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World economic dynamics and technological change: projecting interactions between economic output and CO₂ emissions^{1 2}

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Abstract

With the emergence of accelerated technological change and progress, economic growth has been exhibiting increasingly complex features. Trade within and across industries, countries and regions, has risen sharply, and the globalisation effects of economies of specialisation, low-cost information technologies and networks have taken a stronger grip on economies. Furthermore, long-run economic growth backed by conventional fossil-based technologies (within the context of an increasing population and escalating demands for goods and services) are exerting an unprecedented pressure on the environment, particularly in terms of greenhouse gas emissions and climate change. We investigate not only the historical dynamics of the world economic system, but also project likely long-term changes in the structure of economic output across economies, and assess co-movements between economic activities and greenhouse gas emissions, with an emphasis on the role of endogenous technological change. This is mostly a methodological paper with innovative large-scale econometric modelling techniques with dynamic structures being brought to the fore. We find that century-long projections of economic systems are seldom addressed in the literature, not least because of the inability of models to predict structural changes and the penetration of new technologies. We argue that four key features need to be adequately addressed when modelling long-run economic changes at the macro-level, with particular relevance for climate change analysis. First, in projecting economic systems one needs to first consider their behaviour in the past. Second, the channels of international transmission and the increasing economic interdependence across markets and countries have to be incorporated. Third, there is a need for explicitly modelling the effects of endogenous technological change on economic systems. And fourth, which is the focus of our future research, our understanding of the uncertainties underlying the projections should be explored to avoid misleading deterministic solutions based on the assumed properties of the systems.

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² The research reported in this paper was conducted as a contribution to Work Programmes M2 and S (scenarios) of the ADAM FP6 project (no. 018476-GOCE): Adaptation and Mitigation Strategies: Supporting European Climate Policy (www.adamproject.eu).

1. Introduction

Robust economic growth with all the material wealth that it may bring has been high, if not on top of governments' list of priorities. Since the start of the industrial revolution in the 18th century, the mechanisms underlying economic growth and development have been the subject of intensive debate and research. This paper supports the view that when projecting into the future, it is first necessary to consider the past. The historical features of long-run changes in socio-economic systems need to be identified and understood when undertaking long-run scenario work.

Understanding why some countries are more economically successful than others and what would the ingredients for sustained economic growth be have since long preoccupied both researchers and policy makers alike. Theories of economic growth have increased in complexity and variety over time in order to explain the dynamics of national and global economic systems. Economic theories have evolved from the classical school, with a pessimistic view on the long run sustainability of growth (that was argued to reach a stationary, stagnant state in the long-run), to the marginalist revolution of the 1870s and the emergence of neo-classical economics (acknowledging sustained growth through sustained technical change) with its heavy emphasis on the analytical apparatus and abstract mathematical reasoning that continues to significantly influence important strands of modern growth theories. The neoclassical growth framework with its emphasis on factor inputs, factor accumulation, and equilibrium has given rise to supply-side modern economic growth theories. These date back to Solow (1956, 1957) attributing economic growth to changes in labour and capital inputs and exogenous technological progress, and developing later into endogenous growth theories (where total factor productivity is in turn determined by a series of other factors), particularly through the contributions of Romer (1986, 1990), applied in neoclassical growth models or in computable general equilibrium models (with their emphasis on inter-temporal optimisation).

In parallel, a contrasting theoretical approach (that we adopt in this paper) is that economic growth is demand-led and supply-constrained arising out of increasing returns which engender technological change and diffusion (i.e. waves of investment in new technologies) (Young, 1928, Kaldor, 1957, Setterfield, 2002). The demand-led approach views economic growth as an open-ended process that proceeds

unevenly, is constantly subjected to shocks, and is rooted in actual history.³ This approach rejects general equilibrium as an appropriate concept and methodology for understanding the dynamic processes of economic growth; it also underlies the agent-based modelling of the complexity economics proposed by Beinhocker (2006) as an alternative to traditional equilibrium economics. The world economy is a complex adaptive system, with the attractors of complexity theory (because the system as depicted in Figures 1 and 2 clearly exhibits boundaries to the annual growth rates) which prevent growth being sustained at either high or low levels relative to the historical average. The economic, social and political responses involved are likely to include: monetary policies raising interest rates in responses to inflation and political responses to widespread unemployment.

Non-economic approaches to explaining economic change have also emerged mostly as a response to the various shortcomings of the economic growth theories, particularly those drawing on the neoclassical/neoliberal framework, in accounting for historical social change when investigating economic growth processes. For example, a historical and sociological approach emerged in the 1970s under the label of world-systems analysis and its subsequent qualifications and improvements that views growth processes within a one-world capitalist system of complex economic exchange inter-relationships dominated by an endless desire for capital accumulation by competing agents and a fundamental and institutionally established dichotomy of capital and labour (Wallerstein, 1974, 1980, 1989, Amin et al, 1982). Other approaches to the analysis of economic change have instead emphasised the cultural dimension, asserting that economic growth is not only market driven but also culturally embedded (Benton 1996). However, these approaches seem consistent with the view we adopt of the economy behaving as a complex adaptive system, subject to cultural and other institutional norms and laws.

We apply our historical approach to modelling economic systems within the context of projecting economic growth and the impact of dynamic shifts in the composition of output on CO₂ emission trends. This is because long-run economic growth backed by conventional technologies within the context of an increasing population and escalating demands for goods and services are exerting an unprecedented pressure on the environment, particularly in the last couple of decades. At a global level, climate change and global warming represent a critical issue and a major challenge

³ In this sense, Kaldor (1972, 1985) and Robinson (1962) were amongst main contributing economists to expose the weaknesses of the neoclassical orthodox economic theory in terms of emphasising the gap between history and equilibrium, or between historical and logical time.

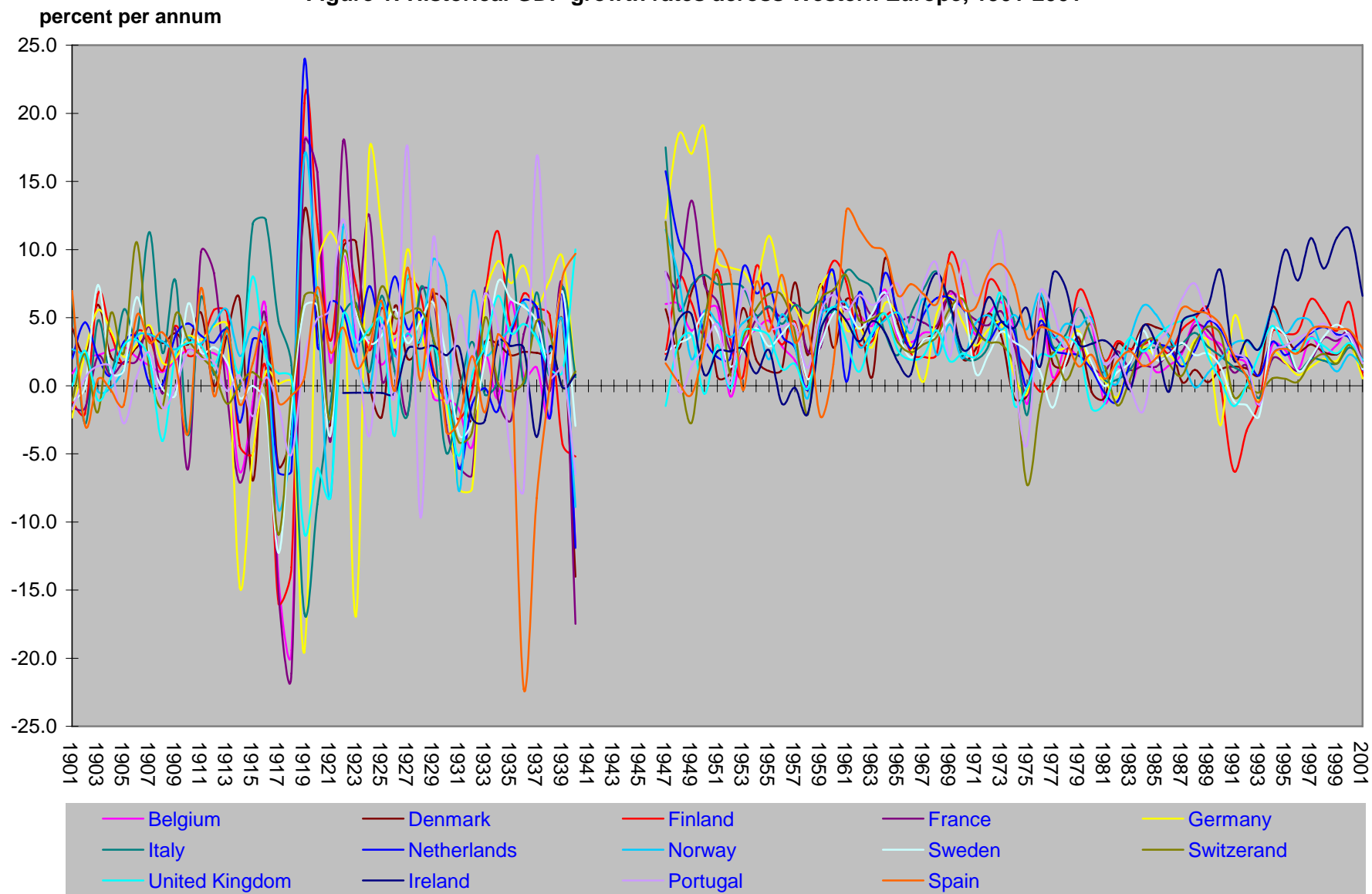
for societies and the world economy, especially within the context of emerging fast-growing large consuming developing societies, such as China and India. The study aims to contribute to the literature mostly from the methodological perspective of investigating (century) long run future changes in economic systems of particular relevance for climate change analysis. The paper not only projects the dynamics of the global economy, but also assesses co-movements between economic activities and CO₂ emissions, with an emphasis on technological change and diffusion.

