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Warwick J McKibbin
Peter J Wilcoxen
Wing Thye Woo

International Economy Program

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China Can Grow and Still Help Prevent the Tragedy of the CO2 Commons*

Warwick J. McKibbin
Centre for Applied Macroeconomic Analysis
in the ANU College of Business and Economics;
The Brookings Institution;
The Lowy Institute for International Policy, Sydney
Warwick.Mckibbin@anu.edu.au
&
Peter J. Wilcoxen
The Maxwell School, Syracuse University;
The Brookings Institution
wilcoxen@maxwell.syr.edu
&
Wing Thye Woo
The Brookings Institution;
University of California, Davis
Central University of Finance and Economics, Beijing
wwoo@brookings.edu

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Abstract

Under reasonable assumptions, China could achieve parity in living standard with Western Europe by 2100, and India by 2150. Climate change, however, may be a key obstacle preventing such a convergence. The business-as-usual (BAU) growth path of the world might increase concentration of atmospheric to unsafe levels and cause significant negative environmental feedback before China achieves parity in living standards with the OECD countries. We use a dynamic multi-country general equilibrium model (the G-Cubed Model) to project a realistic BAU trajectory of CO2 emissions, and we find it to be even above the CO2 emissions from the high-growth scenario estimated by the Energy Information Agency in 2007. This outcome is a reminder that it has been usual so far to underestimate the growth in China energy consumption.

We compare the merits of the different market-based CO2 reduction mechanisms like a carbon tax, a cap-and-trade scheme, and the McKibbin-Wilcoxen Hybrid (MWH) approach. Unexpected developments cause the different CO2 reduction mechanisms to create very different costs. Both the international carbon tax and the MWH approach are more economically efficient responses to uncertainty than the cap-and-trade scheme of the Kyoto Protocol. We use the G-Cubed Model to study the economic outcomes under each CO2 reduction mechanism, and under the deployment of advanced green energy.

The reduction of CO2 emissions would only delay, not stop, the increase in CO2 concentrations toward the "danger level". As the only long-term solution is likely to be shifting to non-fossil emitting energy, it is important to combine a market-based CO2 reduction mechanism with an ambitious program to accelerate the development of green technology. Such a program would probably have a higher chance of success if some important parts of it were based on international collaboration. We conclude the paper with recommendations about the form of future international climate agreements and how China could be encouraged to participate.

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1. On the Road to Prosperity

China and India have finally embarked on the path of modern economic growth. China has grown at an average annual rate of almost 10 percent for the past thirty years, and India has grown above 8 percent every year since 2004. Just like the experiences of post-1868 Japan and post-1960 South Korea and Taiwan, China and India are now on the trajectory of catch-up growth that would bring them in the long-run to the same living standard as Western Europe, Japan and the United States. At that point in time, the share of world income produced by China and India would equal their share of world population (which is anticipated to be about 35 percent).

This projected parity in living standards in the long-run would represent a return to the world economic situation that had persisted in the first 1,600 years of the Gregorian calendar (see Table 1). In year 0, China and India had 58 percent of the global population and 59 percent of global GDP in that year; and the respective numbers in year 1600 were 53 percent and 52 percent (despite the growing divergence in GDP per capita with Western Europe from 1500 onward). The relatively slow growth of China and India in the last four hundred years, however, changed the situation dramatically. By 1973, China and India's share of world GDP had fallen to only 7.7 percent although the two countries accounted for 37 percent of world population. The economic deregulation and integration in the world trade and financial systems by China since 1978 and by

India since 1991 have raised their share of world GDP to 20.6 percent in 2003.[1] Given the still large gap between the average income in China and Western Europe in 2003 -- $4,803 and $19, 912 respectively (measured in 1990 International Geary-Khamis dollars, henceforth denoted as 1990$[2]) -- continued high growth in China could continue for the next two decades.

The very likely return of China to the center stage of the global economy has given rise to immense optimism on some fronts, and intense pessimism on a number of other fronts. Optimistic analysts have predicted that China's re-emergence as an independent growth pole would create a new web of synergistic relationships that would unleash greater global prosperity. On the other hand, pessimistic analysts have pointed out that the major new rising powers in the 20th Century had come into conflict with the existing powers: Germany and First World War, the Japan-Germany axis and Second World War, and the Soviet Union and the Cold War.

The important lesson from the history of the 20th Century, however, is not that conflict is inevitable but that rising powers and existing powers should work hard together to avoid past mistakes; to falsify Karl Marx's quip that "history repeats itself, first as tragedy, second as farce." It is really not naive to think that conflict is preventable because the most important power to rise and prevail in the 20th Century was the United States and it has, in general, been a stabilizing force in the international order. Averting the pessimistic outcome requires adherence

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[1] The Japanese growth experience since 1870 clearly suggests that the income disparity between China and Western Europe is not independent of Chinese economic policies. In 1870, the average Japanese income was 37 percent than of the average Western European income, but after a century of policy-induced convergence of economic institutions in Japan to those in Western Europe and the U.S., average Japanese income in 1973 was equal to average income in Western Europe. The growth experiences of South Korea and Taiwan since the early 1960s confirmed that catching-up growth was not unique to Japan.

[2] Unless otherwise specified, all $ numbers refer to 1990$.

to the multi-lateralist principle of the existing powers accommodating rising powers, and the latter becoming responsible stakeholders in the international system.

The dialogue between the existing and rising powers must necessarily be comprehensive because the range of global public goods that must be supplied is very broad (ranging from the maintenance of the Universal Postal System to the peaceful use of outer space), and the nature of some of these global public goods are highly complicated (e.g. a scheme to control the emission of greenhouse gases). In this paper, we will confine discussion to an economic issue where the need to engage China in constructive dialogue is important for sustainable global growth. The issue is the protection of the world environmental commons by addressing China's emissions of carbon dioxide (CO2).

The paper is organised as follows. Section 2 makes the case that climate change could be a key obstacle for China. It shows that even under conservative assumptions, the business-as-usual (BAU) growth path might cause an environmental collapse before China achieves parity in living standards with the OECD countries. Section 3 reviews the history of energy production and consumption in China, and then uses a dynamic multi-country general equilibrium model (the G-Cubed Model) to project a realistic BAU trajectory of CO2 emissions. Section 4 proposes a novel hybrid policy as an alternative to the commonly-discussed cap-and-trade mechanism to control CO2 emissions. Section 5 employs the G-Cubed Model to examine the economic consequences of the different instruments to reduce CO2 generation. Section 6 concludes the paper with recommendations about the form of future international climate agreements and how China can be encouraged to participate.

2. The Fallacy of Composition in Modern Economic Growth?

We started this paper with the optimistic projection that China and India would achieve parity in living standards with Western Europe, which immediately leads to the question of when this convergence would occur. During the 1913-2003 period, when Japan was on the catch-up growth trajectory, the annual growth rate of average income was 3.1 percent in Japan, and 1.9 percent in Western Europe and the United States. It is possible to use this information to undertake a very crude back-of-the-envelope calculation to see what stresses might begin to emerge over time. Suppose we assume:

- Western Europe would grow 1.5 percent annually from 2003 onward; and
- China and India would grow 3.1 percent annually from 2003 until reaching parity with Western Europe, and then 1.5 percent annually.

Under these assumptions, China would achieve income parity with Western Europe by 2100, and India by 2150.[3] The common GDP per capita in 2150 would be about $180,000.

This extrapolation might fail to be realised, however, not because of political reasons as commonly feared but because of environmental reasons. It would not be wars that would derail the catch-up growth; rather, the growth process could prove to be unsustainable because of the fallacy of composition. Specifically, it is possible that a continual improvement in living standards might be achievable for a small subset of large countries, but not for all large countries together. A global equilibrium with a common living standard, which existed in the first millennium, might not be replicable in 2150 because the earlier situation was a agriculture-dominated equilibrium where the average income was stagnant at $440. In contrast, the

[3] At these growth rates, GDP per capita in 2100 would be $84.4 thousand in Western Europe, and $92.8 thousand in China; and GDP per capita in 2150 would be $177.7 thousand in Western Europe and $192.1 thousand in India.

envisaged global equilibrium would have an average income of $180,000, which would be growing at 1.5 percent annually.

