Climate change scenarios and long term projections

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Abstract Predictions of future temperature increases depend critically on the projections of future greenhouse gas emissions. Yet there is a vigorous debate about how these projections should be undertaken. This paper explores a range of methodological issues surrounding projecting greenhouse emissions over the next century. It points out that understanding future emissions requires a framework that deals with the sources of economic growth and allows for endogenous structural change. It also explores the role of convergence assumptions and the “Castles and Henderson Critique” of the Special Report on Emission Scenarios (SRES) regarding use of

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Market Exchange Rates (MERs) rather than Purchasing Power Parity exchange rates (PPPs) to benchmark income differentials in the world economy. In the G-Cubed multi-country model, we show that emission projections based on convergence assumptions defined in MER terms, are 40% higher by 2100 than emissions generated using a PPP comparison of income differentials between economies. We support the argument presented by Castles and Henderson, that the use of MERs in the SRES represents a serious analytical error. It is not clear what this means for the SRES projections because the SRES is not transparent in its assumptions. In the G-Cubed model, the error leads to considerably higher emissions projections.

1 Introduction

Forecasting the future evolution of the world economy over a timeframe that is relevant for climate change projections is fraught with difficulty. The crucial starting point for any climate projections are the projections of emissions of greenhouse gases, which themselves depend on the various human activities (mostly, but not entirely, energy related) that generate the emissions. While converting these emissions to temperature and climate change is the domain of atmospheric and meteorological sciences, generating the emission predictions is the domain of the sciences of human activity, most notably economics.

Of the various attempts to generate emissions projections for input into climate models, the IPCCs *Special Report on Emission Scenarios* (IPCC 2000), or SRES, is probably the most comprehensive and visible, and as a result has attracted considerable critical analysis. Some of this critique focuses on the approach to uncertainty adopted by the SRES (see, for example, Schneider 2001). Other aspects of the critique have focused on the apparently high economic growth rates in some of the scenarios and the ways in which this may have emerged (see Castles and Henderson 2003a, b). Indeed, of the many critiques of the SRES, the Castles and Henderson critique has generated considerable public attention through its subsequent publication in relatively popular media.

This paper sets out some of the methodological issues that arise when attempting to project emissions over the long time frames necessary for climate predictions. In particular, we are concerned with: the analytical issues behind designing projections exercises; understanding the sources of economic growth; examining the role of the idea of ‘convergence’ in generating economic growth projections; and considering the role of ‘purchasing power parity’ (PPP), versus market exchange rates (MER) in understanding economic growth and implementing particular convergence models (the basis of the Castles and Henderson critique).

It is, of course, very difficult to predict the long run evolution of global economic growth. The task is made more difficult, particularly in the context of emissions projections, in that it is not just the rate of growth that matters, but the composition of that growth and its geographical location. The same projected rate of aggregate economic growth over the coming century could be associated with a wide range of emissions profiles. The driver is not growth per se, but the sources of that growth.

There are different methodologies for predicting future carbon emissions. One of the key issues in looking forward is how history is understood since this is critical to

Fig. 1 GDP, energy and emissions for US and Japan

different views of how to project the future. Figure 1¹ shows the paths of real GDP (in domestic units), energy use (in BTU) and carbon emissions for the United States and Japan from 1965 to 1990 plotted as an index equal to unity in 1965. A dominant feature of this figure is that emissions, energy use and real GDP tended to follow a common trend until 1972 (although in Japan emissions rise faster than economic growth before 1972). When the OPEC oil price shocks dramatically changed the price of energy in 1972, there was a shift in the relationship with GDP growth continuing on a slightly different trend but energy use and emissions rising much less quickly. How is this historical experience interpreted? In projecting forward it is critical how this historical experience is built into the projections. In our view it is not sufficient to attribute this change to AEEI, but rather to attempt to further decompose and understand it.

In this paper we set out the methodology for undertaking long run projections used in the G-Cubed multi-country economic model. We illustrate how different assumptions about economic growth at the individual sector level can have large implications for economy wide economic growth and economy wide carbon dioxide emissions from burning fossil fuels.

As part of our analysis we examine the magnitude of the consequences of the Castles and Henderson critique of the SRES by generating a baseline projection from the G-Cubed model based on our usual growth convergence assumptions using a PPP measure of initial gaps between countries. To explore whether the different assumptions about growth projections make any difference to the emissions projections, we then regenerate these projections assuming a MER based gap between economies. In G-Cubed, the difference in emission outcomes turns out to be substantial. If developing countries grow more quickly over a century (because the potential for 'catch-up' is larger in the MER case), then the income and expenditure of both developing countries and developed countries rise. This causes an increase in energy use and a rise in carbon emissions globally—not just in developing countries.

¹Adapted from Fig. 1 in Bagnoli et al. (1996).

We find that by 2050 the projection of emissions from fossil fuels use based on the MER measures of GDP gaps is 22% higher than our base projection (using PPP) and by 2100, projected emissions are 40% higher than baseline emissions. About half of the higher emissions are generated from countries that are classed as developing in 2002 and about half from industrial economies. These numbers are almost three times those found in Manne and Richels (2003) who undertake a similar exercise. There are a number of reasons for these differences, which are open to debate. We do not change assumptions about exogenous technological developments caused by higher growth except those generated by relative price changes. Others might argue that higher economic growth would lead to faster AEEI and therefore emissions change by less. This is an open question. We also have much greater international interdependence between countries through trade and capital flows than the Manne and Richels study. The greater the positive spillovers from growth in developing countries to growth in industrial countries the larger the emissions, taking all other things equal.

Although the results we find are significant, they cannot be directly applied to the SRES approach. Firstly, it is not clear that the SRES actually based any or all of the projections in the study on a standard growth convergence model, despite spending considerable space summarizing that literature. In many of the models used in the SRES the entire economy is summarized by the exogenous path for GDP growth and emissions growth is driven by technology. GDP plays a minor role except as the scale variable.