The paper is structured into five sections. The following section briefly discusses key features that may be associated with long-run economic growth. Section 3 undertakes a review of the literature projecting economic growth trajectories. The methodological approach in projecting the global economic system with application to output-emissions interactions including relevant results are put forward in section 4. Section 5 concludes and identifies crucial areas for future research.

2. A note on the historical features of long-run economic growth

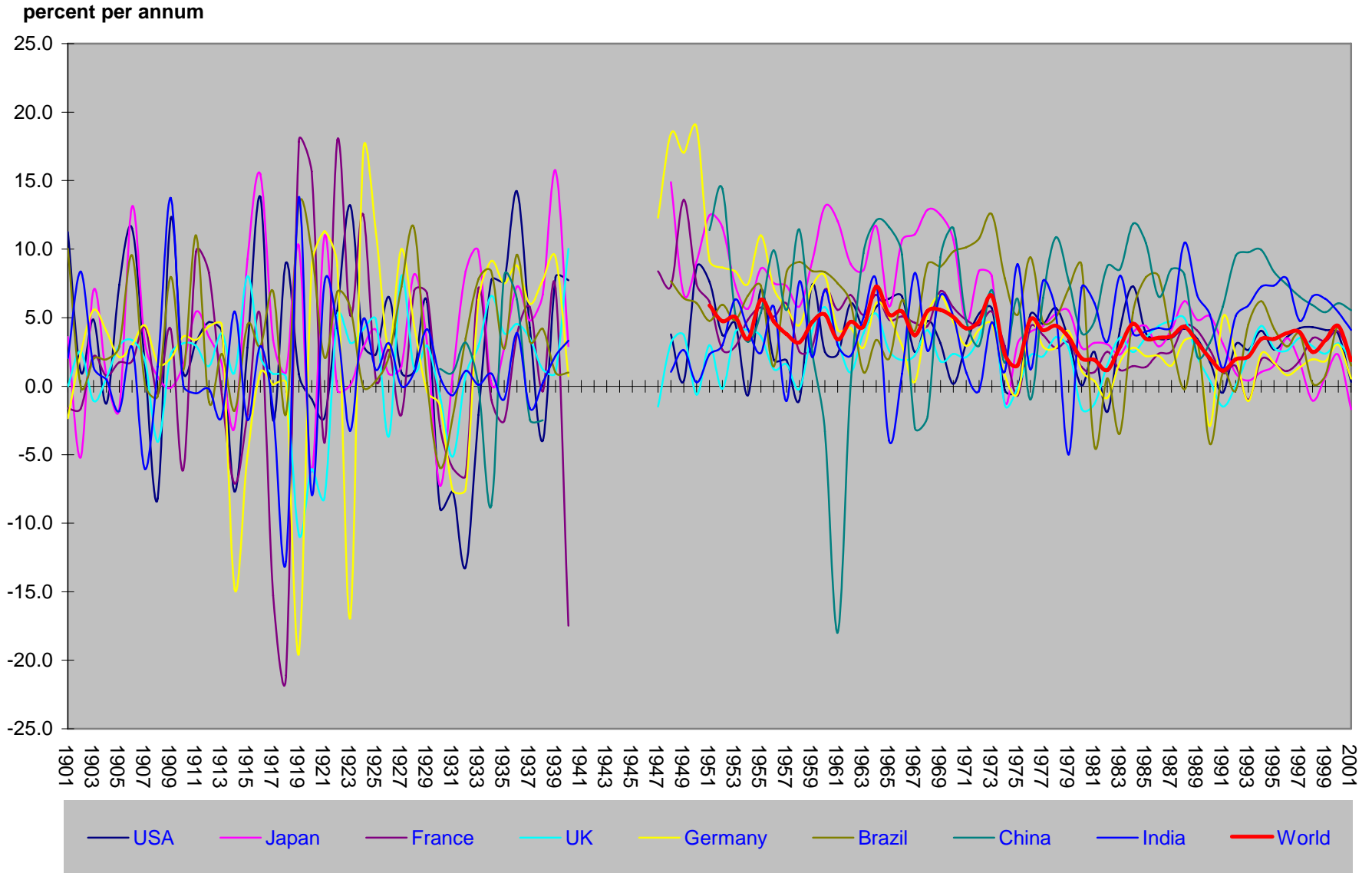
Looking at the historical data for economic growth over the past 100 years, socio-economic systems have been displaying ongoing fundamental change rather than convergence towards an equilibrium state. Any steady-state equilibrium of economies has been at most temporary, whereas open-ended transformation appears to be the norm of economic growth processes. The historical data shows that economic growth across countries and regions is highly volatile and subject to dynamic disequilibrium forces. The growth process across Western Europe, for instance, in the first half of the twentieth century has proceeded unevenly and has been grounded in substantial instability (see Figure 1). However, there is greater evidence for convergence and more stable growth rates in Western Europe since 1950. This may be largely due to post WWII co-efforts for reconstruction and the emergence of the European single market and union project, highlighting, amongst others, the importance of international cooperation and multilateral institutional support for inducing economic convergence and sustained economic growth across countries. Nonetheless, when one looks across the globe, volatility in growth rates is far greater and there is little evidence of worldwide convergence, even though there are limits to the variation in economic growth rates (see Figure 2a). Figure 2b is a continuation of figure 2a containing GDP projections to 2100 for the selected economies across the globe, which will be discussed in section 4.1.

Figure 1: Historical GDP growth rates across Western Europe, 1901-2001



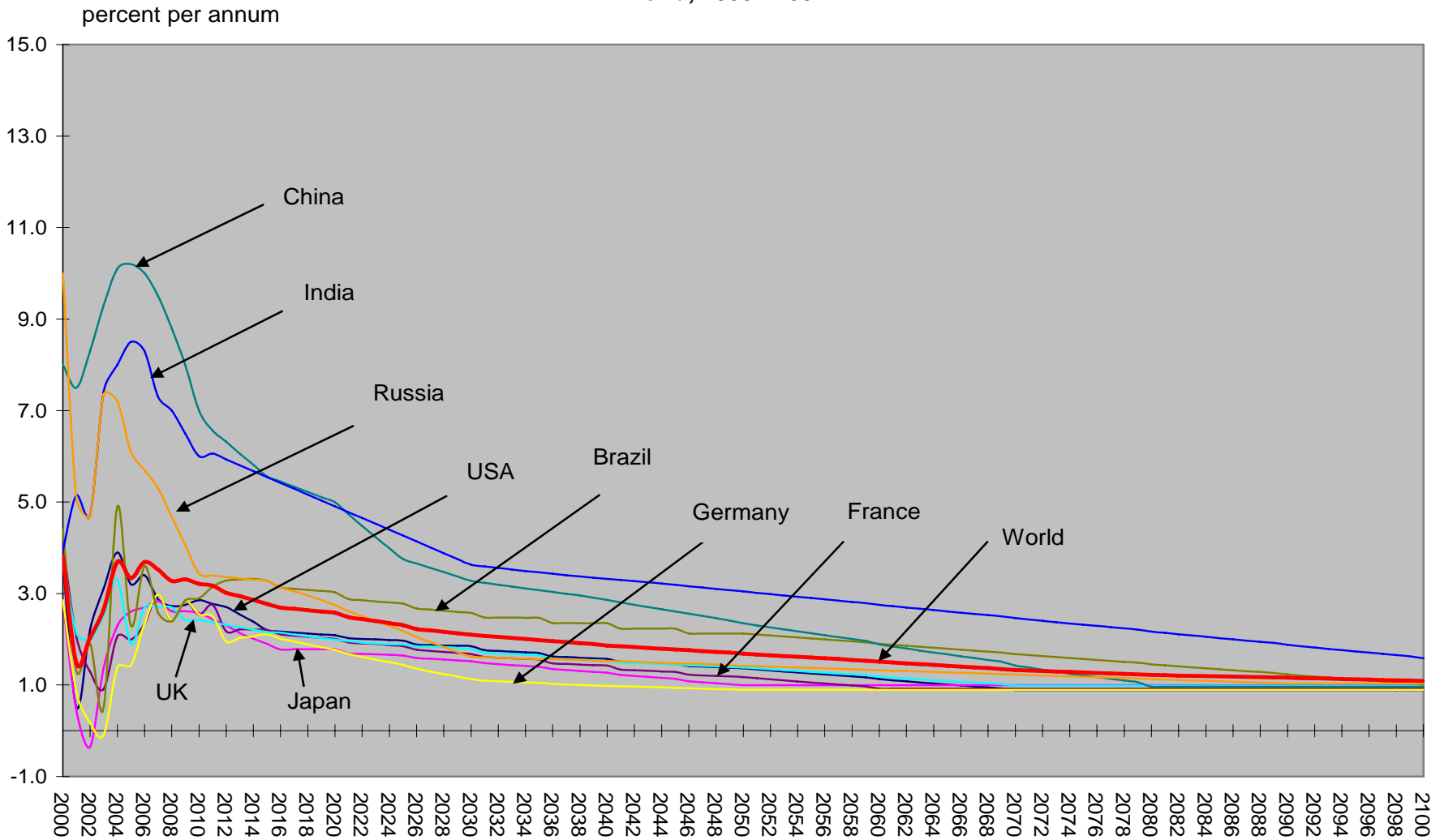
Source: based on data from A. Maddison (2003) "The World Economy: Historical Statistics", OECD, CD-ROM