The difference is between the vicious circle of Malthusian growth and the process of what Simon Kuznets (1966) has labeled "modern economic growth (MEG)." In MEG, society is urbanised, the economy is industrialised and increasingly service-oriented, and human capital rivals physical capital in contribution to economic growth. A key ingredient, so far, in this historically unprecedented sustained growth in prosperity has been energy from fossil fuels. The result is that the concentration of CO2 in the Earth's atmosphere has risen from 280 parts per million (ppm) in the pre-industrial age to 379 ppm in 2005.[4]

Under existing energy technologies, the scale of growth in China and India would be associated with a very large increase in global CO2 emissions and with rapidly rising CO2 concentrations. There is now a substantial literature suggesting that the increase in CO2 concentrations has contributed substantially to global warming and climate change.[5] According to the Intergovernmental Panel on Climate Change (IPCC), climate change has:

- "*very likely* contributed to sea level rise during the latter half of the 20th century
- *likely* contributed to changes in wind patterns, affecting extra-tropical storm tracks and temperature patterns
- *likely* increased temperatures of extreme hot nights, cold nights and cold days
- *more likely than not* increased risk of heat waves, area affected by drought since the 1970s and frequency of heavy precipitation events

[4] Intergovernmental Panel on Climate Change (2007, p37); henceforth referred to as IPCC (2007)

[5] The possibly most authoritative recent statement of this position is IPCC (2007).

- led to the ocean becoming more acidic with an average decrease in pH of 0.1 units."[6]

There is serious concern in IPCC reports that there could be severe and irreversible problems resulting from climate change.[7] What is the level of the threshold CO2 concentration that would unleash calamity on the world economy and human life? The truth is that we do not know. David King, the chief scientific advisor to the British government, suggested that "we should prevent atmospheric CO2 [concentrations] going beyond 500 ppm",[8] and Michael Raupach, an Australian atmospheric scientist, advocated a limit of 550 ppm.[9] It has become quite common to adopt the position that the threshold CO2 concentration for dangerous consequences is 560 ppm -- a doubling of the pre-industrial value of 280 ppm. Of course, the possibility that the threshold is 500 ppm or even 840 ppm cannot be ruled out definitively on *a priori* grounds.

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[6] Quotes are from IPCC (2007). The first four effects are from page 6, and the fifth from page 9. On the last effect, IPPC added that "while the effects of observed ocean acidification on the marine biosphere are as yet undocumented, the progressive acidification of oceans is expected to have negative impacts on marine shell-forming organisms (e.g. corals) and their dependent species."

[7] "As global average temperature increase exceeds about 3.5°C, model projections suggest significant extinctions (40 to 70% of species assessed) around the globe." (IPPC, 2007, pp.13-14)

[8] Kirby (2004). The tipping point is defined as when the melting of the Greenland ice cap becomes irreversible.

[9] Beer (2007). Raupach is quoted as saying:

> " ... if we manage to bring CO2 to equilibrium at 450ppm, we would be looking at a temperature rise of 1 to 1.5 degrees above pre-industrial levels, some changes to rainfall patterns, some melting of the Arctic, significant acidification of the oceans through CO2 rise and so forth. But these are issues which would not cause widespread devastation .... If we reach 550ppm, we're getting into 2 to 2.5 degree temperature rise and the amount of climate damage that we would be looking at will in some cases would probably involve crossing thresholds that we can't recover from. If we keep on the present growth projectory then we get there by about 2046."

At the present increment rate of 2 ppm of atmospheric CO_2 annually, the 560 ppm mark would be breached by 2100 just when China is about to reach parity in living standard with Western Europe.[10] If there were indeed a catastrophic threshold at CO_2 concentration of 560 ppm, then China and India could achieve income parity with Western Europe, Japan and the USA in 2150 only because the environmental collapse triggered by the growth of the former brought down to the incomes of the latter! This new equilibrium of income parity produced by the "fallacy of composition" could well be characterized by global acrimony and strife.

The crucial point is that one does not have to accept the existence of a catastrophic threshold level of CO_2 concentration in order to conclude that unless there are future revolutionary breakthroughs in green technology or fundamental shifts in the nature of economic growth, China and India could achieve income parity with the rich countries only by creating serious global environmental problems. Clearly China is one of the key countries that need to be brought into the global framework with a clear commitment to take action on greenhouse gas emissions.

Moreover, it is important to bring China quickly into an international agreement because its dramatic recent rise in energy use and greenhouse gas emissions has been unanticipated by most analysts, and the potential for further upside surprises on emissions remains as China's strong growth could be more durable than anticipated. For example, the Energy Information Administration (EIA) of the United States Department of Energy provides projections of CO_2 emissions by major countries in its annual *International Energy Outlook*. The EIA makes projections for Chinese energy consumption for three scenarios – high economic growth, the reference case, and low economic growth.

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[10] Increment was 2.08 ppm in 2002 and 2.54 ppm in 2003, see Kirby (2004). The concentration of atmospheric CO_2 is taken to be 380 ppm in 2008.

Figure 1 reports projections from the *2002 International Energy Outlook* and the *2007 International Energy Outlook*. The shocking fact is that for the future years that were overlapping in both reports, in every case China's projected energy consumption in the *low*-growth scenario in the 2007 report was above the projected energy consumption in the *high*-growth scenario in the 2002 report. The 2002 high-growth forecast for 2020 was 102.8 quadrillion BTU and the 2007 low-growth forecast for 2020 was 106.6 quadrillion BTU. The 2002 "reference case" forecast was 84.4 quadrillion BTU in 2020, and the 2007 "reference case" forecast was 112.8 quadrillion BTU in 2020 – an upward revision of 33.6 percent. Even more important, CO2 emissions in 2005 were 50% higher than the forecast made in 2002.

3. Past and Future Pattern of Energy Use and Carbon Dioxide Emissions in China

China is now the second largest user of energy in the world after the United States, and is projected by the Energy Information Agency (2007) to be the largest by 2025 – see Table 2 – when China would consume 19.6 percent of the world supply of energy and the US would consume 19.0 percent. China would, however, become the world's biggest emitter of CO2 earlier than 2025. In 2015, China would account for 20.7 percent of global CO2 emission while using 17.4 percent of global energy, and the same figures for the US would be 19.4 percent and 20.1 percent respectively. This is partly because China is anticipated to expand in its use of fossil fuels.

The fuel composition of energy consumption in China is shown in Figure 2. Much of the recent rise in energy consumption took the form of increased use of coal. Coal has been the major energy source in China throughout the period of growth since the reforms in the early 1990s. The surge in energy use since 2002 is obvious from the figure, and it resulted from a number of factors including rising GDP growth since 1998 (Figure 3) as well as a recent rise in the energy intensity of GDP (Figure 4). The shift in the energy intensity of the Chinese economy was due to a number of factors driving structural change including: increased electrification; greater energy demand from manufacturing; greater energy demand by households; and greater use of cement and steel as infrastructure spending has risen.

Perhaps more interesting than the historical experience of Chinese energy use are future trends in both energy and greenhouse gas emissions, particularly since a more worrying picture for global climate has emerged in the last half-decade. Projecting future energy use and greenhouse gas emissions in China, especially over horizons of more than a decade, is very difficult. It is tempting to construct future projections by simple extrapolation of recent trends. A somewhat more sophisticated approach is to apply the Kaya Identity[11], which decomposes emissions growth into four components: changes in emissions per unit of energy, changes in energy per unit of per capita GDP, growth of per capita GDP, and population growth. The four components are then projected separately. This is the approach taken, for example, in many of the studies cited by the IPCC (2007) and by Garnaut, et al., (2008).

However, the Kaya Identity is a useful historical decomposition but it is not an ideal forecasting framework. Each of its components is actually an endogenous outcome resulting from a wide variety of individual decisions, and cannot be assumed to remain constant in the future. As shown by Bagnoli, McKibbin and Wilcoxen (1996), and McKibbin, Pearce and Stegman (2007), overall economic growth is not the only important determinant of energy use. Identifying and understanding the underlying sources of economic growth is critical, and it is particularly important to understand how the structure of an economy evolves in response to changes in energy prices.

[11] See Kaya (1990)

Figure 5 shows EIA projections for carbon dioxide emissions by energy source in China for the reference case scenario. It is clear that coal is the overwhelming source of carbon dioxide emissions in China, both historically and in these projections. It is expected to be the major source of energy, and therefore emissions, in the foreseeable future. This is not surprising given the large quantity of low cost coal available in China and the assumptions of unchanging relative energy prices in these projections. Over time, the share of emissions from petroleum is projected to rise with greater use of motor vehicles and other transportation. These types of projections are very dependent on assumptions about the relative price of energy to other goods and the relative price of alternative energy sources.

Figure 6 shows the global sources of carbon dioxide from burning fossil fuels, by region, in 1990 and that projected by in the *2007 International Energy Outlook* for the year 2030. Not only is China currently an important source of carbon dioxide emissions, it is expected to grow quickly as well. Its absolute size shown in Figure 6 and its share in global emissions (shown in Table 1) emphasize that China is a critical country in the debate over policies to deal with climate change.

We now present our own projections of carbon dioxide emissions from the G-Cubed multi-country model.[12] A summary of the approach is provided here but further details on the technique used in the G-Cubed Model can be found in McKibbin and Wilcoxen (2007). In the following discussion, the sources of economic growth are labor-augmenting technical change at the industry level, and population growth. The population growth assumptions are based on the 2006 UN population projections (Mid-Scenario). In order to simplify the discussion, labor augmenting technical change is referred to as "productivity growth" throughout the remainder of this paper.