If the modelers in the SRES used market exchange rate GDP differentials but the rate of convergence from the PPP convergence models then there is a problem as argued by Castles and Henderson (2003a) and as we illustrate in this paper. If the SRES models used a MER based convergence model by adjusting the rate of convergence to be consistent with the MER approach then there is still a problem because there is no evidence of convergence of GDP per capita in MER terms. This is why the growth convergence literature that has been published since the development of PPP GDP data does not use market exchange rates. Secondly there is also no evidence of convergence between MER and PPP exchange rates so in our opinion there is no way to go from a PPP convergence model to a MER convergence model.

However, it may just be that the models did something completely different to what is suggested in the SRES report. One alternative that likely underlies some of the projections is that the concept of convergence is implemented by specifying a gap between \$US incomes per capita at the start of the projection period and an arbitrary gap between \$US incomes per capita at the end of the projection period. The problem with this approach is that it relies on the evolution of the real exchange rate between countries to be able to say anything about the underlying drivers of growth at the sectoral level within a country. Many of the models used do not have the real exchange rate modeled and therefore cannot back out the underlying drivers of growth within a country for driving real economic growth. Even this approach would suffer from the same critique that income gaps measured in \$US at different points in time cannot be used to derive underlying economic growth.

While it is possible that some of the SRES scenarios contain growth rates that are higher than would be case if PPPs had been used in comparing base GDP, it does not

follow in these scenarios that lower GDP growth would translate to lower emissions. We illustrate in this paper that the relationship between emissions and GDP depends on the relative importance of various sources of growth. It is possible to have a model with growth drivers and parameter settings that result in GDP and emissions moving in opposite directions.

Holtmark and Alfsen (2005) argue that the use of MERs in the SRES actually leads to two types of errors (overstatement of both income per capita and emissions intensity gaps) that effectively “cancel each other out” (p18) in a convergence model. Their analysis has been used to dismiss the importance of the PPP and MER issue in the SRES. As discussed in Stegman (2006), this result critically depends on the assumptions Holtmark and Alfsen make regarding driving forces. Holtmark and Alfsen implicitly assume that once GDP and emissions growth have been exogenously determined in the OECD region, the only factors driving emissions in the other regions are exogenously determined future GDP per capita ratios to the OECD and exogenously determined future emissions per GDP ratios to the OECD.

Whilst the MER inaccuracies may cancel each other out in Holtmark and Alfsen’s simple model, they should not do so in a well developed model where sectoral productivity growth is a driver of future emissions and structural change and where endogenous interactions between regions and within regions are accounted for. In the G-Cubed model, GDP per capita and emissions per GDP ratios are endogenously determined. A convergence model is used to project technical efficiency in input use (or sector level productivity) but convergence in GDP per capita or emissions intensity is not imposed.

It is not clear whether the MER inaccuracies would cancel each other out in the SRES, because the report is not transparent about the assumptions or methodology used and whilst the impact of these inaccuracies has been the focus of the present debate, the discussion generated by Holtmark and Alfsen (2005) highlights a deeper debate that needs to be undertaken on the overall world view that drives the models underlying the SRES type exercises of predicting more than 100 years into the future. In response to the Holtmark and Alfsen (2005) paper, Henderson argued that “it is hardly a merit of a modelling exercise that it provides for the closing of two exaggerated gaps rather than one, and that it incorporates twin analytical errors which happen however to be offsetting in their effects” (Henderson 2005a). The usefulness and relevance of emissions projections based solely (or largely) on convergence in GDP and emissions variables is limited since this behavior is not empirically observed and is difficult to support on theoretical grounds.

It is clear that there are alternative approaches (such as the sectoral approach of G-Cubed) to generate emission profiles. Given the inherent uncertainty of projecting the future, clearly a suite of approaches should be considered in future work on projecting greenhouse emissions. There is enormous uncertainty over the likely path of emissions, let alone how this will impact on climate outcomes. The policy implications are that whatever is done should take this uncertainty fundamentally into consideration.

The PPP ‘controversy’ arises in the context of one particular approach to forecasting (the use of some notion of convergence). Even if this issue is resolved, there remain many more fundamental issues to be considered and discussed between modelers and policy makers.

2 Some theoretical considerations

2.1 Source of economic growth²

To project growth, it is important to first understand the ultimate sources of growth. A considerable amount of work has been undertaken on growth theory in recent years, and our general understanding of the drivers of growth has improved considerably.

At an abstract level there are four sources of growth within an economy: (1) increases in the supply of labor, capital and other inputs; (2) increases in the quality of these inputs, (3) improvements in the way inputs are used (technical change); and (4) improvements in the way that inputs are allocated across industries. For the world economy as a whole, a fifth source of growth is reallocation of inputs among countries.

Jorgenson (1988) has shown that for the economy as a whole there is also another potential source of growth: reallocation of resources between industries. To see this, consider an economy with two sectors, X and Y . If the overall productivity of labor in sector X is higher than it is in sector Y (say because of prior technical change), a shift in final demand from Y to X shifts primary factors from Y to X and will result in growth of total output. This occurs even if there is no concurrent productivity growth in the individual sectors. The effect is even more pronounced if the composition of demand shifts toward sectors which have productivity growth rates that are higher than average.

Thus, in order to project the world economy over a number of decades into the future we would need underlying projections of each country's labor force, capital stock, materials inputs, changes in factor quality and changes in product demand patterns. Many of these will lead to changes in relative prices and thus change the structure of each region's economy. Moreover, the evolution of each country's capital stock will be an endogenous result of domestic and foreign investment decisions. In order to combine all of these projections, capture the effects of relative price changes, and project the future path of the capital stock you need a disaggregated intertemporal general equilibrium model.

2.2 Sources of emissions growth

The evolution of GDP will likely, but not necessarily, be related to the path of carbon emissions. Because energy use is both an input and output in the process of generating GDP, the path of energy use will be determined from the bottom up. GDP growth is determined by the path of input use and technology. Just having a view of aggregate GDP growth does not mean that carbon emissions are residually determined. Bagnoli et al. (1996) show how a given path of GDP for an economy can yield very different profiles of energy use and carbon emissions depending on the sources of growth behind GDP.