Figure 2a: Historical GDP growth rates across selected economies throughout the world, 1901-2001



Source: based on data from A. Maddison (2003) "The World Economy: Historical Statistics", OECD, CD-ROM

Figure 2b: Long-term projections of GDP growth pathways across selected economies throughout the world, 2000-2100



Source: based on historical data up to 2006 and on projections thereon sourced from a combination of GVAR modelling, neoclassical growth modelling as in Poncet (2006) and expert opinion

The underlying causes of the large variations in growth rates across countries and across time have been the subject of voluminous analysis in the economic growth literature. Though theory provides systematic explanations of the growth process, these are not empirically validated both across time and across countries. In other words, the empirical evidence insofar does not support unanimously a particular view on the growth process, and a universal and ahistorical explanation of growth does not hold (Kenny and Williams, 2001). However, global economic growth is argued to display distinct common features characterising its ongoing fundamental change, such as diversity across nations and time periods, increasing inequalities and technological progress (Maddison, 2001). With regard to technical change, on one hand, modern economic theories of supply-side (neoclassical endogenous) growth have emphasised the crucial role of human capital accumulation as an underlying source of sustained supply-oriented growth (Romer, 1986, Lucas, 1988, Mankiw et al, 1992), whereas demand-led growth approaches have highlighted the role of gross investment, infused technical progress, and increasing returns in shaping the demand-driven but supply-constrained development of economies (Young, 1928, Kaldor, 1957). Education and training (Lucas, 1988), scientific thinking (Romer, 1990), learning-by-doing (Arrow, 1962), process and product innovations (Grossman and Helpman, 1991), and industrial innovations (Aghion and Howitt, 1992) are all argued to theoretically contribute to technological progress, an increase in product or service quality, and economic growth.

The idea that technological progress associated with research, innovation, learning by doing and increasing returns to scale is a key feature of the growth process have also been supported by empirical studies (Solow, 1957, Denison, 1985, Wolf, 1994, Cameron, 1996). This is not to say that technological change has been the universal driving force of the growth process across time and countries, as the underlying sources of technical change are in turn context-specific and time-bounded. Nonetheless, it may be argued that technological progress linked to the accumulation of knowledge and innovation is a necessary factor, though not sufficient, for ensuring higher long-term growth rates. Furthermore, technological change is important not only for sustained economic growth but also for climate change analysis. This is because on one hand, past and existing technologies have allowed anthropogenic climate change to happen with the large-scale use of coal and oil transforming economies and societies for the last two hundred years, and on the other hand widespread development and deployment of new, low-carbon technologies will be required to mitigate the climate change effects (Barker et al, 2006).

3. Literature review on projecting long-run economic growth

Having briefly discussed key features historically associated with the growth of economies, we now turn our attention to the literature aiming to project growth trends and patterns in the long run, with some discussion about the more voluminous literature on short-term projections and forecasts. The theoretical approach adopted when investigating the historical determinants or patterns of economic growth influences in turn discussions about future growth prospects, particularly in the longer run when one has to make consistent economic judgements. In other words, discussions on future alternative development pathways or scenarios (as in the climate change literature) typically rest on corresponding views on the mechanisms generating economic growth processes, how these are understood, interpreted or assumed to occur.

There are a multitude of methods for projecting GDP growth. Heterogeneity in forecasting models is the norm in the marketplace (Kurz, 2005). For sake of simplicity, we classify these into four categories: statistical methods, neoclassical growth modelling and accounting, macro-econometric modelling, and judgemental assessment or consensus agreement. This taxonomy is not meant to be exhaustive but to provide a brief summary of the literature concerned with GDP projections. The focus of the remainder of this section is on the former three approaches. The underlying logic of the latter methodology is that using a consensus prediction from a group of expert forecasters can improve accuracy and arguably provide a better track record than most of the individual forecasts which make up the consensus, since seldom individual teams manage to consistently outperform the average (Batchelor, 2001).⁴

Statistical methods are typically employed for forecasting (monthly) GDP in the short run based on a large array of time series forecasting techniques. The literature is abundant in short-term GDP forecasting, most of the studies focusing on a particular country. They are less under the influence of particular strands of long-run economic growth theory since their forecast horizon is concerned with business cycles, hence looking at a couple of months ahead and seldom extending beyond 1-2 years (with the exception of statistical filtering that also addresses longer-term growth trends).

⁴ For instance Consensus Economics is one of the main providers of consensus forecasts. They poll 700 economists each month to obtain their forecasts and views on more than 1000 variables from over 70 countries in North America, Europe, Asia Pacific and Latin America, and provide typically 5 and 10 year economic forecasts (see: www.consensuseconomics.com)

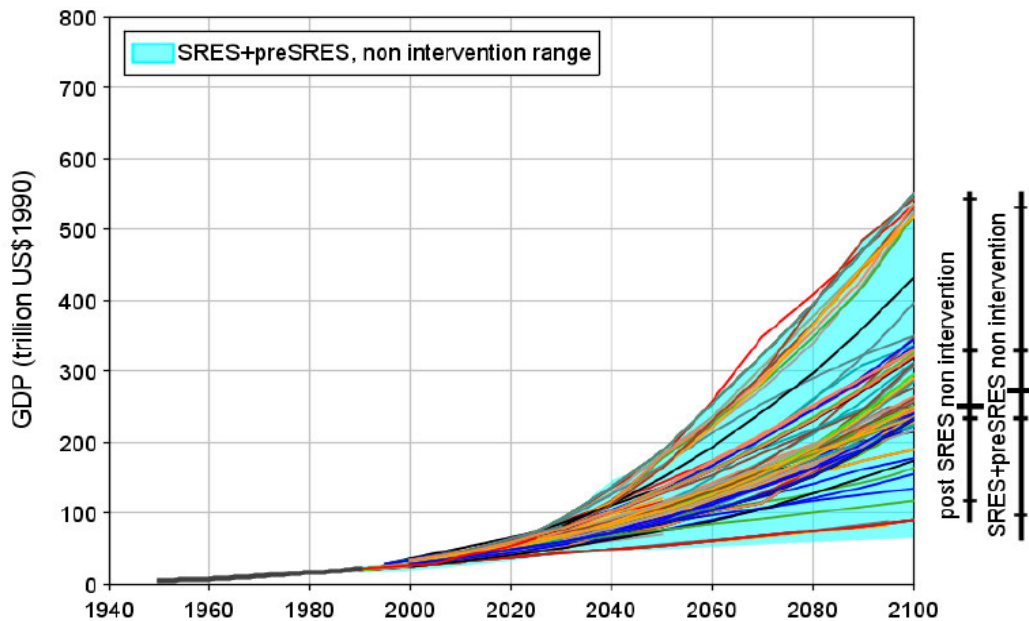
These statistical forecasting methods may account or not for non-linearities between GDP and the variables affecting growth, and include amongst others, vector-autoregressive (VAR) specifications and techniques, statistical filtering, standard and dynamic factor analysis using for instance the principal components estimation approach, artificial neural networks and static or dynamic genetic programming.

Linear regression models, often referred to as indicator-based models, have been widely employed in the literature on short-term forecasting of economic activity. They impose very few restrictions on the relationships between variables, aiming to find patterns and economic explanations in the large amount of data with which they are provided (Demiroglu and Salomon, 2001, Petersen, 1997). These indicator-based models tend to mechanically extrapolate past relations between GDP growth and the chosen input data in the form of leading (business cycle, financial and monetary) indicators affecting real economic activity. These may provide accurate estimates in the short-run particularly for stable economies (Sédillot and Pain, 2005) as economic systems are less likely to be affected in the short-term by unforeseen shocks, though longer-term forecasts are less reliable. Indicator-based models have often been undertaken by central banks aiming to forecast business conditions and anticipate changes in business cycles mostly at the country level (e.g. Stockman and van Rooij 2000, Mourougane, 2006). They rely mostly on univariate or multivariate statistical techniques such as single equation OLS, VAR or factor analysis for extracting the leading indicators. Furthermore, statistical filtering techniques are often applied to improve the accuracy or frequency of short-term forecasts (Mitnik and Zadrozny, 2004) or extract longer-term growth trends (French, 2001). For instance, the DG ECFIN of the European Commission employs a dynamic factor analysis approach (enhanced with data filtering) to forecast quarterly GDP growth in the euro area over a period of usually three quarters (Grenouilleau, 2004). The author's factor model is based on the Stock and Watson (1988, 2002) methodology and used to extract and consistently estimate (using the principal components analysis) common unobserved factors reflecting the business cycle from large underlying time-series data. The IMF (2007) also uses dynamic factor models for extracting unobservable common elements from the co-variance of observable macroeconomic time series across countries to forecast economic activity for world economies. Factor analysis is argued to represent a powerful tool for disentangling noise from signal in very large number of series and to outperform traditional forecast models based on regression on a few leading indicators selected according to their goodness of fit, which are unstable and include a great deal of noise (Camba-Mendez et al, 1999, Grenouilleau, 2004).