[12] See McKibbin and Wilcoxen (1998) and documentation at http://www.gcubed.com

In the G-Cubed Model, productivity growth by sector and by country is assumed to be driven by a productivity catch-up model. The United States is assumed to be the technological leader in each sector. Other countries are allocated an initial productivity gap by sector and a rate at which this gap is closed. For industrial countries and China this is assumed to be a time-varying rate which on average is two percent per year from 2006. For other developing countries it is assumed to range between two percent per year and one percent per year depending on the region. In this paper, initial Chinese productivity is assumed to vary across sectors and averages around 20 percent of the productivity in the equivalent sector in the United States in 2002.

The results from the G-Cubed Model for Chinese carbon dioxide emissions are shown in Figure 7. This has a business as usual baseline (BAU) as well as two other lines which will be discussed in section 5 below which involve different assumptions about policy interventions. The BAU projections from G-Cubed are higher than the projections in EIA (2007). CO2 emissions in:

- the EIA low-growth scenario rose from 6,400 million metric tons in 2010 to 10,143 million metric tons in 2030;
- the EIA reference case scenario rose from 6,497 million metric tons in 2010 to 11,239 million metric tons in 2030;
- the EIA high-growth scenario rose from 6,615 million metric tons in 2010 to 12,500 million metric tons in 2030; and
- the G-Cubed Model rose from 7,855 million metric tons in 2010 to 14,114 million metric tons in 2030.

The difference between the EIA projections and those of G-Cubed is reminiscent of the difference between the 2002 and 2007 EIA projections. The higher projections by G-Cubed come from it forecasting a higher economic growth rate in China and a smaller change in the energy intensity of GDP in China (the latter being an endogenous result of the assumptions imposed about sectoral productivity growth in China) than the EIA (2007). It must be stressed, however, that our G-Cubed projections (like projections by others) are highly uncertain and change quite significantly if assumptions about the rate of catch-up are varied.

4. The Principles to Guide Reduction in CO2 Emissions

There are many vexing fundamental issues in deciding how to prevent catastrophic climate change. Amongst these issues are:

- There is still much about the science of climate change that we do not fully understand. Is climate change a linear or an abrupt discontinuous function of CO2 concentration?[13] Is there are saturation point in the absorptive capacity of the Earth's sinks for atmospheric CO2?
- There are immense difficulties in computing the costs and benefits of climate change. How should we value irreversible events like species extinction? How should we value the benefits to the present generation and the costs to the not-yet-born future generations?
- There are serious challenges to designing effective implementation and oversight mechanisms for the CO2 reduction process. How can national CO2 caps be enforced? How can we build in incentives for mutual policing among the polluters dispersed round the world?

[13] Gulledge (2008, pp.52) has described the proposition that "future climate change will be smooth and gradual" as a myth: "The history of climate reveals that climate change occurs in fits and starts, with abrupt and sometimes dramatic changes rather than gradually over time." Figure 3-1 in Gulledge (2008) makes this point dramatically by the time profile of the number of storms of tropical hurricane force in the North Atlantic in the 1930-2007 period.

- The reduction of CO_2 emissions would only delay, not stop, the increase in CO_2 concentrations toward the "danger level". The only long-term solution is likely to be shifting to non-fossil energy. It is, however, impossible to know when this alternative fuel would be available at commercially viable costs, and at the vast scales that will ultimately be required. If the CO_2 reduction mechanism is designed to buy time for this development, how long will we need?
- There is unlikely to be an amicable way to distribute the burden of reducing CO_2. Should the existing polluters be "grandfathered" into the international treaty? What should be the relative burden for the rich, middle-income, and poor nations? Alternatively, should the cap be based on CO_2 allowances per person?

The world, obviously, cannot afford to continue on the BAU path until there is broad consensus on most of the above issues. Rates of CO_2 emissions are increasing, the tangible consequences of climate change are already evident, and there is the real possibility that "projections from climate models have been too conservative."[14] The sense of urgency is real, and this is why a large part of the world signed the Kyoto Protocol on December 11, 1997 as a pragmatic way to effect at least a temporary improvement over the business-as-usual (BAU) situation. The signatories from industrial countries agreed to reduce their CO_2 emissions in the 2008-2012 period to 95 percent of their 1990 levels on average (that is, 5 percent below their 1990 emissions) , and to allow the permits for CO_2 emissions to be tradable internationally. China was not required to undertake any reduction obligations because it was a developing

[14] Gulledge (2008, pp.56) pointed out that "the models used to project future warnings either omit or do not account for uncertainty in potentially positive feedbacks that could amplify warming (for example, release of greenhouse gases from thawing permafrost, reduced ocean and terrestrial CO_2 removal from the atmosphere), and there is some evidence that such feedbacks may already be occurring in response to the present warming trend."

country. The United States signed the treaty but never ratified it because it exempted large developing countries, particularly China and India. Since US and China are the world's two largest CO2 emitters,[15] the Kyoto Protocol was rendered grossly inadequate as a CO2 reduction mechanism. Nordhaus (2008, pp.92) has estimated that global emissions in 2010 under the Kyoto Protocol would only be 1.5 percent lower than under the BAU outcome.

To be effective, any CO2 reduction scheme must include as many of the large CO2 emitters as possible and it should move them toward substantial long-term reductions in emissions. There are three classes of market-based mechanisms that could put the world on this agreed global CO2 emissions path:

- mechanisms that do not specify the CO2 emissions path for each country, e.g. a global carbon tax; and
- mechanisms that specify an "immediately binding" CO2 emissions path for each country, e.g. a domestic cap-and-trade scheme, an international cap-and-trade scheme; and
- mechanisms that specify a CO2 emissions path that is "not immediately binding", e.g. a domestic carbon tax, the McKibbin-Wilcoxen Hybrid (MWH) approach.

In practice, actual emissions are unlikely to hit target emissions at every point in time. We label the quantity target to be "immediately binding" if the emissions above the target are explicitly penalized. The quantity target is labeled "not immediately binding" when the above-target emissions pay the same carbon tax as the below-target emissions, and the carbon tax is later adjusted to bring anticipated emissions to the target path. Naturally, the global and national target paths, and the level of international and domestic carbon taxes are modified over time to

[15] Table 2 reports that US and China accounted for 35.2 percent of global CO2 emissions in 2004, and would account for 39.1 percent in 2010.

take in account of how close the actual emissions have been to target emissions, revelations in abatement costs, and developments (and anticipated developments) in areas like technology.

The Global Carbon Tax

Given a desired time path of global CO2 emissions, it could be possible to identify a time-varying common carbon tax that would motivate the private sectors in each country to hold collective CO2 emissions to the target amount in the absence of unexpected developments. A global carbon tax would have to be revised at fixed periods in light of its performance, improvements in technology, advances in scientific knowledge, and new information and ideas. The global carbon tax has the virtue of not distorting the comparative advantage of the different countries.

Since much of the increase in atmospheric CO2 concentrations since the Industrial Revolution has been due to the rich countries, perhaps developing countries could be exempted from the global carbon tax for a period of time or after they have reached a certain level of income.

The Domestic Carbon Tax

A carbon tax could be applied at the domestic level as well. Given a time profile of desired CO2 emissions for a country, it would be possible to identify the carbon tax required to achieve it. However, this approach is likely to be inefficient in the global sense because it would not guarantee that the marginal cost of emissions reductions would be the same across countries. The probable outcome would be a distortion of comparative advantage. Again, developing countries might be exempted temporarily from having to impose this domestic carbon tax.

Domestic Cap-and-Trade

A country could issue emissions permits to match a national target emissions path. The permits could be given free to existing CO2 emitters or auctioned to the general public, and would be tradable within the country but not across borders. This approach, like the domestic carbon tax, is unlikely to produce a globally efficient pattern of abatement. The developing countries might be given ceilings on CO2 emissions that are binding only when they attain a particular income level.

International Cap-and-Trade

An international treaty that establishes a global CO2 emissions path and allocates CO2 emissions among countries could also allocate internationally-tradable emission permits to the countries. The Kyoto Protocol falls under this category. The developing countries could be given more permits than they would need for their current emissions, and they could then sell the excess and use the revenue to accelerate development and buy green technology. This approach would equate the costs of abatement at the margin and does not distort comparative advantage.

5. The McKibbin-Wilcoxen Hybrid (MWH) Approach

McKibbin and Wilcoxen (2002a, 2002b) have proposed a hybrid approach that combines:

- an internationally-determined path for emissions reductions for each country, which is translated into a limited supply of long-term national permits, with
- sales of annual national permits (in order to accommodate deviations from a national path) sold at a price that is determined by international negotiations, say, every five years.