It is natural to an economist to form a global projection of GDP by projecting underlying sectoral productivity growth, efficiency improvements and population

²This section draws heavily on. Bagnoli et al. (1996).

or labor force growth and then incorporate these into a model with endogenous decisions on other inputs such as energy use, materials use and capital accumulation to build up the economy wide projection for GDP growth. The emissions projections which accompany this growth projection are determined by the sectoral use of fossil fuels in energy generation that are the outcome of the decisions of firms and households.

2.3 Convergence of economic growth between countries

Ideally the projection of economic growth within countries would be determined within the context of each country since, as we have shown above, the drivers of growth are many and varied. However because our understanding of technical change is incomplete, it is useful to incorporate as much of the observed empirical relationships between growth rates across countries as possible. One of these issues is the observation that various measures such as income per capita or technology in sectors across countries tend to “catch up” to the leading country. Thus although it is desirable to focus on the sources of growth within each country it is nonetheless important to take into account the issue of convergence across countries. This section examines the theoretical basis for assumptions of convergence in GDP per capita levels and provides a brief review of the empirical evidence on income convergence.

Studies of convergence often distinguish between conditional and unconditional convergence. Conditional convergence refers to convergence that exists as long as certain characteristics across the sample remain the same. Unconditional convergence does not require this restriction. The concept of convergence itself is often defined in different ways. Defining convergence and using the appropriate concept is an important consideration in convergence studies.

2.3.1 Neoclassical growth theory and convergence

The neoclassical growth models of Ramsey (1928) and Solow (1956) suggest that there is an inverse relationship between the growth rate of income or output per capita and the initial starting level (Sala-i-Martin 1996a). Barro and Sala-i-Martin (1992) argue that if countries are similar with respect to preferences and technology then poor countries tend to grow faster than rich countries and “there is a force that promotes convergence in levels of per capita product and income” (p224). The model implies *conditional* convergence in that *for a given steady state*, the growth rate is higher the lower the initial level of output per effective labour unit. This type of convergence is often referred to as conditional beta (β) convergence. The neoclassical growth model does not predict *unconditional* convergence. Poor countries are predicted to grow faster than rich countries only if they share the same steady state characteristics.

2.3.2 Empirical evidence on convergence

Empirical research on convergence has received considerable attention in the economic literature. Most of this research is concerned with the distribution of income per capita (living standards) and, to a smaller extent, the distribution of output per worker or per hour worked (productivity).

The literature is not uniform in its approach to convergence analysis and alternative measures of convergence have important implications for the definition of convergence and its existence. Four broad approaches to convergence analysis can be identified in the literature: beta convergence, sigma convergence, time series (co-integration) analysis, and distributional analysis. Sala-i-Martin (2002) and Quah (1996) provide summaries of the alternative approaches to convergence analysis.

In general, there is little evidence for unconditional convergence of income per capita or productivity levels when a large cross section of countries is considered (see Sala-i-Martin (1996b) for beta and sigma convergence analyses, Quah (1995) for a distributional analysis, and Bernard and Durlauf (1995) for a time series analysis).

The evidence for alternative forms of *conditional convergence* is stronger (see Quah (1995, 1997) and Barro and Sala-i-Martin (1995)), although there is considerable debate about the appropriate interpretation of these results.

The neoclassical growth model predicts *conditional* (beta) convergence: initially poor countries will grow faster than initially rich ones assuming they are converging to the same steady state. In practice, countries differ in many respects including their levels of technology, propensities to save, and population growth rates (Sala-i-Martin 1996a). Whilst analyses of conditional beta convergence may be useful in examining the *speed* at which countries converge to their steady states, they do not provide empirical support for a closure of the income gap: “only if all countries converge to the same steady state does the prediction that poor economies should grow faster than rich ones holds true” (Sala-i-Martin 1996a, p1027).

Likewise, conditioning in distributional analyses of convergence (as undertaken by Quah (1997)) may be useful in understanding the distribution of income across countries but the sense in which convergence exists in these studies is restrictive.

Although the evidence in favor of *unconditional* income convergence across countries is weak, the analyses provide useful information that can be used in economic projections. Empirical analyses of productivity convergence at the sectoral level are limited (see Barro and Sala-i-Martin (1991) and Bernard and Jones (1996a, b)) and the growth convergence literature gives some useful guidance for formulating projections of sectoral productivity growth. However it is critical to measure the initial gaps correctly. The rate of growth of either sectoral productivity or income per capita or whatever is assumed to converge across countries depends critically on this initial gap. This is because with a constant rate of gap closure, the larger the initial gap, the higher the rate of growth required to close the gap by the constant factor each year. Thus the way the initial gap is measured is fundamental. This is why there is a debate on the difference between PPP and MER measures of economic variables across countries.

2.4 PPPs versus market exchange rates

International comparisons of national income (and other aggregates) require that income levels across countries are expressed in a common unit. The simplest way to convert income levels expressed in different currencies is to use exchange rates. Exchange rate based conversions of international Gross Domestic Product (GDP) are easy to calculate and available from the OECD’s National Accounts (<http://www.oecd.org>) database and the World Bank’s World Development Indicators

(<http://www.worldbank.org>). There are, however, a number of problems that arise with the use of exchange rates as conversion factors. Exchange rates reflect the relative purchasing powers over *traded* goods and services. They may be useful for the comparison of domestically produced traded goods and services. They are not appropriate for the international comparison of volume measures that include production for domestic consumption, such as output and productivity. The use of exchange rates in such situations leads to a traded sector bias. Exchange rate conversions tend to understate the real incomes of poorer countries and overstate the degree of inequality between countries because they ignore the lower cost of living that is typically observed in poorer economies (Dowrick 2001). Furthermore, exchange rates are not solely determined by relative prices. They are increasingly influenced by speculative capital movements and therefore expectations and, as a result, may be too volatile to be used reliably as conversion factors.

Castles and Henderson (2003b) have strongly argued the case against the use of market exchange rates as conversion factors:

[Market exchange rate] valuations across countries, since they do not measure quantity differences, have no place in international comparisons of output or real expenditure, nor in constructing measures of the growth of output or real expenditure that extend across national boundaries (p420).