Non-linear forecasting statistical methods (such as threshold auto-regressive models or self-exciting threshold auto-regressive models using artificial neural networks) are argued to display superior forecasting performance relative to the linear models, due to their ability to relate GDP to business cycle fluctuations where asymmetric behaviour is a stylised fact (Kiani, 2005). Tkacz and Hu (1999) also account for non-linearities using neural network models to investigate the GDP forecasting performance of financial and monetary leading variables. The authors find that, at a four-quarter horizon, the improved forecast accuracy of this non-linear technique is statistically significant and thus fares better than its linear counterpart. In other words, linear regression models are not adequate for assessing the impact of monetary policy or any other shocks on GDP in countries where business cycle asymmetries prevail (e.g. OECD economies) (Kiani, 2005). However, the forecasting supremacy of non-linear models over their linear counterpart is not evident and has been disputed in other studies demonstrating that the sometimes excellent in-sample fit of non-linear models on real business variables does not mirror itself in excellence of out-of-sample forecasting (Crespo-Cuaresma, 2000, using self-exciting threshold auto-regressive statistical methods).

Though statistical methods tend to deal with short-term GDP forecasting, other approaches such as the neoclassical growth models and macro-econometric modelling containing economic judgements of growth processes are better suited for long-term projections. However, though there is a great need for century-long term projections of economic systems particularly for energy and environmental impact analyses, these are seldom available in the literature, the "long-term" in economic analysis usually referring to 10-20 years of projections (Nakićenović et al, 2000). An exception is the set of long-run projections of GDP at the global level provided in the IPCC's 2007 Report (Fisher et al. 2007), reproduced as Figure 3. These compare new "business-as-usual" (non-intervention) economic growth pathways with those employed in IPCC's previous analysis of the determinants of the world's climate change throughout the 21st century. Likely long-term economic development trajectories across the globe are essential for understanding and projecting future greenhouse gas emissions. These economic growth pathways (one of the most uncertain determinants of future emissions) are largely governed by assumptions related to the pace of future productivity growth and population growth, and to the possibilities for development catch-up and income per capita convergence (Nakićenović et al, 2000).

Figure 3: Comparison of global GDP projections in post-SRES emissions scenarios with those used in previous 25 scenarios



Source: Fisher et al, 2007, p.18

Note: The median of the new scenarios is about 7 percent below the median of the pre-SRES and SRES scenario literature. Two vertical bars on the right extend from the minimum to maximum of the distribution of scenarios by 2100. The horizontal bars indicate the 5th, 25th, 50th, 75th and the 95th percentiles of the distributions

These projections come from a variety of models and methods. The mainstream neoclassical growth (Solow-type) models, placed within optimal growth settings, have been highly influential in providing such GDP projections over the longer term, although it should be stated from the outset that the projections are largely given by assumption. The neoclassical growth modelling approach sometimes referred to as the production function approach due to its focus on the supply potential of an economy (as well as dynamic computable general equilibrium models drawing on neoclassical economic theory and inter-temporal optimisation) are dominated by theory and very poorly represented by data and statistics. They are often poor in dealing with long-term dynamics and economic projections since they assume exogenous long-run productivity growth and technological change (Nakićenović et al, 2000). CBO (2004) employs, for example, a Solow-type neoclassical growth model that attributes the growth of U.S. real GDP to the growth of labour, capital, and technological progress (total factor productivity), and extracts the trends in the labour and productivity components by using a variant of Okun's law (the inverse relationship between the size of the output and employment gaps).

Related to neoclassical growth models are the growth accounting approaches that use available indicators to develop forecasts of GDP components and then aggregate the components. Khan (1996) adopts a labour productivity growth accounting approach, modelling potential output for the U.S. economy as a function of cyclically-adjusted labour and labour productivity. A (Cobb-Douglas) production function or neoclassical growth approach is also adopted by the European Commission to calculate potential output and provide medium term growth projections for the euro area extending three years beyond the short-term forecast (Roeger, 2006). Poncet (2006) assumes as well that economies may grow either by deploying more inputs or by becoming more efficient. Though econometric estimation is employed to describe physical capital accumulation and a generalised catch-up model of technological diffusion, the author's resulting economic output long-term projections are mostly driven by the imposed rate of technological progress, the underlying neoclassical growth theoretical structure and tractable mathematical relationships with their associated sets of strong assumptions. Hence, neoclassical growth models tend to be calibrated theory models where all relationships follow from theoretical derivation, and parameter values are seldom based on estimation of the system (Solheim, 2005).⁵ For instance, assumptions that may not be consistent with the data considered in these models may include: the functional form of the production technology, constant returns to scale, exogenous technological progress, and full employment at the global level (or guess-estimates of the slack in the labour market and of the natural rate of unemployment).

More generally, the production function approach is beset with fundamental problems of interpretation and validity. The most telling is that the capital stock is essentially so heterogeneous that it is impossible to measure with any meaning in aggregate. The problem led to the Cambridge re-switching controversy of the 1950s with the Cambridge UK argument being that the relationship between the capital-output ratio and the rate of profit is not identifiable. However the problem persists in any aggregation of capital (Garrison, 2006). In effect the micro-production function (which is itself highly complex and must represent the dynamic irreversibilities inherent in the chemical and engineering processes of production to be feasible) cannot be meaningfully aggregated (Felipe and Fisher, 2003). Indeed, the estimated

⁵ However, some recent modelling work attempts to combine the modern theory of supply-side economic growth with econometric estimation and trend analysis (see for example the Formel-G model developed in Bergheim, 2005, for Deutsche Bank)

production function used in the growth literature discussed above is no more than an approximation to an accounting identity at the macro and sectoral levels (Felipe and McCombie, 2005). They show that the underlying estimated and guess-estimates are reporting apparent, not real, constant returns to scale since the method adds no extra empirical content to the identities such that the results could equally come from quasi-randomly-generated data.

Macro-econometric models include simultaneous econometric modelling that allows for the specification of full simultaneous systems of equations describing the behaviour of economic variables and economic relationships. They draw on statistics and economic theory, thus benefiting from both the advantages of time-series modelling in terms of parameter estimation and data consistent relationships among variables and equations in the system, and the advantages of providing economic explanations backed by relevant economic theories. Though macro-econometric models have been at times dismissed simply on the grounds that they cannot predict the future (Solheim, 2005), they are arguably relatively more adequate to project economic activity and undertake scenario work (particularly in the longer term) relative to pure statistical methods on one hand, or to growth models, on the other hand, which are highly reliant on theory and mathematical relationships. Nevertheless, the improved performance of macro-econometric models has historically depended on and has been inextricably linked to developments in time-series analysis (e.g. autocorrelation, co-integration, structural breaks, time-varying parameters) (Granger and Jeon, 2003). Though the use of macro-econometric models has become relative scarce compared to previous decades (Granger and Jeon, 2003),⁶ there is an important potential for a revival of this modelling approach, particularly with the increase in data availability for an increasing number of variables across time, countries, and industries, and with the accelerated expansion of computing power modelling and simulation.

The paper exemplifies this potential through the long-term modelling of co-movements between economic growth, energy use, technological change, and CO₂ emissions. For this purpose, it employs innovative large-scale econometric modelling techniques with dynamic structures that are discussed in the following section.

⁶ Granger and Leon (2003) provide several reasons to the decline in the academic interest in large macro models: disappointment with the results obtained, their long presence in the literature and the gradual disappearance of an interest in this modelling methodology, and a decline in the availability of research grants to enable the formation of research teams to undertake large-scale model building (the latter taken from Klein in Mariano, 1987).

4. Methods and results

The paper is mainly concerned with long-term projections of changes in the structure of economic activity and their emission consequences on a global scale. The long-term is necessary because climate change analysis considers emission pathways typically by 2100. The international-global dimension is also crucial since undoubtedly, the economic world is characterised by increasing international interdependence, and national economies and markets need to be placed within a global perspective. In addition, climate change is a global environmental phenomenon in contrast to most other environmental impacts that tend to be local and space bounded. This invariably means that many different channels of transmission must be taken into account. We are therefore presented with the task of modelling complex high dimensional systems. However, judging from the literature review discussed in section 3, studies forecasting economic growth trajectories mostly focus on the short term (particularly the statistical methods), with some exceptions amongst neoclassical growth inspired or macro-econometric models looking at the medium to long term, albeit rarely exceeding a 50-year horizon (e.g. Poncet, 2005 projects GDP up to 2050). In other words, there is a need for consistent methodological tools to capture potential century-long economic development pathways and their implications for greenhouse gas emissions.

We propose an innovative approach in modelling the long-term economic output-emissions links based on a large-scale macro-econometric dynamic model, which is both 20-region and 42-sector specific (E3MG). It is a simulation model with an open structure such that labour, foreign exchange and public financial markets are not necessarily closed. Formal national accounting identities are imposed on the solutions and co-integration econometric techniques are deployed to identify long-run trends from panel data analysis of the global system spanning the period 1970-2002. 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).⁷

4.1 Projecting business-as-usual GDP growth

Although GDP is endogenised in the E3MG model, a business-as-usual long-term projection of economic activity is initially assumed within the respective modelling framework. The assumption is necessary because the model has not yet been fitted

⁷ Also see www.camecon.co.uk/e3me/intro.htm

as a system to the historical data, but has only been fitted as sets of independent equations. For the purpose of developing long-term projections of total economic output across the major countries and regions modelled, we have linked a global vector auto-regressive model (GVAR) with projections in the literature, particularly those from the neoclassical growth work of Poncet (2006) and expert opinion.⁸

The GVAR model represents an alternative approach to modelling international transmission channels and global economic interdependence. The other main method of modelling international transmissions is based on latent factor models, estimated by the use of principal components and popularised by Stock and Watson (2002). The factor models highlighted in the literature review in section 3 are generally used to summarise by a small set of factors a large empirical content of a large number of variables. Although unobserved factor models have important applications in forecasting, the identification of factors is often problematic, especially when we wish to give them an economic interpretation. In addition, no application to the global economy is yet available.⁹ The GVAR modelling approach initially proposed in Pesaran et al (2004) and further developed by Dees et al (2007) uses instead trade-weighted observable macroeconomic aggregates and financial variables to model global inter-linkages.¹⁰ The model hence bridges the gap between pure statistical analyses and macroeconomic modelling approaches that is capable of providing (to some extent) economic interpretations to business cycle co-movements in the world economy based on time-series developments. In particular, it provides a theoretical framework where the GVAR is derived as an approximation to a global unobserved common factor model¹¹ that is able to account for various global transmission channels (e.g. financial linkages).