Both types of permits would be only valid in the country of issue: there would be no trade across borders.[16] Every year, firms would be required to hold a portfolio of permits equal to the amount of carbon they emit.[17] The portfolio could include any mix of long-term and annual permits. The long-term permits could be owned outright by firms, or they could be leased from other permit owners. Except for the case of developing countries, which we will discuss in detail later, the amount of long-term permits for each country would be intentionally set lower than the anticipated amount of emissions (e.g. set below the target emissions path). If the target turns out to be sufficiently tight, there will be demand for the annual permits, which will impose an internationally-fixed upper bound on the short term price of carbon emissions.

Each country would manage its own domestic hybrid policy using its own existing legal system and financial and regulatory institutions. There would be no need for complex international trading rules, or for the creation of a powerful new international institution, or for participating governments to cede a significant degree of sovereignty to an outside authority. The international dimension of the McKibbin-Wilcoxen Hybrid (MWH) consists of two actions: (a) setting a notional (or "aspirational") greenhouse gas (GHG) emissions trajectory for each country, and (b) harmonizing the price of annual permits across participating countries.[18]

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[16] Strictly speaking, the term "country" is too narrow. The permits would be valid only within the political jurisdiction of issue. If the relevant jurisdiction is multinational—the EU, for example—permits could be traded between countries within the broader jurisdiction.

[17] This approach is known as a downstream policy because it applies to fuel users. It would also be possible to apply the policy upstream by imposing limits on the carbon embodied in fuels when they are produced (e.g., at the mine mouth or wellhead).

[18] The negotiations, of course, would not be trivial: getting agreement on the annual price would require considerable diplomacy. It is interesting to note that a treaty of this form has a strong built-in incentive for countries to participate in the initial negotiations. Countries that participate will have a role in setting the annual price while those who remain on the sidelines will not. We are indebted to Jonathan Pershing for pointing this out.

The number of long-term permits would be guided by the international negotiations over the target emissions path for the country. For example, the international treaty establishing the MWH mechanism could suggest that signatories distribute no more long-term permits than their allotments under the Kyoto Protocol. The number of long-term permits would be set when a country joins the scheme, but the country's government would have considerable flexibility in how the permits were used. A government that wished to tackle climate change more aggressively could choose to distribute few long-term permits;[19] and a government that prefers a carbon tax could distribute no long-term permits at all.[20] The treaty would not need to specify rigid allocations of long-term permits because emissions will generally be controlled at the margin by the price of annual permits. The number of long-term permits only affects the distribution of permit revenue between the private sector and the government; it does not affect the country's total emissions. Distributing a small number of long-term permits means the government will earn a lot of revenue from annual permit sales, but it may also lead to significant political opposition. Distributing a larger number means less government revenue but the permits would be very valuable to the private sector and permit owners could be expected to form a powerful lobby in support of the policy. In either case, one country's decision has little effect on other signatories.

Long Term Permits

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[19] Countries have different degrees of concern about climate change and different abilities to implement climate policies. A coordinated system of hybrid policies provides participants with the ability to tailor the policy to their own circumstances.

[20] A government might prefer a carbon tax if it lacks the institutional and administrative mechanisms needed to operate a permit market.

A 100-year permit would be akin to a book of 100 coupons, with each coupon corresponding to a particular year and stating the amount of GHG emissions the holder is entitled to emit. In line with a declining level of target emissions, the coupon for each year would allow a smaller amount of GHG emissions than the previous year. Once distributed, the long-term permits could be traded among firms, or bought and retired by environmental groups. The permits would be very valuable because: (1) there would be fewer available than needed for current emissions, and (2) each permit allows annual emissions over a long period of time. As a consequence, the owners of long-term permits would form a private-sector interest group which would greatly enhance the long-term credibility of the policy: permit owners would have a clear financial interest in keeping the policy in place.

When initially distributed, the long-term permits could be given away, auctioned, or distributed in any other way the government of the country saw fit. One option would be to distribute them for free to industry in proportion to each firm's historical fuel use, e.g. a firm might receive permits equal to 90% of its 1990 carbon emissions. Such an approach would be relatively transparent and would limit the incentives for lobbying by firms. Although the allocation would be based on historical emissions, the tradability of the permits mean that they are not tied in any way to the original recipient or any particular plant, and hence would not create differences in marginal costs across firms or plants. Moreover, the existence of annual permits limits the ability of incumbent firms to create entry barriers by keeping their long-term permits off the market: entrants could simply buy annual permits. Incumbent firms would benefit financially from the initial distribution of permits, but unless they were previously liquidity-constrained, they would not be able to use their gains to reduce competition.[21]

[21] In passing, it's worth noting that anti-competitive behavior by the incumbents, while unlikely, would have an environmental benefit: it would reduce overall carbon emissions.

Another alternative would be to auction the permits. Auctioned permits would be exactly like a carbon tax except that the industry would have to pay the entire present value of all future carbon taxes up front. As the number of long-term permits was intentionally kept below the target path of emissions, at least a few annual permits would be sold in every year. The price of a permit during the auction would be bid up to the present value of a sequence of annual permit purchases.

Annual Permits

The government would sell annual permits for an internationally-agreed price, say for $20 per ton of carbon. There would be no restriction on the number of annual permits sold, but each permit would be good only in the year it is issued. The annual permits give the policy the advantages of an emissions tax: they provide clear financial incentives for emissions reductions but do not require governments to agree to achieve any particular emissions target regardless of cost. The existence of the annual permits introduces a degree of flexibility in the target. Over time the global carbon price would be readjusted if either the global target were not being met as well as desired or if the global target were changed because of new information about climate science or marginal abatement costs.

Treatment of Developing Countries

To be effective in the long run, the agreement will eventually need to include all countries with significant greenhouse gas emissions. However, it is unlikely that all countries will choose to participate at the beginning. Developing countries, for example, have repeatedly pointed out that current greenhouse gas emissions are overwhelmingly caused by industrialized countries, and that those countries, therefore, should take the lead in reducing emissions. As a result, an international climate policy will need to cope with gradual accessions taking place over many years. Its design, in other words, must be suitable for use by a small group of initial participants, a large group of participants many years in the future, and all levels in between.

One important role for the treaty's long-term permit guidelines would be to distinguish between developed and developing countries. For example, a country like China would be allowed to distribute more long-term permits than needed for its current carbon emissions. In that case, it would be committing itself to slowing carbon emissions in the future, but would not need to reduce its emissions right away. As the country grows, its emissions will approach the number of long-term permits. The market price of long-term permits would gradually rise, and fuel users would face increasing incentives to reduce the growth of emissions. Once the long term target becomes a constraint, annual permits would begin being sold and would smooth out the evolution of annual carbon costs.

A generous allotment of long-term permits would reduce the disincentives to join faced by developing countries, but that alone might not be enough to induce widespread participation. If stronger incentives are needed, it would be possible to augment the treaty with a system of foreign aid payments or with programs for technology transfer to participating developing countries.

The Firewall of Separate Markets under MWH

Because the permit markets under this policy are separate between countries, shocks to one permit market do not propagate to others, e.g. accession by a new participant has no effect on the permit markets operating in other countries.[22] Likewise, collapse of one or more national

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[22] In contrast, a conventional international permit system could be particularly difficult to enforce because of the links it creates between countries. Restricting sales of permits by non-complying

permit systems would be unfortunate in terms of emissions control, but it would not cause permit markets in other countries collapse as well. In contrast, under the Kyoto Protocol shocks in one country — ineffective enforcement, or withdrawal from the agreement, for example — would cause changes in permit prices around the world. For both permit owners and permit users, investments in emissions reductions would be more risky under the Kyoto Protocol.

Compartmentalization is especially important for a climate change agreement because of the uncertainties surrounding climate change: it must survive through intervals where warming seems to be proceeding more slowly than expected, which could create political pressure to abandon the agreement on the grounds that it is not necessary. Such intervals could arise because of random fluctuations in global temperatures from year to year, or because the policy is actually succeeding in reducing the problem. The latter point is worth emphasizing: if a climate regime is successful at reducing warming and preventing significant damages, it will be easy for complacency to arise: many people may interpret the absence of disasters to mean that the risks of climate change were overstated.

Another advantage of multiple national permit markets, rather than a single international one, is that the incentives for enforcement are stronger. Individual governments would have little incentive to monitor and enforce an international market within their borders. It is easy to see why: monitoring polluters is expensive, and punishing violators would impose costs on domestic residents in exchange for benefits that will accrue largely to foreigners. There would be a strong temptation for governments to look the other way when firms exceed their emissions permits. For a treaty based on a single international market to be effective, therefore, it will need

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countries, as would be required under the Kyoto Protocol, would harm the interests of compliant countries by raising permit prices. The international links between permit markets thus provide a strong incentive against enforcement of the agreement.

to include a strong international mechanism for monitoring compliance and penalizing violations. National permit markets reduce the problem substantially because monitoring and enforcement becomes a matter of enforcing the property rights of a group of domestic residents — the owners of long-term permit — in domestic markets.