Nordhaus (2007) agrees stating that “estimates of output or income at MER are simply wrong—they are constructed on an economically incorrect basis” (p351) and “provide inaccurate estimates of relative incomes and outputs” (p366). He argues that the errors generated by using MERs in today’s world are large: “underestimating incomes in low-income countries by a factor of at least three relative to high-income countries” (p366) and concludes that “the use of MER is not a fine technical detail” (p352):

Incomes estimated at MER are fundamentally wrong because they use the prices of a non-representative bundle of goods to compare the different countries. To use exchange rates is analytically no better than using the ratio of the prices of oranges or gasoline or haircuts to convert domestic incomes (p352).

There is therefore a need for appropriate conversion factors that eliminate differences in price levels and allow reliable international volume comparisons of output. The most widely used conversions factors that attempt to account for price level differences are purchasing power parities (PPPs). PPPs are designed to only reflect differences in the volume of goods and services between countries.

The main source for PPPs over a wide range of goods and services is the United Nations International Comparison Program (ICP) database. The ICP was established in 1968 as a joint venture of the UN and the International Comparisons Unit of the University of Pennsylvania, with financial contributions from the Ford Foundation and the World Bank. In 1970 the comparison included just ten countries, by 1993 country coverage had increased to 118. The OECD, in collaboration with the Statistical Office of the European Union (Eurostat) has continued to collect price data to estimate PPPs in its member states and currently operates on a 3-year cycle. Since 1993, the World Bank has assumed the role of global coordinator for the ICP in non-OECD countries. Through its Development Data Group the Bank coordinates ICP surveys and publishes global PPP data sets.

The World Bank recently released the results of 2005 International Comparison Project (see <http://go.worldbank.org/VMCB80AB40>).

The resources necessary to construct the ICP database are considerable and there have been significant funding and data collection problems. The ICP recently argued that “data quality has been severely damaged by a lack of timeliness, continuity, consistency and reliability. Without a substantial increase in funding to tackle these problems the ICP will fail, undermining the accurate monitoring of progress towards development goals.” (<http://www.worldbank.com/data/icp/pdf/ICPbrochure.pdf>)

Despite these issues, most researchers agree that the ICP estimates remain the best statistics available for volume comparisons at the disaggregated level (Dowrick 2001). There remains considerable debate, however, over the appropriateness of alternative *aggregate* PPPs. Aggregate PPPs refer to PPPs that have been aggregated to correspond to broad consumption headings and total GDP. The debate concerns the method by which these aggregate PPPs are calculated. Despite the aggregation issue, the use of PPP however constructed gives a much better picture of the underlying income difference than the market exchange rate measure.³

2.5 Conversion factors and income convergence assumptions

The choice between using market exchange rates or PPPs to convert GDP has a significant impact on international income level and growth comparisons. How and why this might affect projections of future emission levels depends on the assumptions that underlie the projection model. If income convergence assumptions are an important determinant of economic growth rates, as they appear to be in the SRES scenario families A1 and B1, then accurately measuring the income gap becomes an important consideration.

The rate of growth in a convergence model will be determined by the size of the initial gap, the rate of change of the frontier, and the assumed degree of convergence.

In looking at arguments for and against the use of PPPs when making inter-country comparisons—such as in Manne and Richels (2003)—there is a tendency to confuse PPP the hypothesis (that price bundles across countries will tend to equalise) with PPP the empirical technique (in which the value of an equivalent bundle of goods is compared across countries). These are very different concepts and it is unfortunate that they have the same name. If the hypothesis of PPP held, then there would be no issue in the use of either PPPs or MERs in developing some form of convergence model, because there would be a unique relationship between relative prices and the exchange rate between countries.

Empirical comparisons of prices show convincingly that the hypothesis of one price does not hold over the history of the last 50 years or so. That is, PPP conversion factors and market exchange rates are not the same. Further there is no observed tendency for these to move in any systematic way relative to each other and more particularly there is no evidence that they tend to converge over time. Sure it is possible to construct a model where a relationship between PPPs and MERs holds

³A detailed discussion can be found in McKibbin et al. (2004). Nordhaus (2007) also discusses this issue in depth.

and assume that one can always be converted easily into the other so that it can be seen purely as a “numeraire choice”. But that doesn’t mean it is a useful assumption to base real world analysis on.

Because the hypothesis of Purchasing Power Parity does not hold in any current data set, there can be no empirical basis for using it as an assumption in constructing a model of the evolution of prices and quantities. In particular, the fact that PPP and MER estimates can be significantly different for some countries over time means that the choice of the appropriate conversion factor (PPP or MER) at the starting point matters. It also matters over time because if there is no systematic relationship between MER and PPP conversion factors then they can’t lead you to the same point at some arbitrary point in the future. For example, the appreciation of the US dollar between 1982 and 1985 by 50% in real and nominal terms shows that neither the real or nominal exchange rates during this period were useful in comparing the relative size of the US and European economies. A convergence model starting in 1982 would clearly lead to a very different world in 2050 than a model starting in 1985.

Now consider the argument that it is perfectly reasonable to specify a scenario defined as some relationship in MER terms between the incomes of industrialized economies and developing countries at some point in the future. If there is an underlying convergence of income measured in PPP terms but there is no relationship between PPPs and MERs then there can be an infinite number of growth paths in MER terms between now and 2100 including perhaps one in which there is no convergence because of a trend in the MER. You can of course assume that there is a relationship between PPPs and MERs and make the problem disappear but only wishful thinking as a basis.

3 The G-cubed approach to long run projections

3.1 The G-cubed model

The G-Cubed model outlined in McKibbin and Wilcoxon (1998) is ideal for undertaking global projections having detailed country coverage, sectoral disaggregation and rich links between countries through goods and asset markets. A number of studies—summarized in McKibbin and Vines (2000)—show that the G-cubed model has been useful in assessing a range of issues across a number of countries since the mid-1980s.⁴ A summary of the model coverage is presented in Table 1.