GVAR estimates and projects dynamics of the world economic system that links exchange rates, interest rates, oil prices, and GDP variables across markets and countries to account for increased economic and financial integration. A more recent version of GVAR (used in our GDP forecasting) also tests and imposes (where

⁸ The construction of the GDP baseline up to 2100 has been undertaken mostly under the auspices of the **ADaptation And Mitigation Strategies Supporting European Climate Policy (ADAM)** project, funded by the European Commission and co-ordinated by the Tyndall Centre for Climate Change Research in the UK. See www.adamproject.eu for details.

⁹ Recently Bernanke et al (2005), and Boivin and Giannoni (2006) have considered including the estimated factors as additional variables in VAR models, the so called Factor Augmented vector auto-regressions (FAVAR). However, the approach has been applied only to the US and not at a global level.

¹⁰ Trade weights are based on 1999-2001 period and provide a snapshot of the inter-relations in the global economy. The results are not sensitive to the choice of the weights.

¹¹ An example of a common global unobserved factor that may influence the international transmissions of business cycles is the diffusion of technological progress. An example of a common global observed factor producing global shocks is the change in oil prices.

applicable in terms of passing econometric tests on validity) long-run structural relationships, suggested by economic theory, in industrialised economies plus China, with a particular focus on interest rates, real output, inflation and exchange rate prices (see Dees et al, 2007a, for further details).¹² While long term properties of the model are based on market arbitrage and stock-flow equilibrium conditions, the short run dynamics are left unconstrained. The model consists of 26 countries, with the Euroarea being treated as a single economy, over the period 1979-2003 (on a quarterly basis). Using average pair-wise cross-section error correlations, the GVAR approach is shown to be quite effective in dealing with the common factor interdependencies and international co-movements of business cycles to include output, inflation, interest rates and real equity prices. The GVAR links vector error-correcting models in which core domestic variables are related to corresponding country-specific (i.e. trade-weighted) foreign variables, which are taken to be weakly exogenous for estimation purposes, an assumption found acceptable when tested. First, the individual country models are estimated, after which all endogenous variables (i.e. country-specific variables) of the global economy are solved simultaneously.¹³

However, the GVAR model features several limitations when projecting GDP over the longer term. First, it proved that without any conditioning on assumed projection paths for particular variables, the model projected dramatic declining oil prices (largely based on the downward trend over the period 1979-2003), e.g. below 20 \$/bbl by 2050. Oil prices have nonetheless increased considerably in the years after 2003 and are projected to further increase in the longer term. Second, GDP projections for some countries proved unrealistically high, as in the case of China, India and the Newly Industrialised Countries (e.g. Korea, Malaysia, Singapore, Thailand), again mostly because of recent historical trends. And third and most importantly, the stochastic trends in the GVAR model mean that the variance of the forecasts increases at a rate proportional to the forecast horizon. Forecasts themselves are likely to have large standard errors which will increase with the projected horizon. This in turn implies that such a model is more suitable for short

¹² Among the relationships considered are the purchasing power parity (PPP) relation, the term structure condition that involves the vertical spread of the yield curve being stationary, the uncovered interest parity condition, and the Fisher equation.

¹³ With the exception of the US model, all individual country models include the country-specific foreign variables: real output, rate of inflation, real equity prices, short- and long-term interest rates, and oil prices as weakly exogenous. In the case of US, oil prices are included as an endogenous variable with real exchange rate, real output, and the inflation rate as weakly exogenous. Given the importance of the US for the global economy, the US specific foreign financial variables (interest rates and equity prices) were not included in the US model as they are unlikely to be long-run forcing on the domestic counterparts (Dees et al, 2007a).

rather than long horizon forecasts. These shortcomings of the GVAR approach led to the adoption of GDP forecasts for our business-as-usual growth scenario only over a short-term horizon, i.e. from 2007 to 2010, conditioned by assuming specific projection growth paths for global oil prices¹⁴ and for the GDP of particular economies, for which the growth process was in our view not realistically being projected.¹⁵ The short-term GVAR projections were also conditioned on the 2004-2006 updated oil prices and GDP growth rates for all the 26 countries/regions incorporated in the model to account for recent developments in economic output.¹⁶

Our business-as-usual growth scenario up to 2100 further soft-links GVAR projections with results from a neoclassical growth study undertaken in Poncet (2006) and used by the POLES model¹⁷ as an input for the European Commission's World Energy Technology Outlook 2050 (WETO-H2) baseline scenario,¹⁸ as well as with expert opinion on century long-run economic trajectories.¹⁹ This led to the formulation of a GDP baseline consisting of: economic growth rates obtained from GVAR over the period 2007-2010; a moving average between the GVAR forecasts and the WETO-H2 projections from 2011 until 2015; the adoption of growth paths largely from the WETO-H2 baseline for 2016-2050; and our expert opinion on long-term growth rates thereafter up to 2100. The results have been displayed in Figure 2b above at a global level and for major economies over the period 2000-2100. The decline in growth rates in the long term after 2050 is largely attributed to a slowing down of rural to urban internal labour migration, particularly for developing countries. An exception is India (and other parts of the developing world), where based on extrapolating past trends there appears to be sufficient potential for rural to urban labour migration to fuel relatively higher economic growth rates up to 2100. In other words, in contrast to historical growth rates displayed in Figure 2a (and

¹⁴ Nominal oil price projections were sourced from the POLES model used in providing projections for European Commission's WETO-H2 baseline. For a detailed description of the POLES (Prospective Outlook on Long-term Energy Systems) model see: <http://webu2.upmf-grenoble.fr/iepe/Recherche/Recha5.html>

¹⁵ These include China, India and newly industrialised countries (e.g. Korea, Malaysia, Singapore, Thailand), for which GDP growth rates consistently came out very high, and Argentina and UK, for which GDP growth rates proved consistently low (even reaching negative rates by 2015).

¹⁶ In addition, as GVAR only has an aggregate of the Euroarea, some soft links with the Cambridge Econometrics macro-econometric model E3ME have been developed to obtain the GDP projections for each individual member of the Eurozone.

¹⁷ The POLES model developed at ENERDATA / LEPII-EPE, Université Pierre Mendès France is a world energy sector simulation model aimed at projecting the world energy system to 2050 under various constraints and climate policies. See European Commission (2006) and Criqui and Kitous (2003) for model description.

¹⁸ See European Commission (2006) for a discussion of the GDP forecasts used in the WETO-H2 baseline. The neoclassical growth model in Poncet (2006) was developed at CEPII in France and assumes exogenous technological change and explicit consideration of human capital.

¹⁹ Century long-term future scenarios have been particularly developed with the context of the ADAM project on climate change adaptation and mitigation for Europe involving several researchers from several institutions.

Figure 2b up to 2006), which have not been showing evident signs of convergence over the last century, we argue nevertheless that some global convergence towards a lower global real GDP growth rate will occur towards the end of the 21st century (see Figure 2b), as rural to urban internal migration flows dwindle worldwide, formal and informal unemployment is reduced, and economies, particularly those of developing countries move towards full employment. Furthermore, a decline in the projected long-term global growth rate may also be argued from the perspective of technological lock-in and dependency path. This is because initially self-perpetuating high relative growth may endogenously create the conditions of a subsequent era of slow relative growth due to the technological lock-in of particularly techniques, the rising obsolescence of maturing technologies, and the decreasing potential for sustained long-term investments that these may embed (Frankel 1955, Setterfield, 1997).

A key caveat is that the projected growth paths displayed in Figure 2b need to be considered within an uncertainty analysis context. Economies are highly complex non-linear systems and it is impossible to accurately determine their future evolution. Each GDP growth trajectory is subject to considerable uncertainty. Nonetheless, we argue that projected economic growth rates may be confined to a limited feasible sub-space of variation, and moreover, the irregularities in each economy's growth paths tend to fluctuate around a particular growth trajectory. This view draws on the chaos theory applied to economics according to which, though economic systems are inherently complex and exhibit chaotic behaviour in an ever changing environment, they tend to oscillate around a defined dynamic structure or "attractor". With regard to projecting economic systems, the chaos theory argues that although future behaviour can not be accurately predicted, the possibility of an awareness of a range of future states is allowed for (Hayward and Preston, 1999). In other words, the business-as-usual growth paths presented in Figure 2b are taken to define such an "attractor" or long-term patterns, providing a reference point or average from which uncertainty analysis may be carried out. Furthermore, the uncertainty range resulting from our approach is likely to be of a lesser magnitude (the feasible sub-space of variation is reduced) compared to the range that may be associated with an approach considering several low and high growth baseline scenarios and attaching uncertainty boundaries to each of these.