Incentives for Investments in CO2 Reduction under MWH

The MWH mechanism is argued by some to be more complex than an emissions tax or conventional permit system but it is more likely to encourage private sector investments in capital and research that will be needed to address climate change. To see why, consider the incentives faced by a firm after the policy has been established. Suppose it has the opportunity to invest in a new production process that would reduce its carbon emissions by one ton every year. If the firm is currently covering that ton by buying annual permits, the new process would save it $20 per year every year. If the firm can borrow at a 5% real rate of interest, it would be profitable to adopt the process if the cost of the innovation were $400 or lower. For example, if the cost of adoption were $300, the firm would be able to avoid buying a $20 annual permit every year for an interest cost of only $15; adopting the process, in other words, would eliminate a ton of emissions and raise profits by $5 per year.

Firms owning long-term permits would face similar incentives to reduce emissions because doing so would allow them to sell their permits. Suppose a firm having exactly the number of long-term permits needed to cover its emissions faced the investment decision in the example above. Although the firm does not need to buy annual permits, the fact that it could sell or lease unneeded long-term permits provides it with a strong incentive to adopt the new process. To keep the calculation simple, suppose that the permits are perpetual and allow one ton of emissions per year. At a cost of adoption of $300, the firm could earn an extra $5 per year by borrowing money to adopt the process, paying an interest cost of $15 per year, and leasing the permit it would no longer need for $20 per year.

The investment incentive created by MWH rises in proportion to the annual permit fee as long as the fee is low enough to be binding – that is, low enough that at least a few annual permits are sold. For example, raising the fee from $20 to $30 raises the investment incentive from $400 to $600.

The upper limit on incentives created by the annual fee is the market-clearing rental price of a long-term permit in a pure tradable permit system. Above that price, there would be enough long-term permits in circulation to satisfy demand and no annual permits would be sold. For example, if long-term permits would rent for $90 a year under a pure permit system, the maximum price of an annual permit under the hybrid will be $90.

The critical importance of credibility becomes apparent when considering what would happen to these incentives if firms are not sure the policy will remain in force. If the policy were to lapse at some point in the future, emissions permits would no longer be needed. At that point, any investments made by a firm to reduce its emissions would no longer earn a return. The effect of uncertainty about the policy's prospects is thus to make the investments it seeks to encourage substantially more risky.

Since the incentives created by the policy increase with the price of an annual permit, a government might try to compensate for low credibility by imposing higher annual fees. For example, suppose a government would like a climate policy to generate a $400 incentive for investment but firms believe that there is a 10% chance the policy will be abandoned each year. For the policy to generate the desired incentive, the annual permit price would have to be $60 rather than $20. That is, the stringency of the policy (as measured by the annual permit fee) must triple in order to offset the two-thirds decline the incentives arising from the policy's lack of credibility. In practice, the situation is probably even worse. Increasing the policy's stringency is likely to reduce its credibility further, requiring even larger increases in the annual fee. For example, suppose that investors believe that the probability the government will abandon the policy rises by 1% for each $20 increase in the annual fee. In that case, maintaining a $400 investment incentive would require an annual fee of $70 rather than $60, which would be accompanied by an increase in the perceived likelihood of the policy being abandoned from 10% to 12.5%.

The general lesson is that a low-cost but highly certain policy generates the same incentives for action as a policy that is much more expensive but less certain. A hybrid policy with a modest annual permit price would generate larger investment incentives than a more draconian, but less credible, emissions target imposed by a more conventional system of targets and timetables. The MWH proposal is more credible than a carbon tax because it builds a political constituency with a large financial stake in preventing backsliding by future governments. It is, thus, likely to provide more incentive to the private sector to make investments to reduce greenhouse gas emissions.

Coping with New Information

Over time, more information will become available about climate change, its effects, and about the costs of reducing emissions. If it becomes clear that emissions should be reduced more aggressively, the price of annual permits can be raised. The political prospects for an increase would be helped by the fact that raising the price of annual permits would produce a windfall gain for owners of long-term permits, since the market value of long-term permit prices would rise as well.[23]

If new information indicates that emissions should drop below the number allowed by long-term permits, raising the price of annual permits would need to be augmented by a reduction in the stock of long-term permits. One option would be for each government to buy and retire some of the long-term permits it issued. Other approaches would be possible as well: for example, accelerating the expiration date of the permits.

6. Comparing Methods for Reducing China's CO2 Emissions

Three Market-Based Mechanisms

The Clean Development Mechanism (CDM) of the Kyoto Protocol allows developed countries to use credits for emissions-reducing actions taken in China to help meet their obligations under the protocol. This approach cannot be scaled up sufficiently to have the required effect of significantly reducing China's carbon emissions because it is project-based and has proven very complex and costly to administer.

In this section we show some results for alternative policy regimes and discuss what they imply for emissions and economic growth China. Figure 7 contains various paths of greenhouse gas emissions from energy use in China under three different policy regimes:

- a domestic carbon tax
- an international cap-and-trade scheme, and
- the MWH approach.

[23] Although long term permit owners would welcome an increase in the annual price, there is little risk that they would be able to drive prices up on their own. Given that other energy users provide countervailing pressure to keep energy prices low, it is hard to imagine that permit owners would be able to push a government into adopting an inefficiently high price and excessively stringent emissions policy.

The business as usual line in Figure 7 is the projection of Chinese emissions from energy use from the G-Cubed model under the assumptions already discussed above.

In order to compare the key aspects of the three policy regimes, we assume that all countries take on the emissions reduction path that is contained in the recent IMF World Economic Outlook (2008). Emissions in each country, and for the world as a whole, rise along the BAU path for a number of years, gradually peak in the year 2028, fall back to 90 percent of the 2002 emissions level around 2050, and then drop to 40 percent of the 2002 level by 2100. Along this BAU trajectory China and other developing countries would take on the same commitment as industrial countries but initially with a more gradual reduction target.[24]

In the first policy option, labeled "Country Target" in Figure 7, China reaches its target by implementing a domestic carbon tax. All other countries are assumed to follow a similar strategy and achieve their targets through domestic actions only. This country-by-country targeting achieves a common global outcome but with a wide variety of costs across countries.

The results indicated by the "International Cap and Trade" line in Figure 7 are the emissions outcome when China is given a permit allocation based on its target emissions and is then allowed to buy or sell emissions permits on international markets. China can hence change its emissions outcome by selling permits at the world price (which is thus common to all countries). In the G-Cubed Model under this allocation of permits, China has amongst the lowest marginal abatement costs in the world (i.e., it is much cheaper to reduce a unit of carbon in China than in most other countries, reflecting the energy infrastructure and sources of emissions in China). The outcome is that emissions fall more quickly in China as China cuts its emissions

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[24] The exact details of the target are not central to this paper because we will be comparing alternative policies for reaching a single set of targets. However more rapid cuts in emissions would clearly give different results to those presented here.

domestically to sell permits abroad. Eventually, the marginal cost of abatement in China rises enough to reach equilibrium with the rest of the world.

The third policy option shown in Figure 7 is the McKibbin Wilcoxen Hybrid approach where China is allocated an amount of long-term permits equal to twice its 2008 emissions (which is more than the actual amount of emissions in the first few years of its accession to the international climate treaty) but declining over time at the same rate as other countries.[25] These permits cannot be used outside China and therefore do not directly affect the emissions in other countries. In this case, China's short term carbon price is zero for a number of years because there are more permits available than needed, and emissions in China continue to rise along the BAU path. When China grows enough to reach its emissions constraint, it starts to sell annual permits at the price stipulated by international agreement. Eventually, the carbon emissions path begins to fall until it reaches the emissions outcome under the international cap and trade system. This is not surprising since the uniform price under the McKibbin-Wilcoxen Hybrid is designed to be almost the same as the price that would be delivered under the cap and trade policy[26]. The results are the same because the model is run under conditions of complete certainty about future

[25] The excessive amount of long-term permits in the first few years of the this policy option means that the global emissions of CO2 in the third policy option exceeds the amount of global CO2 emission in the first and second policy option (whose emission equals each other's). It is interesting that if China were given an excessive amount of carbon credits in the second policy option, its emissions path and GDP path would still be the same as shown in Figure 7 and Figure 8 as long as the extra amount of carbon credits given to China is small and hence has no effect on the world price of carbon credits. As production in China is guided by the world price of carbon credits, it would remain unchanged, and China would just sell off the extra carbon credits and cause the global emissions to be larger than under the first policy option (domestic carbon tax) and the original second policy option (international cap-and-trade) where the allocated carbon credits were binding from the beginning.

[26] A difference arises because the transfer of income across countries with different spending patterns can change CO2 emissions and therefore the price required for an equivalent global target path.

events. Under uncertainty, it would be necessary to refine the carbon price iteratively over time to try to reach the desired global target in a "learning by doing" fashion. Under the cap and trade system, however, the target would be reached but at the cost of potentially very high volatility in carbon prices, and therefore economic costs.