Some of the principal features of the model are as follows:

- The model is based on explicit *intertemporal* optimization by the agents (consumers and firms) in each economy.⁵ In contrast to static CGE models, time and dynamics are of fundamental importance in the G-Cubed model.
- In order to track the macro time series, however, the behavior of agents is modified to allow for short run deviations from optimal behavior either due to myopia

⁴These issues include: Reaganomics in the 1980s; German Unification in the early 1990s; fiscal consolidation in Europe in the mid-1990s; the formation of NAFTA; the Asian crisis; and the productivity boom in the US.

⁵See Blanchard and Fischer (1989) and Obstfeld and Rogoff (1996).

Table 1 Overview of the G-cubed model

Regions
United States
Japan
Australia
Canada
New Zealand
Europe
Rest of the OECD
China
Brazil
Mexico
Rest of Latin America
Oil exporting developing countries
Eastern Europe and the former Soviet Union
Other developing countries
Sectors
Energy:
(1) Electric utilities
(2) Gas utilities
(3) Petroleum refining
(4) Coal mining
(5) Crude oil and gas extraction
Non-energy:
(6) Mining
(7) Agriculture, fishing and hunting
(8) Forestry/wood products
(9) Durable manufacturing
(10) Non-durable manufacturing
(11) Transportation
(12) Services
(Y) Capital Good Producing Sector

or to restrictions on the ability of households and firms to borrow at the risk free bond rate on government debt. For both households and firms, deviations from intertemporal optimizing behavior take the form of rules of thumb, which are consistent with an optimizing agent that does not update predictions based on new information about future events. These rules of thumb are chosen to generate the same steady state behavior as optimizing agents so that in the long run there is only a single intertemporal optimizing equilibrium of the model. In the short run, actual behavior is assumed to be a weighted average of the optimizing and the rule of thumb assumptions. Thus aggregate consumption is a weighted average of consumption based on wealth (current asset valuation and expected future after tax labor income) and consumption based on current disposable income. Similarly, aggregate investment is a weighted average of investment based on Tobin's q (a market valuation of the expected future change in the marginal product of capital relative to the cost) and investment based on a backward looking version of Q .

- There is an explicit treatment of the holding of financial assets, including money. Money is introduced into the model through a restriction that households require money to purchase goods.

- The model also allows for short run nominal wage rigidity (by different degrees in different countries) and therefore allows for significant periods of unemployment depending on the labor market institutions in each country. This assumption, when taken together with the explicit role for money, is what gives the model its “macroeconomic” characteristics. (Here again the model’s assumptions differ from the standard market clearing assumption in most CGE models.)
- The model distinguishes between the stickiness of physical capital within sectors and within countries and the flexibility of financial capital, which immediately flows to where expected returns are highest. This important distinction leads to a critical difference between the *quantity of physical capital* that is available at any time to produce goods and services, and the *valuation of that capital* as a result of decisions about the allocation of financial capital.

As a result of this structure, the G-Cubed model contains rich dynamic behavior, driven on the one hand by asset accumulation and, on the other by wage adjustment to a neoclassical steady state. It embodies a wide range of assumptions about individual behavior and empirical regularities in a general equilibrium framework. The interdependencies are solved out using a computer algorithm that solves for the rational expectations equilibrium of the global economy. It is important to stress that the term ‘general equilibrium’ is used to signify that as many interactions as possible are captured, not that all economies are in a full market clearing equilibrium at each point in time. Although it is assumed that market forces eventually drive the world economy to a neoclassical steady state growth equilibrium, unemployment does emerge for long periods due to wage stickiness, to an extent that differs between countries due to differences in labor market institutions.

3.2 The G-cubed projection approach

As with the growth accounting framework outlined in Section 2, the assumptions about the inputs into growth projections are from the fundamental sources of growth in the G-Cubed approach. There are two key inputs into the growth rate of each sector. The first is the economy wide population projection. The second is the sectoral productivity growth rate. In Bagnoli et al. (1996) we modeled economy wide productivity and then used the historical experience of differential growth across sectors to apportion the aggregate productivity projections to each sector within an economy.

We now assume that each sector in the US will have a particular rate of productivity growth over the next century. We then assume that each equivalent sector in each other country will catch up to the US sector in terms of productivity, closing the gap by 2% per year. The initial gaps are therefore critical for the subsequent sectoral productivity growth rate. We follow a two step process in determining the initial size of the gap. The first step is to specify the gap between all sectors and the US sectors equal to the gap between aggregate PPP GDP per capita between each country and the US. We can’t easily use sectoral PPP gap measures because these are difficult to get in a consistent manner and with a wide enough coverage for our purposes. Thus the initial benchmark is based on the same gap for each sector as the initial gap for the economy as a whole. If we then have evidence that a particular sector is likely to be closer to or further away from the US sectors than the aggregate numbers suggest, we adjust the initial sectoral gaps attempting to keep the aggregate gaps consistent with

the GDP per capita gaps. We then assume that productivity growth in each sector closes the gap between that sector and the equivalent US sector by 2% per year. The productivity growth is calculated exogenously to the model. We then overlay this productivity growth model with exogenous assumptions about population growth for each country to generate two of the main sources of economic growth.

Given these exogenous inputs for sectoral productivity growth and population growth, we then solve the model with the other drivers of growth, capital accumulation, sectoral demand for other inputs of energy and materials, all endogenously determined. Critical to the nature and scale of growth across countries are these assumption plus the underlying assumptions that financial capital flows to where the return is highest, physical capital is sector specific in the short run, labor can flow freely across sectors within a country but not between countries and that international trade in goods and financial capital is possible subject to existing tax structures and trade restrictions.

Thus the economic growth of any particular country is not completely determined by the exogenous inputs in that country since all countries are linked through goods and asset markets.

Carbon emissions are determined in the model by the amount of fossil fuels (coal, oil, natural gas) that are consumed within each country in each period. These primary factors are endowed within countries but can also be traded internationally subject to transportation costs (captured implicitly through the elasticities of substitution between each good in the model). Thus economic growth can occur within a country, without any particular pattern implied for energy use. The pattern for energy use will be dependent on the underlying inputs into the growth process. The illustration in Fig. 1 of the change in energy use relative to GDP after the oil price shocks of the early 1970's would be explained in this approach by a substitution away from energy into the other inputs of capital and labor. This could be achieved both within sectors as well as by changing the composition of sectors in aggregate GDP with services (less energy intensive) becoming a larger share of the economy than energy intensive manufacturing sectors. There can also be some technological change that is part of this story.