4.2 Long-run projections of future growth-emissions interactions

Economic output pathways can be derived across sectors and industries within each country or region being considered in the analysis. This provides not only an insight into how the structure of economies might change in the future, but also a better explanation as to the likely growth-emissions interactions by looking at a more disaggregated sectoral level and acknowledging the varying energy-intensity patterns of different industries within an economy. Furthermore, understanding the dynamics of economic systems is dependent not only on international interactions between national economies but also on inter- and intra-sectoral interactions of the various industries operating within and across economies.

Compared to other existing models aiming to project economy-emissions interactions, the advantages of the E3MG model are found in four key areas. First, the theoretical approach on economic growth and technological change underpinning the model are arguably well suited to tackle economic activity-emissions interactions. E3MG is based upon a Post Keynesian economic view of the long-run. In other words, in modelling long-run changes in economic patterns and technology, the "history" approach of cumulative causation and demand-led growth (Kaldor, 1957, 1972, 1985; Setterfield, 2002), focusing on gross investment (Scott, 1989) and trade (McCombie and Thirwall, 1994, 2004) has been pursued. The role of history in determining future patterns in economic activity and the occurrence of cumulative causation in the context of technological and institutional regimes (Setterfield, 1997) are acknowledged. Other Post Keynesian features of the model include: varying returns to scale (that are derived from estimation), non-equilibrium, not assuming full employment, varying degrees of competition, the feature that industries act as social groups and not as a group of individual representative firms (*i.e.* no optimisation is assumed but bounded rationality is implied), and the grouping of countries and regions has been based on political criteria. However, at the global level various markets are closed, *e.g.* total exports equal total imports at a sectoral level allowing for imbalances in the data. Technological change is endogenously modelled in E3MG, *i.e.* the choice of technologies is included within the model and affects energy demand and/or economic growth (in contrast to exogenous or autonomous technological change imposed from outside the model typically applied in neoclassical growth models). The treatment of endogenous technological

change in E3MG is achieved largely through three main mechanisms (Barker et al, 2006). Econometric estimations to identify the effects of technological change in the form of accumulated investment and R&D on energy demand are employed. The sectoral export demand equations include the same indicators of technological progress, such that extra investment induces more exports and therefore investment, trade, income, consumption and output in the rest of the world.²⁰ And the approach has also been developed to include the bottom-up energy technology model, ETM (Anderson and Winne, 2004), within the top-down highly disaggregated macroeconomic model, E3MG,²¹ which incorporates learning curves through regional investment in energy technologies that depend on global scale economies.

Second, for a global model, E3MG is highly disaggregated, with 20 world regions (including the 13 nation states with the highest CO2 emissions in 2000), 12 energy carriers, 19 energy users (including the energy intensive sectors), 28 energy technologies, 14 atmospheric emissions and 42 industrial sectors, with comparable detail for the rest of the economy. The disaggregation of energy and environment industries is central for capturing the energy-environment-economy interactions. For example, countries and sectors have widely varying emissions characteristics, with transport and buildings being the two largest end-use sources of energy demand. Third, the econometric grounding of the model that consists in a set of dynamic and long-run time-series econometric equations estimated on annual macro-level data 1970-2001 with a base year in 2000 makes it better able to represent and project performance.²² And fourth, 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 only assume a one-way causation. These interactions are achieved through the hybrid modelling of the top-down macro-econometric modelling E3MG and bottom-up energy technology submodel ETM. The latter models in a simplified way the switch between different energy technologies based on the concept of a price effect on the elasticity of substitution between competing technologies (see Anderson and

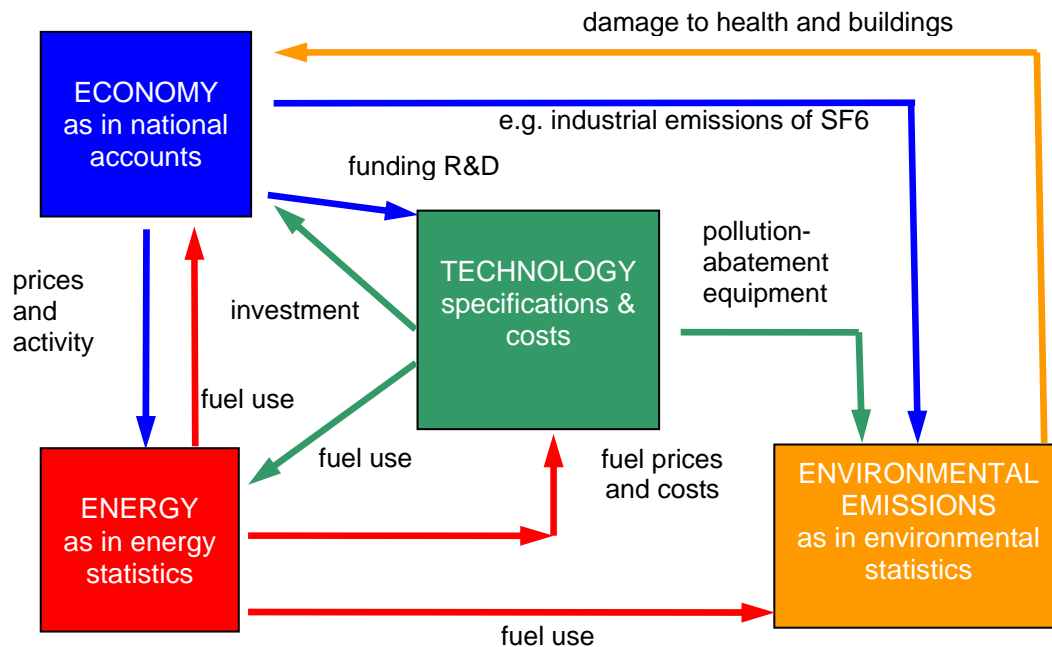
²⁰ The estimations of E3MG's export equations "protect against both spurious correlations (by using cointegration techniques) and the simultaneity between the dependent and the explanatory variables (by using instrumental variables or some other means)" (Barker et al, 2006: 245).

²¹ The advantages of using this combined approach for climate change mitigation analysis have been reviewed in Grubb et al (2002).

²² The E3MG industrial and energy/emissions database is drawn from OECD, IEA, GTAP, RIVM, an other national and international sources and processed to provide 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 supplemented by data on macroeconomic behaviour from IMF and the World Bank.

Winne, 2004 for further details). These energy-economy-environment interactions within the structure of the E3MG hybrid modelling are shown in Figure 5.

Figure 5: E3MG hybrid modelling: engineering E3 Interactions



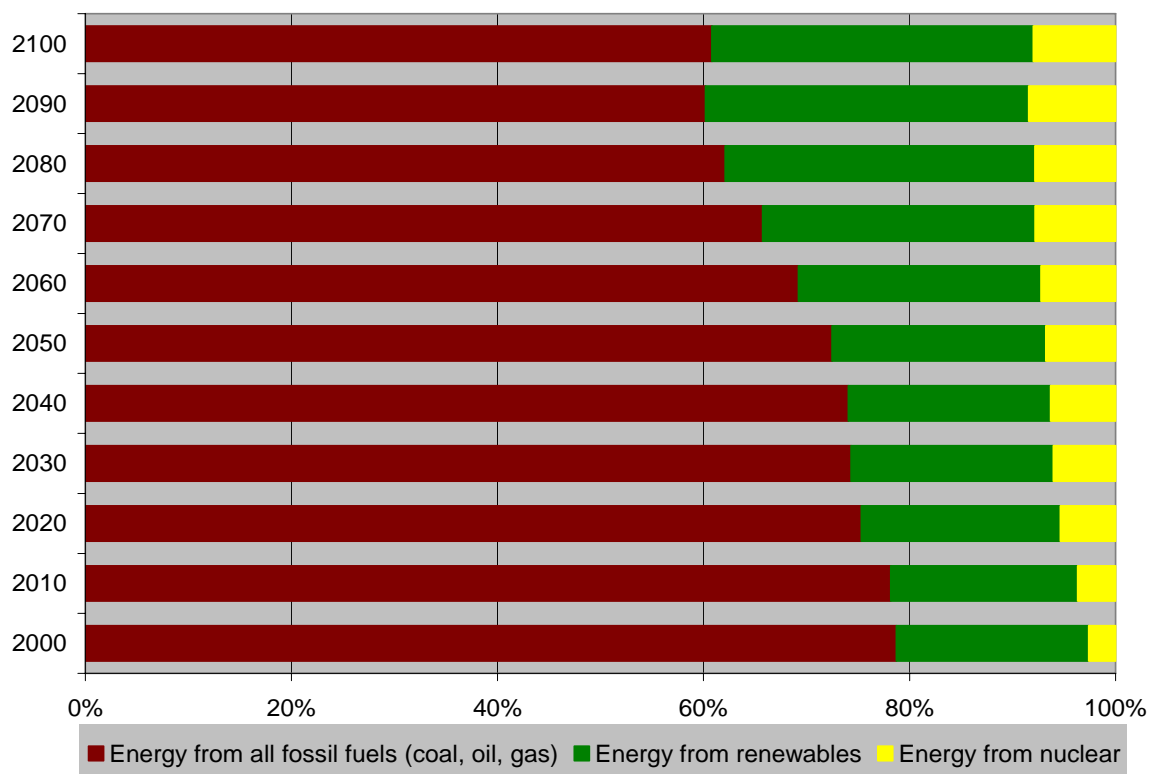
Exogenous inputs in E3MG include the world oil price, regional gas and coal prices, energy supplies, population, participation rates, exchange and interest rates and other fiscal and monetary policies. Though GDP is endogenously determined within the model, E3MG has been calibrated to a set of GDP projections for the business-as-usual case as discussed above in section 4.1. E3MG's sectoral output level projections are consistent with the macro variable totals (i.e. gross value added) so as to maintain adding-up constraints. They allow for the effects of higher long-term energy prices on global and regional GDP and for developments in global time-series modelling.