Figure 8 shows the GDP outcome for China under the three different policies. The results are expressed a percentage deviation from the BAU path. Under the "country target" and "cap and trade" regimes, GDP begins to fall from the beginning of the regime in 2013. By 2025 the GDP loss to China from the carbon policy is about 1.8 percent per year. The international cap and trade policy leads to slightly lower GDP loss than the no-trading case because China is able to sell permits to raise income, which slightly offsets the GDP loss for deeper cuts. The MWH delays the significant GDP losses until China reaches the binding permit constraint which begins around 2028.

Advanced Technology Diffusion

Another policy approach which is often advocated as a means of enhancing emissions reductions world-wide is the deployment of advanced energy technology in China. In this section we present some results from McKibbin and Wilcoxen (2008) where this policy is explored. The BAU path discussed above is based on the assumption that energy technologies in each economy gradually improve at rates similar to those seen in recent historical data. However, many policies now under discussion are explicitly intended to accelerate the development and deployment of advanced technologies that would reduce greenhouse gas emissions. Some of these technologies, such as the integrated gasification combined cycle (IGCC) process to generate electricity from coal, reduce carbon dioxide emissions by substantially improving the efficiency of fossil fuel combustion. Other technologies, such as carbon capture and sequestration (CCS), would reduce emissions by removing carbon dioxide from the exhaust stream after combustion. Yet other technologies, such as hybrid engines or carbon fiber components for automobiles would reduce emissions by lowering the fuel required per unit of service demanded (vehicle miles traveled, for example). Finally, advanced technology for non-fossil sources of electricity, including nuclear power and renewables, would reduce carbon dioxide emissions by shifting the overall fuel mix. In this section, we examine the potential for accelerated deployment of advanced technology to reduce carbon dioxide emissions associated with electric power generation.

Since improved technology would allow more electricity to be produced from any given input of fossil fuel, we represent advanced technologies in the model via fuel-augmenting technical change. In essence, this approach captures the fact that new technology allows the same outcomes (output produced, distance traveled, etc.) to be produced with less physical energy. Factor-augmenting technical change introduces a distinction between physical inputs of energy (kWh, for example) and the effective value of those inputs to energy users. For example, increasing the efficiency of a coal-fired power plant from 41% to 49% using ultra-supercritical boiler technology would allow 19.5% more electricity to be produced from a given amount of coal (an 8% gain on a base of 41%). In effect, the technology allows a new plant using one ton of coal to produce the same amount of electricity that would have required 1.195 tons of coal in an older plant. The technology, in effect, serves to augment the physical fuel used.

Because the G-Cubed Model aggregates all electric power technologies into a single electric sector in each country, shifts of the fuel mix away from fossil fuels toward nuclear and renewables can also be modeled as fossil-fuel augmenting technical change. For example, a country increasing the share of non-fossil generation in its fuel mix from 40% to 55%, and hence reducing its fossil share from 60% to 45%, is effectively generating 33% more electricity for any given input of fossil fuel.

Using industry projections of the rate of diffusion of a range of innovations in electricity generation between 2008 and 2030, we produced the augmentation factors shown in Table 3. The values shown include both effects mentioned above: improvements in the efficiency of fossil fuel combustion, and shifts in the fuel mix away from fossil fuels. By 2030, for example, the 1.66 shown for Japan indicates that advanced technology and fuel-switching will mean that the ratio of total electricity produced to fossil fuel input will be 1.66 times that ratio today. We assume that technology and fuel switching continue beyond 2030, although at a diminishing rate. By 2045, for example, the augmentation factor for Japan increases to 2.09. The augmentation factors vary considerably by country. Improvements are very limited in LDCs other than China and India: the 2030 augmentation factor is only 1.13. India's augmentation factors are quite high, reflecting the fact that India currently relies heavily on coal burned in boilers with very low efficiency. Better technology thus improves India's performance considerably. In contrast, Europe's augmentation factors are relatively low: it currently relies least on fossil fuels of all of the regions, and its current technology is relatively efficient. It thus has less room for improvement.

Figure 9 shows the effect the advanced technology scenario on carbon emissions in China. For comparison, the business-as-usual results are shown as well. The BAU trajectories are indicated with diamonds and the advanced technology trajectories are indicated with triangles and labeled "high innovation". By 2050, emissions are lower by 500 mmt per year. This is significant reduction from only focusing on electricity generation but interestingly it is not as large as might be expected given the substitution we have assumed. This result is seen because in a rapidly growing economy such as China, the introduction of enhanced technology results in greater wealth and this higher wealth is partly spent on greater energy consumption. Thus when we reduce the amount of carbon in per unit of electricity we also raise the amount of electricity used. This rebound effect of technological deployment on income growth is sufficient in China to partly offset the reduction in emissions from the new technology. This suggests that a combination of policies to deploy technology as well as to price carbon to encourage substitution away from carbon intensive inputs is required in a comprehensive approach to tackle the emission of greenhouse gases.

Future research will explore the interaction of alternative technology policies and the cost of carbon abatement under the MWH Policy. Combining these approaches offers a potentially important way forward in cementing a global agreement based on economic incentives and technological innovation.

7. Conclusions

This paper has summarized recent developments in energy use and carbon dioxide emissions in China. The recent increase in emissions since 2002 has taken most analysts by surprise and is a significant concern for global policymakers attempting to deal with climate change. As shown in McKibbin and Wilcoxen (2002a), unexpected developments cause the different market-based CO2 reduction mechanisms to create vastly different costs. Both the international carbon tax and the MWH approach are more economically efficient responses to uncertainty than the cap-and-trade approach of the Kyoto Protocol.

Because it is very difficult to forecast the future energy and emissions paths, concerns about uncertainty could delay or prevent accession by countries (especially developing countries) to a global climate agreement based on rigid targets and timetables. The recent experience of energy use and carbon emissions in China supports the arguments in McKibbin and Wilcoxen (2008) that uncertainty about the economic costs of undertaking binding emission targets is an important problem for a rapidly-developing country like China.

As an alternative, we have outlined the MWH approach, a set of internationally-agreed actions that are based on long-term emissions targets and include an explicit compliance mechanism (annual permits) that allows the constraint to be exceeded at a stipulated international price. This approach would reduce emissions but without requiring that participating countries agree to achieve their emissions targets at any cost. Such an approach is not only very consistent with the UN Framework Convention on Climate Change, it is also likely to be more viable than the current framework being negotiated under the Kyoto Protocol. China is a pivotal country in the global debate. The more that its concerns can be taken into account in the design of a global post-Kyoto system, the more likely the world will begin to take effective action on climate change.

We finish by emphasizing the importance of combining a market-based CO2 reduction mechanism with an ambitious program to accelerate the development of green technology. Such a program would probably have a higher chance of success if some important parts of it were based on international collaboration. For example, since China is building a coal-fired power plant each week, there is considerable opportunity to make some of those plants prototypes that could be used to test the scaling up of experimental technologies like carbon capture and sequestration (CCS). On its own, China would hesitate to incur the costs of such experiments because any useful findings could be quickly learned by others.[27] Clearly, international

[27] This dilemma exists in other forms as well, illustrated by the recent decision of the Virginian regulator of utilities

scientific cooperation paid for by the international community could hasten the progress of a range of new technologies and help prevent the tragedy of the CO_2 commons.

“to turn down to turn down an application by the Appalachian Power Company to build a plant that would have captured 90 percent of its carbon and deposited it nearly two miles underground, at a well that it dug in 2003. The applicant’s parent was American Electric Power, one of the nation’s largest coal users, and perhaps the most technically able. But the company is a regulated utility and spends money only when it can be reimbursed.

The Virginia commission said that it was “neither reasonable nor prudent” for the company to build the plant, and the risks for ratepayers were too great, because costs were uncertain, perhaps double that of a standard coal plant. And in a Catch-22 that plagues the whole effort, the commission said A.E.P. should not build a commercial-scale plant because no one had demonstrated the technology on a commercial scale.” Running in Circles Over Carbon (by Matthew L. Wald), *New York Times*, June 8, 2008

Appendix : The G-Cubed Model

The G-Cubed Model is an intertemporal general equilibrium model of the world economy. The theoretical structure is outlined in McKibbin and Wilcoxen (1998)[28]. A number of studies show that the G-Cubed modeling approach has been useful in assessing a range of issues across a number of countries since the mid-1980s.[29] 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[30]. In contrast to static CGE models, time and dynamics are of fundamental importance in the G-Cubed Model. The G-Cubed model is known as a DSGE (Dynamic Stochastic General Equilibrium) model in the macroeconomics literature and a Dynamic Intertemporal General Equilibrium (DIGE) model in the computable general equilibrium literature.
- In order to track the macro time series, the behavior of agents is modified to allow for short run deviations from optimal behavior either due to myopia 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.