In order to illustrate the importance of sectoral productivity growth Figs. 2, 3, 4 and 5 show the patterns of GDP growth and carbon emissions when we change assumptions about productivity growth at the sectoral level. We change productivity growth in each sector, on a sector by sector basis, by 1% per year for 50 years. Each figure contains 13 groups of two bars. Each group along the horizontal axis is the sector in which the increase in productivity growth occurs. Sector Y at the end of the chart is the sector that produces capital goods. In Fig. 2 we show the percentage deviation of both emissions and GDP as a result of the productivity growth in sector *i*. For example, if sector 9 (durable manufacturing) experiences more rapid productivity growth we see that by 2020, GDP will be approximately 1.1% higher than otherwise and emissions will be 1% higher. Yet in sector 10 (non-durable manufacturing) we see that real GDP will be 0.5% higher but emissions will be lower. This occurs because producers substitute away from energy use in sector 10 when productivity rises. We see that in the services sector (sector 12) there is almost double the GDP impact relative to the increase in emissions. In each of the energy sectors (1 to 5) higher productivity growth has almost no impact on GDP yet leads to significant increases in economy wide emissions. This is not because of

Fig. 2 Percentage change in US emissions and real GDP by 2020

Fig. 3 Percentage change in US emissions and real GDP by 2050

Fig. 4 Percentage change in China emissions and real GDP by 2020

emissions from those sectors, but because productivity growth reduces the relative price of these sectors output (i.e. various forms of energy) which causes other sectors and final demand to substitute into energy and thus raise emissions.

Fig. 5 Percentage change in China emissions and real GDP by 2050

Figure 3 shows the results for the same sectors for the same shocks but with results in 2050 rather than 2020. It is interesting that the ratios of GDP to the change in emissions moves around between 2020 and 2050. This partly reflects the way in which higher wealth generated by productivity growth in some sectors leads to changes in spending patterns across the economy which changes overall emissions.

Figures 4 and 5 show the same style of results but this time for China as a result of changes in US productivity growth by sector. This demonstrates the spillovers from growth in the US to growth and emissions in a developing country. It is interesting that although the US experienced 4% higher GDP by 2020 as a result of productivity growth in sector 12 (services), this spills over to China as a rise in GDP of 0.6% by 2020. This illustrates the importance of international linkages in the G-Cubed model. Secondly notice that the increase in emissions is much larger (1%) in China relative to the GDP increase. This partly reflects the higher emission coefficients in China as well as the higher growth from the US being into higher expenditure on higher energy intensive products in China (less on services and more on energy and energy intensive manufacturing). Note that the spillover of growth in the US in the capital producing good (sector Y) to China is negative. This is because capital flows into the US away from China as the cost of capital goods fall in the US. Therefore both GDP and emissions falls in China for this particular type of productivity growth.

These results demonstrate how emissions intensity is determined in the G-Cubed model and they clearly show that there is no simple relationship between GDP and emissions when the fundamental drivers of growth are taken into account, and when the full range of economic interactions between regions is allowed (both trade and capital flows). Different sectors respond differently to productivity shocks and the structure of economies, and change that occurs as a result of the shock, is fundamental to the aggregate emissions intensity outcome. This shows the importance of getting at the fundamental drivers of economic growth (productivity or technical change, along with population) rather than using an aggregate proxy, such as GDP.

It is important to note that in the default approach used in the G-Cubed model, the initial gaps between countries are calibrated using initial real income comparisons between the US and other regions. These real income comparisons need to reflect the quantity of production and so to make the comparison we use PPPs and not market exchange rates for the reasons outlined above. This is clearly the theoretically correct approach when using G-Cubed. This form of calibration, however, is not fundamental to our approach but is the result of data availability and convenience.

It is interesting to note that the G-Cubed model has a ‘PPP issue’ because of the particular default approach we take to our convergence model. This is not, however, a fundamental feature of G-Cubed itself. Indeed, PPP issues do not arise elsewhere in the model, because as a well specified economic model G-Cubed tracks relative prices and quantities and tells a detailed story about nominal and real exchange rates.

Another challenge in the G-Cubed approach is defining which country is on the frontier. We use the US in our default approach, but we could easily adjust this assumption for particular sectors as empirical evidence became available.⁶

⁶It is also the case that consumers in G-Cubed have homothetic preferences which implies a unitary income elasticity of demand. We adjust for this when generating the baseline projection by exogenous shifts in spending preferences. We believe that this has almost no effect on the

4 Some illustrative implications of the alternative approaches

4.1 Effect of lower GDP growth in the SRES

In its most recent Assessment Report (Fourth Assessment Report: Climate Change 2007), the IPCC argued that “available studies indicate that the choice of exchange rate for Gross Domestic Product (GDP) (Market Exchange Rate, MER or Purchasing Power Parity, PPP) does not appreciably affect the projected emissions, when used consistently” (IPCC 2007 p44). The ‘consistent’ use of MER based measures of GDP presumably refers to the fact that comparisons of output are incorrectly undertaken using MERs throughout the SRES. Holtsmark and Alfsen (2005) indeed argue that emission levels would be unaffected because the effect of overstated income gaps would be offset by the effect of the overstated emissions-intensity gap: “the use of MER in the SRES scenarios has not caused an overestimation of the global emission growth because, as far as global emissions are concerned, the overstated income gap is effectively neutralized by the overstated emissions-intensity gap” (p11). The SRES authors’ initially responded to the Castles and Henderson critique with a similar argument: the effect of lowering the GDP growth assumptions in the developing countries in the A1 and B1 scenario families would “not change anything in the projected emission range of the SRES scenarios” (Nakicenovic 2003, p209) because the upward pressure on emissions from higher growth would be exactly offset by downward pressure from technological advances generated by the growth. However, in their “Final Response” to the Castles and Henderson critique (Grübler et al. 2004) the SRES authors revise their position stating that “lower economic growth might instead increase emissions” (p 20) and they present a modelling exercise where emissions are “substantially” affected. We agree with Henderson (2005b) that the question of how the use of MER based comparisons of output in the SRES affected emissions projections remains unresolved. An examination of the effect on emission projections of changing the economic growth assumptions in the SRES requires knowledge of the assumed relationship between economic growth and emissions in the SRES scenarios. This information is not provided in the SRES. The authors of the SRES argue that the relationship between economic growth and emissions is complex and involves the (endogenous) interrelationships between economic growth, population changes, and changes in emissions intensity.

