,i,j}\, Y_{i,j} + \beta_{2,i,j}\, P_{i,j} + \beta_{3,i,j}\, (\mathrm{TPI})_{i,j} + \varepsilon_{i,j}$$

The Table A1 below presents the respective parameter estimates across global energy using sectors, with the world average added as the final row. More details on underlying theory and econometric work are described in Barker, Dagoumas and Rubin (2009).

Table A1. Weighted Averages (2000 Weights) of the Estimated Elasticities of Global Aggregate Energy Demand from the Energy-use Equations

	Short-term			Long-term		
	Activity	Relative Price	Tech-nology Progress	Activity	Relative Price	Tech-nology Progress
Power own use & transformation	0.39	−0.11	−0.19	0.60	−0.18	−0.17
Other energy own use & transformation	0.81	−0.17	−0.34	0.56	−0.28	−0.08
Iron and steel	0.24	−0.29	–2.40	0.46	−0.49	–3.18
Non-ferrous metals	0.42	−0.10	–4.27	0.49	−0.48	–4.93
Chemicals	0.50	−0.21	−0.05	0.57	−0.36	–1.39
Non–metallics nes	0.62	−0.20	−0.04	0.61	−0.25	−0.28
Ore–extra (non–energy)	0.42	−0.09	−0.31	0.68	−0.20	−0.34
Food, drink and tobacco	0.82	−0.27	−0.34	0.13	−0.26	−0.23
Textiles. clothing & footwear	0.43	−0.16	–1.35	0.44	−0.27	–1.17
Paper and pulp	0.22	−0.25	−0.03	0.43	−0.22	−0.06
Engineering. etc.	0.76	−0.14	−0.11	0.16	−0.21	−0.03
Other industry	0.51	−0.14	−0.15	0.62	−0.39	−0.27
Rail transport	0.87	−0.31	−0.21	0.75	−0.25	−0.29
Road transport	0.69	−0.21	−0.17	0.74	−0.70	−0.01
Air transport	0.51	−0.13	−0.06	0.40	−0.41	−0.06
Other transportation services	0.93	−0.25	–1.26	0.92	−0.84	–2.48
Households	0.48	−0.24	−0.05	0.65	−0.32	−0.01
Other final use	0.39	−0.14	−0.15	0.56	−0.27	−0.14
Non-energy use	0.12	−0.17	−0.16	0.00	−0.23	−0.26
World average for all sectors	0.51	−0.18	−0.25	0.59	−0.34	−0.33

Source: E3MG 2.4 and 4CMR, and Barker, Dagoumas and Rubin (2009); Notes: The TPI includes R&D and capital investment effects. The high elasticities for TPI for the energy-intensive industries (iron and steel, non-ferrous metals) are largely attributed to Russia.