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[28] Full details of the model including a list of equations and parameters can be found online at: www.gcubed.com

[29] These 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.

[30] See Obstfeld and Rogoff (1996).

- 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.

Table A-1: Overview of the G-Cubed Model (version 80J)

Regions
United States Japan Australia Europe Rest of the OECD China India Oil Exporting Developing Countries Eastern Europe and the former Soviet Union Other Developing Countries
Sectors
Energy: Electric Utilities Gas Utilities Petroleum Refining Coal Mining Crude Oil and Gas Extraction Non-Energy: Mining Agriculture, Fishing and Hunting Forestry/ Wood Products Durable Manufacturing Non-Durable Manufacturing Transportation Services Capital Producing Sector

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Table 1: Global Economic and Demographic Changes from 0 A.D. to 2003 A.D.

Year	0	1000	1500	1600	1700	1820	1870	1913	1950	1973	1998	2003
Part A: GDP per capita (1990 international $)												
Western Europe	450	400	774	894	1,024	1,232	1,974	3,473	4,594	11,534	17,921	19,912
United States			400	400	527	1,257	2,445	5,301	9,561	16,689	27,331	29,037
Japan	400	425	500	520	570	669	737	1,387	1,926	11,439	20,413	21,218
China	450	450	600	600	600	600	530	552	439	839	3,117	4,803
India	450	450	550	550	550	533	533	673	619	853	1,746	2,160
World	444	435	565	593	615	667	867	1,510	2,114	4,104	5,709	6,516
Part B: Share of World GDP (percent of world total)												
Western Europe	10.8	8.7	17.9	19.9	22.5	23.6	33.6	33.5	26.3	25.7	20.6	19.2
United States			0.3	0.2	0.1	1.8	8.9	19.1	27.3	22.0	21.9	20.6
Japan	1.2	2.7	3.1	2.9	4.1	3.0	2.3	2.6	3.0	7.7	7.7	6.6
China	26.2	22.7	25.0	29.2	22.3	32.9	17.2	8.9	4.5	4.6	11.5	15.1
India	32.9	28.9	24.5	22.6	24.4	16.0	12.2	7.6	4.2	3.1	5.0	5.5
Part C: Share of World Population (percent of world total)												
Western Europe	10.7	9.5	13.1	13.3	13.5	12.8	14.8	14.6	12.1	9.2	6.6	6.3
United States	0.3	0.5	0.5	0.3	0.2	1.0	3.2	5.4	6.0	5.4	4.6	4.6
Japan	1.3	2.8	3.5	3.3	4.5	3.0	2.7	2.9	3.3	2.8	2.1	2.0
China	25.8	22.0	23.5	28.8	22.9	36.6	28.2	24.4	21.7	22.5	21.0	20.5
India	32.5	28.0	25.1	24.3	27.3	20.1	19.9	17.0	14.2	14.8	16.5	16.7
Memo items												
World GDP (in billion)	103	117	247	329	371	694	1,101	2,705	5,336	16,059	33,726	40,913
World Population (in million)	231	268	438	556	603	1,041	1,270	1,791	2,525	3,913	5,908	6,645

Data for 0 to 1998 are from Maddision (2001); and for 2003 are from Maddison (2007)

Table 2: China's Share of Global Energy Consumption and CO2 Emissions, 1990-2030

Energy Consumption

	1990	2003	2004	2010	2015	2020	2025	2030
United States	24.4	23.1	22.5	20.8	20.1	19.5	19.0	18.7
OECD Europe	20.1	18.7	18.2	16.5	15.3	14.2	13.4	12.7
Japan	5.3	5.2	5.1	4.6	4.3	4.1	3.8	3.6
Australia/New Zealand	1.3	1.4	1.4	1.3	1.3	1.3	1.2	1.2
Other OECD	5.8	6.7	6.5	6.6	6.4	6.4	6.3	6.2
China	7.8	11.7	13.3	16.2	17.4	18.6	19.6	20.7
India	2.3	3.4	3.4	3.6	3.9	4.1	4.4	4.5
Other Non-OECD	33.1	29.8	29.5	30.5	31.4	32.0	32.3	32.2
World Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

CO2 Emissions

	1990	2003	2004	2010	2015	2020	2025	2030
United States	23.5	22.7	22.0	20.1	19.4	18.8	18.7	18.5
OECD Europe	19.3	16.9	16.3	14.6	13.4	12.4	11.6	10.9
Japan	4.8	4.9	4.7	4.1	3.8	3.5	3.3	3.0
Australia/New Zealand	1.4	1.6	1.6	1.5	1.4	1.4	1.4	1.3
Other OECD	4.8	5.7	5.4	5.4	5.2	5.2	5.1	5.0
China	10.5	12.8	13.2	19.0	20.7	22.1	23.5	25.0
India	2.7	4.0	3.8	4.4	4.7	4.9	5.0	5.1
Other Non-OECD	33.1	28.8	28.4	29.1	29.8	30.1	30.1	29.9
World Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

<u>Memo Items on World Total</u>

	1990	2003	2004	2010	2015	2020	2025	2030
Energy Used, Quadrillion BTU	26.2	32.1	33.2	40.4	43.4	46.5	50.1	53.5
CO2 Emitted, Million Metric Tons	21,246	25,508	26,922	30,860	33,889	36,854	39,789	42,880

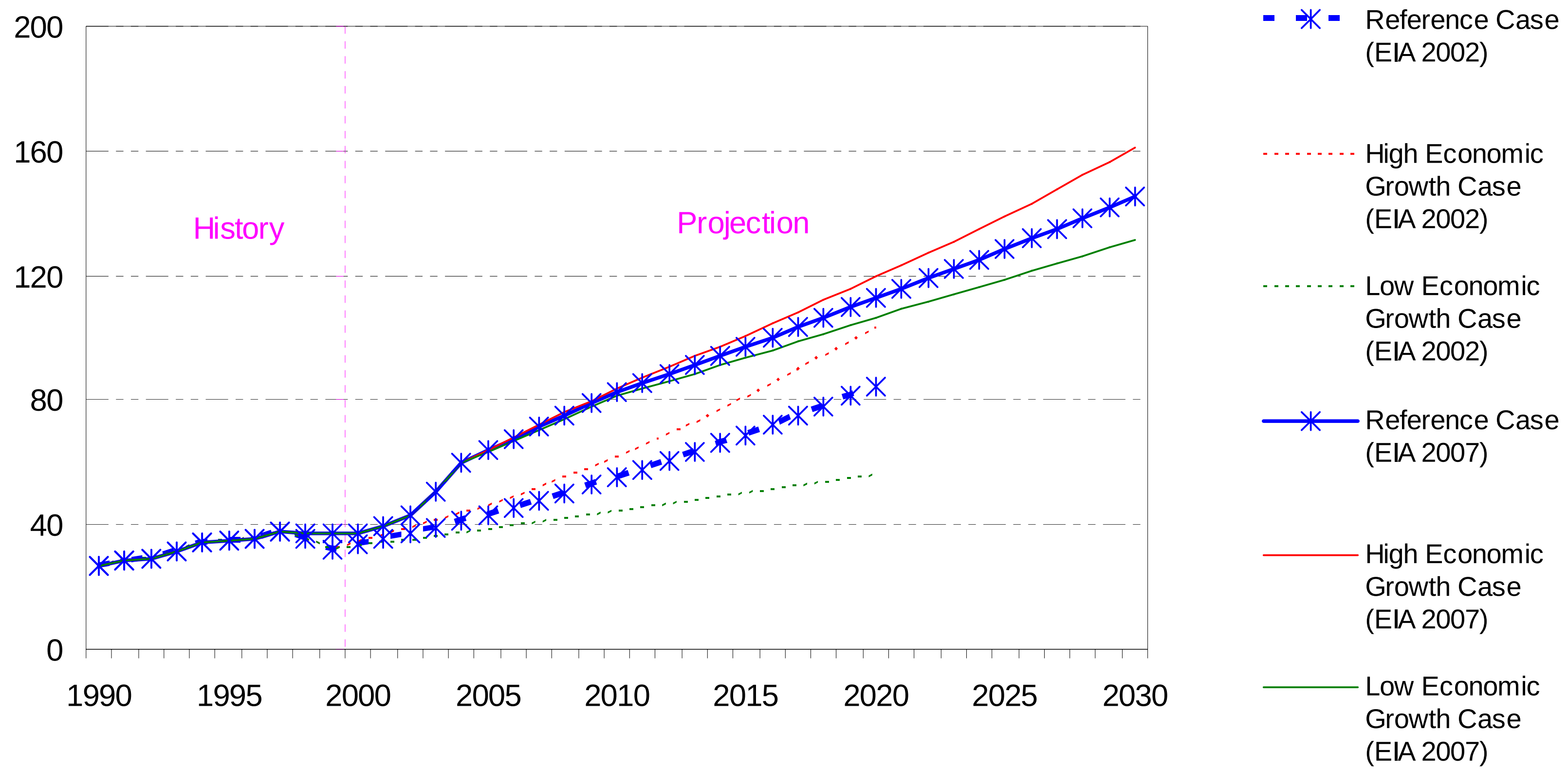
Source: Energy Information Administration / International Energy Outlook 2007