Shifts in the sectoral structure of economies across time and variations in their energy intensities, technological change and GDP dynamics have key repercussions on global anthropogenic CO₂ emissions. In E3MG these interactions are largely captured through feedback effects between the top-down macro-econometric model

and bottom-up energy-technology (supply) ETM submodel. The novel approach to the E3MG hybrid modelling combining energy technology dynamics and macro-econometrics are discussed in detail in Köhler et al (2006). The energy-technology (supply) submodel calculates investment in energy generation (for the electricity sector) and the shares of the different technologies in new investment, for each of the 20 regions in the model (i.e. energy-supply technologies change through investment). This investment is in turn part of overall demand and is included with gross accumulated sectoral investment in the export equations in the macroeconomic model. The ETM also calculates costs of electricity production, through the learning curves, which feed into energy prices and the energy demand equations in E3MG. These interactions are of crucial importance for projecting CO₂ emissions since they capture likely trends in investments in different energy technologies and future energy demand patterns across key fuel users. Under a business-as-usual setup, the costs of low-carbon emerging energy technologies continue to exceed those of carbon-intensive fossil fuel-based conventional technologies for most of the projected period, though some substitution towards low-carbon options is argued to occur by the end of the century through investment, learning-by-doing and innovation.

E3MG projects that energy technologies based on fossil fuels (comprising coal, oil and gas) will continue to dominate the global economy throughout the 21st century, largely due to the favourable impact that economic activity (consumers' expenditure for household fuel demand), average energy prices and technological progress will exert on fossil-fuel demand relative to the demand for low-carbon options. Nonetheless, the share of energy from all fossil fuel in total energy use is projected to decline from almost 80% in 2000 to around 60% in 2100, whereas energy from renewables (particularly hydro) and from nuclear may increase their share from around 20% to 30%, and respectively, from 3% to 8% (see Figure 6).

Figure 6: Business-as-usual projections of the contribution of energy technologies to total energy use using E3MG, 2000-2100

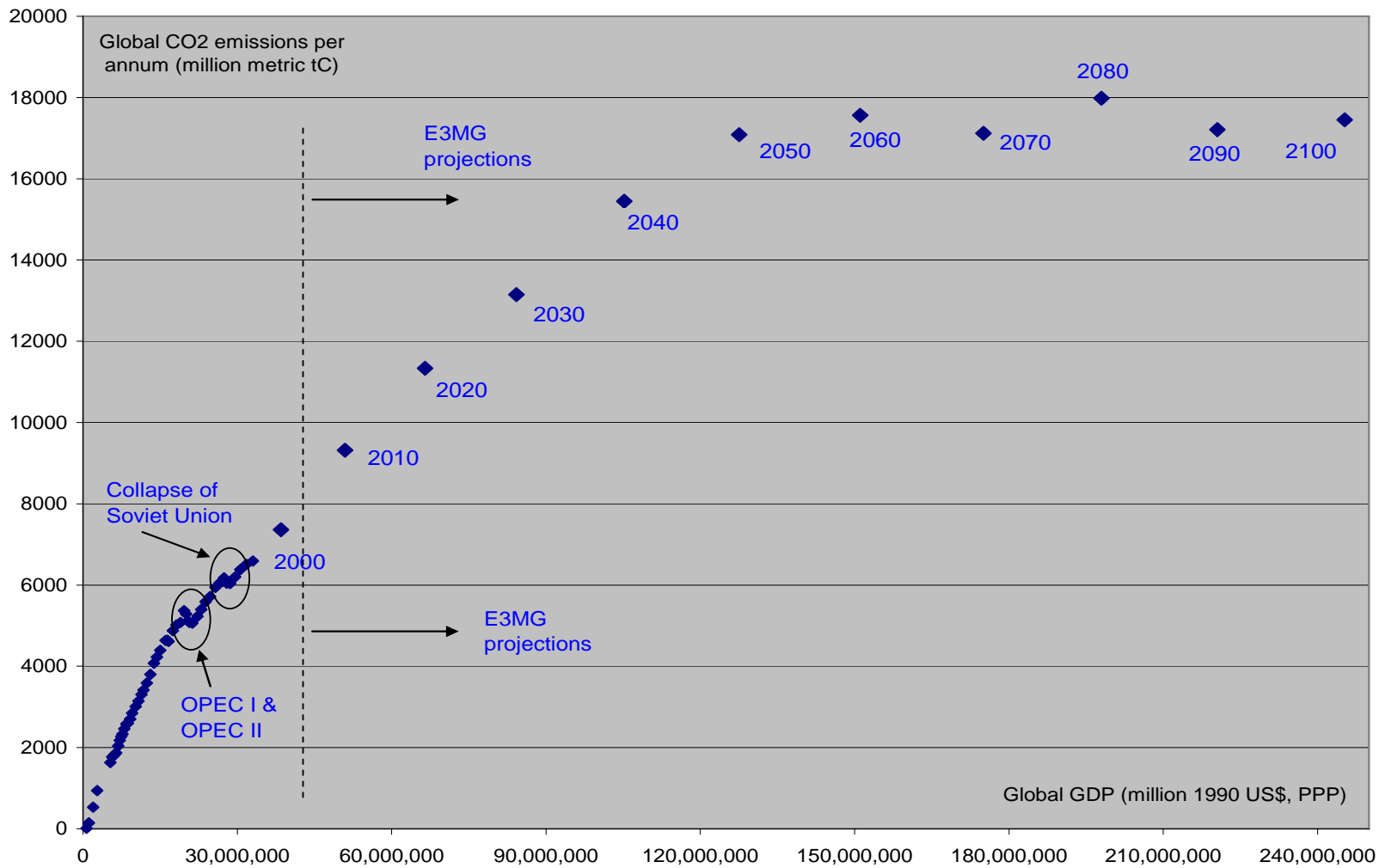


Source: E3MG modelling results

The magnitude and rate of replacement of carbon-intensive technologies with low carbon technologies in a business-as-usual scenario is however far from enough to decarbonise the global economy and avoid dangerous climate change. In other words, relying solely on endogenous technological change, increase in world energy prices, and a process of substitution based on existing trends will not lead to sufficient investment and development of low-carbon technologies to counteract the threatening effects of increased atmospheric concentrations. The annual output of CO₂ emissions from both end-use of different fuels²³ and from primary use of fuels in the energy industry themselves are projected to continue the existing historical trends (captured in the left-hand side of the dashed line in Figure 7, e.g. a 600 percent increase in CO₂ emissions over the period 1913-1997), and increase

²³ Because the fossil-fuel intensive energy and transport sectors are two of the main end-sources of GHG emissions, these are modelled explicitly in E3MG.

Figure 7: Historical (1820-2000) and projected (2000-2100) CO₂ emissions and GDP at the global level



Sources: Tooze and Ward (2005), Maddison (2001) and WRI(2005) for the historical period 1820-1997; E3MG modelling results 2000-2100 (these have been converted from US\$ 2000 MER numbers to US\$1990 PPP numbers to consistently correspond to the units of historical data)