Consider the following equation known as the IPAT identity (Ehrlich and Holdren 1972):

$$\text{Impact} = \text{Population} \times \text{Affluence} \times \text{Technology}$$

which can be expressed as

$$\text{Emissions} = \text{Population} \times \text{GDP per capita} \times \text{Emissions per GDP}$$

$$E = P \times GDP \text{ per capita} \times I \text{ (Emissions Intensity)}$$

counterfactual simulation here as they are deviations from the projections. Future research will incorporate this directly into the specification of the utility function.

If population growth (p), GDP per capita growth ($gdppc$) and growth in emissions intensity (i) are independent then the IPAT identity can be approximated by a linear expression in growth rates:

$$e = p + gdppc + i$$

and changes in income per capita growth would result in corresponding changes in emissions growth. While this relationship appears to indicate that GDP should move with emissions, it is, in fact, quite misleading. Emissions intensity and GDP are closely related, particularly because the drivers of GDP growth may themselves be the same factors that drive changes in emissions intensity.

With endogenous right hand side variables, the relationship between changes in income per capita growth and emissions growth becomes more complicated.

We can examine the factors determining emission intensity, and the relationship between emissions and GDP by considering a simple CES production model. Assume that aggregate output is a CES function of energy (E) and other factors (O , which would include labour and capital). Let P_E be the price of energy and let P_O be the price of other inputs. Further, assume that energy is itself a CES composite of an emitting technology (EM) and a non emitting technology (NE). Let P_{EM} be the price of the emitting energy source and P_{NE} be the price of the non emitting source. With appropriate choice of parameters, this simple setup could represent a variety of styles of models.

Expressing variables in percentage changes (and ignoring any changes in population), we can write:

$$\begin{aligned} emis = & gdppc + p_{EM} (\sigma_1 S_{EM} (S_E - 1) - \sigma_2 (1 - S_{EM})) \\ & + p_{NE} (\sigma_1 S_{NE} (S_E - 1) - \sigma_2 (S_{NE})) + \sigma_1 S_O p_O \end{aligned} \quad (4.1)$$

where σ_1 is the elasticity of substitution between the energy bundle and other inputs; σ_2 is the elasticity of substitution between energy types; S_E is the share of energy in total output; S_O is the share of other inputs in total output; S_{EM} is the share of emitting energy in total energy and S_{NE} is the share of non emitting energy in total energy.

Equation (4.1) shows that the change in emissions depends on the change in GDP plus three other terms which together define emissions intensity. Emissions intensity depends on the changes in the relative prices of energy and non-energy inputs, and emitting and non-emitting energy sources as well as on the ability to substitute between these inputs (and their relative shares in production). Emissions intensity could increase or decline depending on these factors.

Relative input and energy prices will change as a result of the changes in the drivers of growth. For example, productivity improvements in non emitting energy will lead to a decline in its relative price, affecting its use and subsequently emissions intensity.

It is possible for emissions and GDP to move in opposite directions; that is for GDP to increase and for emissions to decline (or vice versa). Put another way, is it possible for changes in emissions intensity to offset changes in GDP in determining emissions?

To address this question, we need to close Eq. (4.1) so as to relate changes in GDP to changes in the price of inputs (or equivalently, to changes in the productivity of inputs). We can close it by assuming a crude reduced form GDP response where

GDP is a function of the price of all inputs. This response represents the net effect of changes in labour and capital inputs that result from changes in the productivity of the underlying factors of production. With this assumption (4.1) becomes:

$$\begin{aligned} emis &= \gamma (S_O p_O + S_E S_{EMP} p_{EM} + S_E S_{NEP} p_{NE}) \\ &\quad + p_{EM} (\sigma_1 S_{EM} (S_E - 1) - \sigma_2 (1 - S_{EM})) \\ &\quad + p_{NE} (\sigma_1 S_{NE} (S_E - 1) - \sigma_2 (S_{NE})) + \sigma_1 S_O p_O \end{aligned} \quad (4.2)$$

where γ (<0) is a parameter capturing the response of GDP to changes in productivity (represented as prices here).

Equation (4.2) shows that the change in emissions depends on the relationship between the drivers of growth (here represented as the prices of different inputs), the substitution relationships and the overall expansions parameter. With appropriate parameter settings, and exogenous changes in prices, it is possible for emissions and GDP to move in opposite directions. How likely is this, or put another way, for randomly chosen parameter sets, how many of them result in GDP and emissions moving in opposite directions?

In order to check the likelihood of GDP and emissions moving in different directions, we calibrate the simple model above using data from G-Cubed and simulate it for a variety of parameter settings. One set of results are set out in Fig. 6 which plots the likelihood of emissions and GDP moving in opposite directions against the relative importance of non emitting energy productivity changes as a source of growth.

Figure 6 shows that as the relative importance of non-emitting energy productivity improvements as a source of growth increases, the probability that any given parameter set will lead to emissions and GDP moving in opposite directions increases. Thus, the more important clean technology is as a driver of growth, the more likely it is that there will be a parameter set that will cause GDP and emissions to move in opposite directions.

This discussion illustrates three important points. First, understanding the relationship between GDP and emissions requires breaking down the sources of growth and the sources of changes in emissions intensity. Second, while this may be complex

Fig. 6 Growth, GDP and emissions

in some cases, it is possible to construct back of the envelope models that draw out the key factors. We have used a simple CES model here, but simple versions of more flexible functional forms could be used to represent a wide variety of models. Third, because the relationship between emissions and GDP depends on the sources of growth, it is quite likely that this relationship will differ for the different SRES scenarios.

4.2 PPP versus MER in G-cubed: an illustration

We now use the G-Cubed model to explore how large the difference between using MER versus PPP initial income levels is for emissions over a century. We solve the G-Cubed model under our conventional assumptions of the gaps in productivity growth being related to the overall PPP GDP per capita gaps. We then regenerate the productivity projection by changing the initial gaps for China and LDCs in the model to be based on MER measures of GDP per capita. This implies that we move from gaps for China from 0.2 of the United States to 0.1 of the United States and for developing economies from 0.4 of the United States to 0.13 of the United States. That is, for China, the gap relative to the US doubles under the MER approach and for developing economies, the gap more than triples.

The results for the difference in emissions in the MER case versus the PPP case are shown in Fig. 7. By 2050 we find that the G-Cubed model produces 21% more emissions than the PPP approach when we base our growth rates on the MER initial conditions. By 2100 this is 40% higher emissions. The impacts on cumulative emissions would be less than this and on temperatures (which depend on cumulative emissions) even less. Nonetheless this is more than three times the overestimate found by Manne and Richels (2003). The higher emissions are due to higher emissions in LDCs and China due to higher growth but also due to higher emissions in industrial economies. Stronger growth and a higher marginal product of

Fig. 7 Change in carbon emissions market vs PPP

capital implies that industrial countries sell more to developing countries as well as receiving a higher return on capital invested in these economies. Both of these effects raise emissions and levels of income in non developing economies.

Based on these estimates from the G-Cubed model it seems that the assumptions about the initial levels of income based on MER versus PPP measures are very important for estimates of future carbon emissions. This is a consequence of the particular assumptions we adopt with regards to the convergence model.

5 Summary and conclusion

Projecting the world economy over long time horizons is challenging. One only has to consider the problems that would have been encountered in 1900 in projecting carbon emissions in the year 2000. Indeed it would have been difficult in 1970 to do well in predicting 2000, given the important structural break in many economic and energy variables resulting from the OPEC oil price shocks. Nonetheless it is important to use the best methodology available to attempt to gain some idea about where carbon emissions might be heading. The mistake would be to rely on the accuracy of these projections for the efficacy of the policy responses that might follow from the predictions. Given the enormous uncertainties in this type of prediction exercise, the policy responses should deal with the uncertainties and the need for flexible responses rather than fixed targets based on projected outcomes⁷.

We have outlined the key issues that need to be considered in undertaking long run emissions projections from an economic point of view. Other researchers with an energy or engineering background would tend to focus on technologies rather than economic drivers of growth. Of course, the two are interrelated and poorly understood in practice and there is room for a variety of approaches in the debate. Nonetheless it is important to use best practice when undertaking such a complex task.

In this paper we have illustrated how projections of global economic activity and emissions are undertaken with the G-Cubed multi-country model and how imprecise relationships between economic growth and carbon emissions can be depending on the source of that growth. There are a number of differences between the approaches taken in the SRES and the approach we take using the G-Cubed model. These range from the role of economic growth to the implications of technology, autonomous energy efficiency improvements and structural change in understanding future emissions.

Projecting emissions requires projecting the levels of activities that produce those emissions. For emissions from fossil fuel combustion, this essentially means projecting energy use within the economy as well as projecting the way in which that energy will be generated. Both the level of GDP growth, and the relationship between GDP and emissions, will depend on the composition of growth, and the

⁷See McKibbin and Wilcoxon (2002a, b) for a long discussion of the range of uncertainties in climate change.

relative importance of the various drivers of economic growth. There is no single aggregate relationship between GDP and emissions, and there is also no single simple measure of AEEI that would mediate between GDP and emissions. Rather, the level of emissions depends on the composition of growth. Projecting emissions therefore requires at the least a model that distinguishes between sectors within an economy.

Within the G-Cubed framework that we use here, the fundamental drivers of growth are population growth and technical change, where this technical change is to be understood at the sectoral level. While there are many ways of projecting technical change at the sectoral level, the default approach that we use with G-Cubed is a variant of a convergence model. Here convergence is not in terms of GDP per capita or some exogenously specified income measure, but in terms of technical efficiency in input use. What happens to GDP per capita is an endogenous outcome, and may or may not involve convergence.

In our default approach we specify convergence to the US, which is modeled as being on the frontier. We use real income differences (expressed in PPP terms) to define the initial gap between other countries and the US. To explore some implications of what has become known as the Castles and Henderson critique of the SRES, we have looked at the effect of using market exchange rate (MER) income comparisons rather than PPP comparisons to define the initial gap in the G-Cubed model. Using MER instead of PPP measures of initial GDP differences across countries results in total emissions that are 20% higher by 2050, and 40% higher 2100, compared with the case of the PPP measure. The properties of the model are unaffected by whether the base year of the model is in PPP or MER units, but the projections of productivity growth are very different if the rate of convergence is assumed to be the empirically measured rate. The difference in emissions under the two approaches implies a significant overestimate of emissions in using MER measures of GDP. This PPP issue arises because we have chosen to construct our convergence model in a particular way. In this context, PPP is the appropriate base to use for real income comparisons between countries. While this is true in the context of G-Cubed, we cannot say how it applies to other models. A PPP issue does not inevitably arise in projecting emissions, however. First, it is possible to drive projections without using any form of convergence modeling. Convergence is, however, a powerful assumption. Indeed conditional convergence has strong empirical support for some countries. Second, using a convergence model at the sectoral level it is possible to avoid real income comparisons by focusing on productivity comparisons which can be defined in quantity terms using original country data. This approach is considerably more data intensive but also potentially very powerful. While in G-Cubed we find that lowering growth results in lower emissions, this result does not necessarily apply to other models and other scenarios. It is not difficult to construct a model in which emissions and GDP move in opposite directions, which appears to be the case for some of the SRES scenarios. While the PPP critique raises issues of good statistical practice, a far more fundamental issue for emissions projections is the underlying nature of the model used to project productivity changes. This is an area with enormous research potential.

For projecting carbon emissions, it is crucial to understand the drivers of emissions projections and their sensitivity to changes in key assumptions.

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