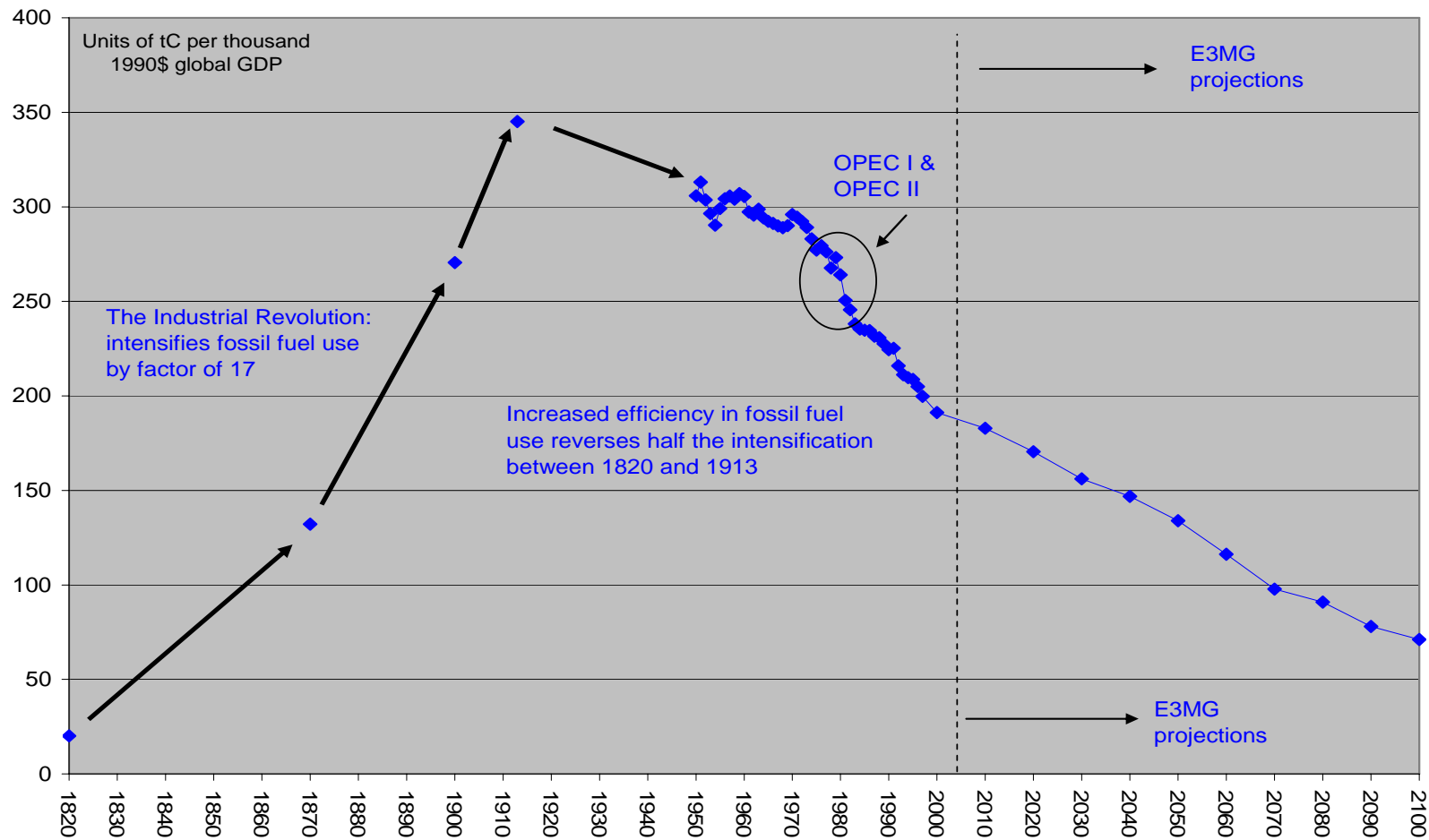
throughout most of the century (at the right of the dashed line in Figure 7).²⁴ Potentially lower annual emissions towards the end of the century may be due to increased efficiency that in the long-run becomes stronger and counteracts the energy demand effects of population and GDP growth, as well as to the long-term decrease in the share of fossil fuels in global energy use.

The intensity of the global economy is also projected to continue the existing historical downward trends in the 20th century (displayed in Figure 8 on the left of the vertical dashed line). The carbon de-intensification historical trends since 1913 are projected to continue over the next century, with carbon intensities further dropping by around 60% by 2100 relative to 2000 levels (see the right-hand side of the dashed line in Figure 8). This may be associated again with a combination of stronger long-term efficiency increases in fossil-fuels sustained by continued investment in fossil fuel-based technologies and the emergence to some extent of low-carbon options.

The projected trends in CO₂ emissions follow in tandem the projected trends for energy use, on the background of a decrease in the energy intensity of the global economy. This highlights the carbon-intensive technology dependency path of the global economy that is likely to prevail in the future in a business-as-usual scenario, where the widespread of new low-carbon technologies is not significantly supported. The slower pace of the decline in energy intensities by 50% by 2100 relative to 2000 levels (from around 290 to 140 toe per million of 2000 US\$ global GDP –see Figure 9) compared to the 70% drop in carbon intensities over the same period further underlines the gradual decrease in the growth of annual output emissions over time. However, from a climate policy perspective the E3MG projected annual output of CO₂ emissions reinforces the need to implement effective global mitigation measures with immediate effect to counteract the potentially disastrous consequences of the corresponding high levels of atmospheric concentrations.

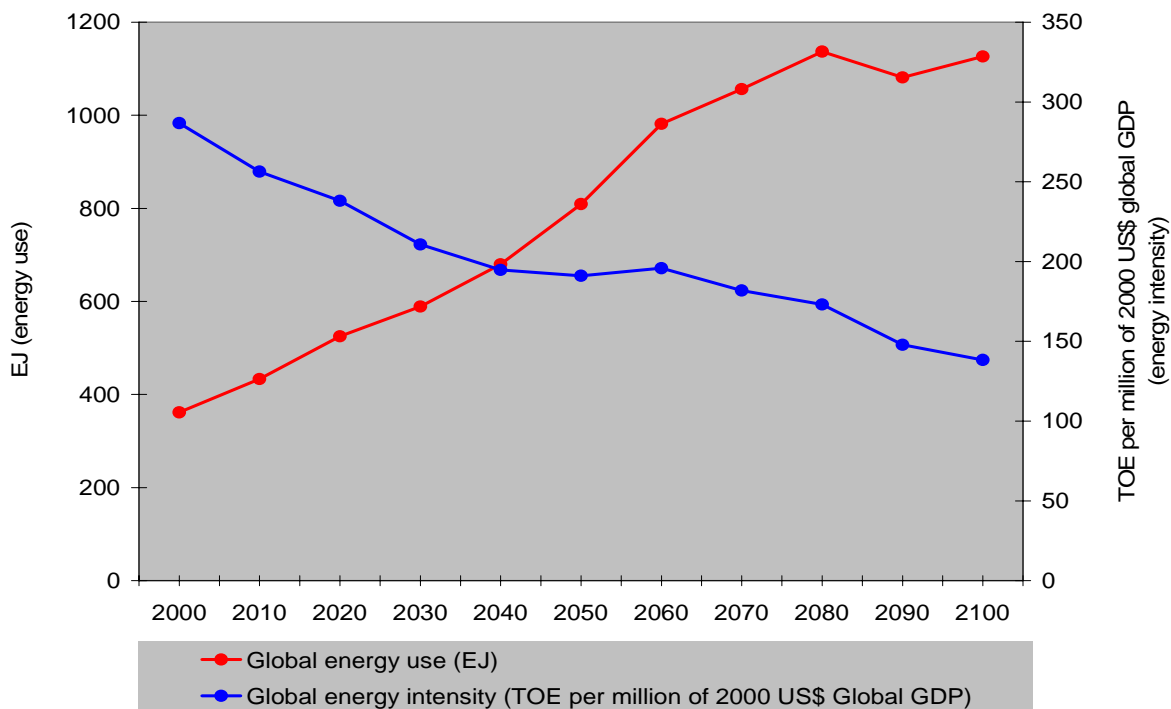
²⁴ The energy component of E3MG econometric estimates of the demand for fuel by fuel user are aggregated into three groups (solid fuels, oil products and gas). However for the full set of 12 fuels emissions data are available and emission coefficients (CO₂ emitted per tonne of oil equivalent) are calculated and stored. The fuel emission coefficients are calculated for each year when data are available, then used at their last historical values to project future emissions. E3MG takes as a point of departure for projecting CO₂ emissions the 2010 values projected by the energy simulation POLES model to account for recent developments and short-term forecasts.

Figure 8: Historical (1820-2000) and projected (2000-2100) carbon intensity of the global economy



Sources: Tooze and Ward (2005), Maddison (2001) and WRI(2005) for the historical period 1820-1997; E3MG modelling results for 2000-2100

Figure 9: Projected global energy use and energy intensity using E3MG, 2000-2100



Source: Based on E3MG modelling results

5. Conclusions and future research

With the emergence of accelerated technical change and progress, the widespread of low-cost information technologies, greater international trade and increased globalisation, economic growth has been exhibiting increasingly complex features. Long-run economic growth backed by conventional fossil fuel-based technologies, within the context of an increasing population and escalating demands for goods and services are exerting an unprecedented pressure on the global natural environment, especially in terms of anthropogenic greenhouse gas emissions and climate change. As such there is a heightened need for long term economic projections into the future spanning 100 years, particularly for climate policy analysis and mitigation.

The literature exploring the likely future behaviour of economies in the very-long term is extremely scarce with GDP projections seldom exceeding a 10-20 year horizon. Also, GDP forecasting has been often undertaken at a country-level with

inadequate consideration of international interdependencies and co-movements between macro-variables within the global economy. In addition, projections of changes in economic systems have been typically given by assumption with a poor representation of dynamics and technological change. This paper has put forward a methodological approach that may be able to more adequately address century-long projections of global economic dynamics. We have applied our approach to the study of the interactions between worldwide economic growth dynamics, structural shifts within economies, technological change and global emissions of carbon dioxide. We found that relying on endogenous (as opposed to policy-induced) technological change, increase in world energy prices, and a process of substitution between competing technologies based on existing trends will not lead to sufficient investment and development of low-carbon technologies to counteract the threatening effects of increased cumulative CO₂ emissions throughout the 21st century.

The emphasis of the paper has been fourfold. First, we have underlined the importance of considering the past, understanding existing trends, and capturing the historical interactions between economies and developments in key factors associated with economic growth. Second, we have highlighted the relevance of incorporating the channels of international transmission and the increasing economic interdependence across markets and countries. Third, we have argued that it is essential that the choice of technologies be included within the model so that it endogenously impacts long-run growth and structural change. Endogenous technological change and diffusion is modelled in our approach through regional investment in energy generation technologies dependent on global scale economies, as well as through accounting for the impact of accumulated investment and research and development on sectoral energy and export demands. And fourth, we have put forward the caveat that all our projections represent at the very best central assumptions on likely future developments in economic growth, energy demand and carbon dioxide emissions. Long-term projections of economic systems should be subjected to uncertainty analysis that investigates the feasible subspace within which the variables of concern may oscillate. This will be the focus of our future research on modelling long-term economic development pathways. Its aim will be to explore and advance our understanding of the uncertainties underlying the projections in order to avoid misleading deterministic solutions based on assumed properties of the systems.

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