Table 3: Fossil Fuel Augmentation Factors i.e. productivity in electricity generation relative to business-as usual

Region	2030	2045
United States	1.67	2.1
Japan	1.66	2.09
Australia	1.73	2.19
Europe	1.49	1.8
Rest of OECD	1.67	2.09
China	1.67	2.1
India	1.8	2.31
Other LDC	1.13	1.22
Former Soviet Union	1.71	2.16
OPEC	1.22	1.35

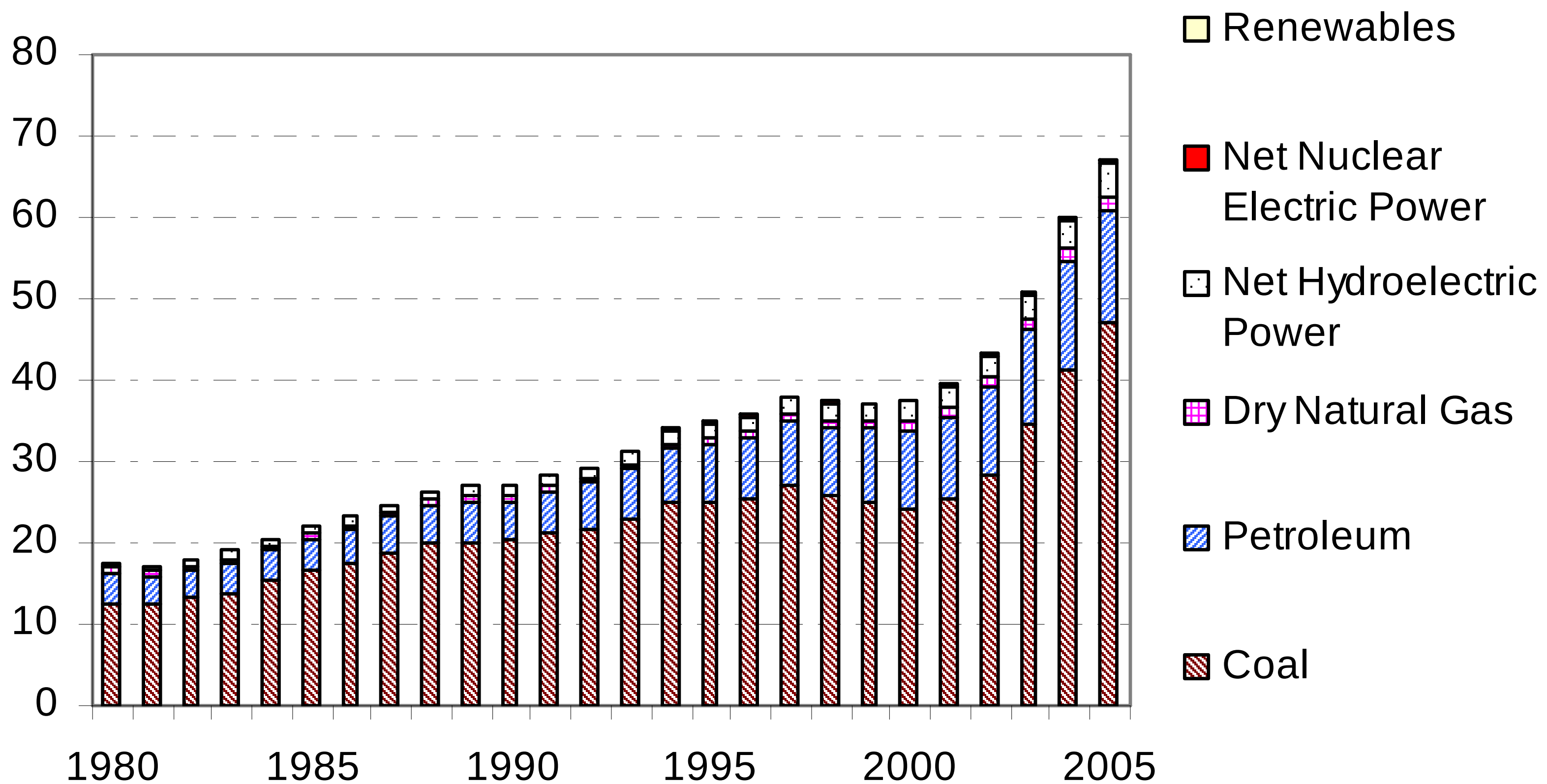
Note: Each number represents the ratio of electricity per unit of fossil fuel consumed in the advanced technology simulation to electricity per unit of fossil fuel consumed in the business-as-usual simulation

Figure 1: Comparison of Projections of Energy Consumption, China
(Quadrillion(10^{15}) Btu)



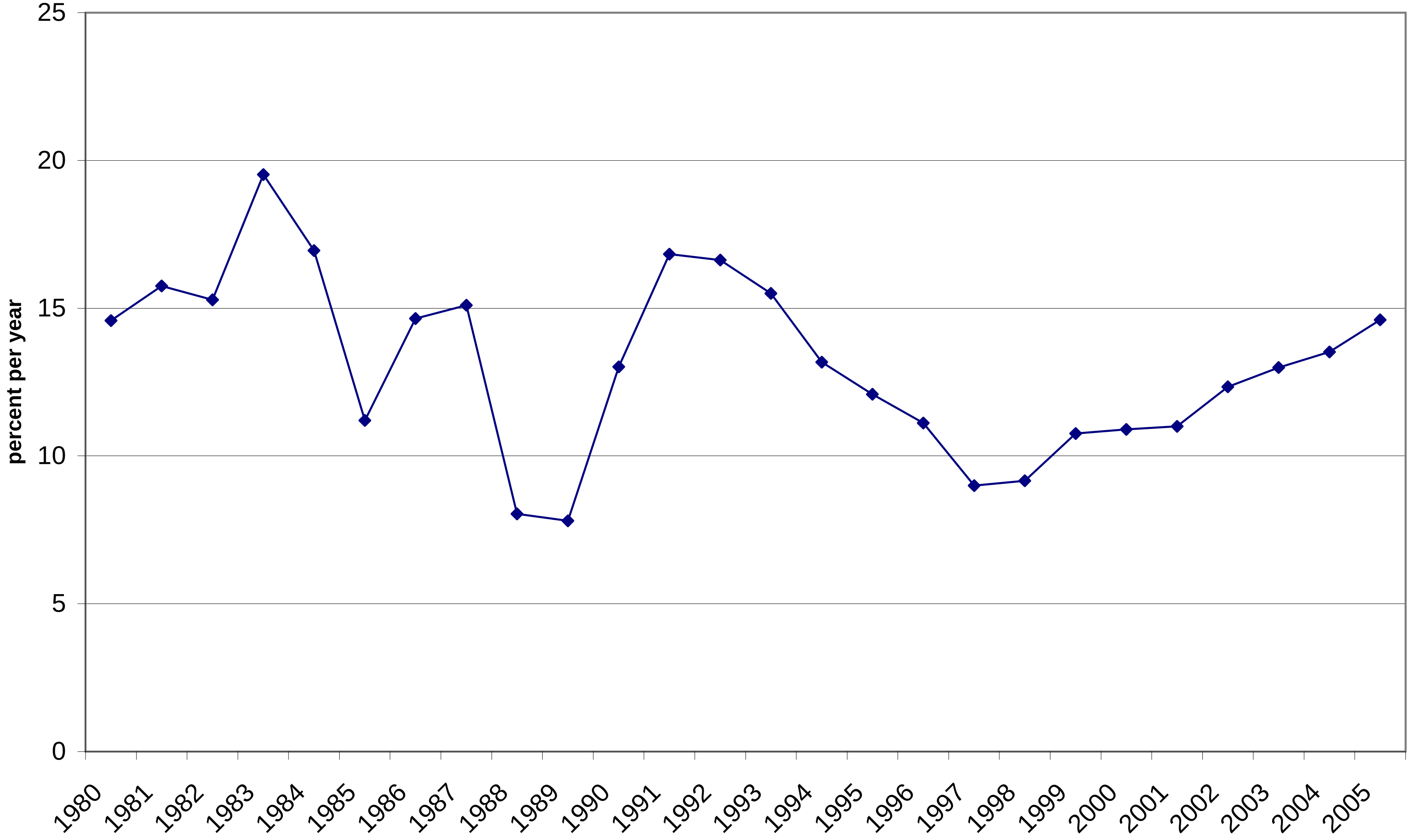
Note: The base years for projections reported in EIA 2002 and 2007 are 1999 and 2004, respectively.
Source: Energy Information Administration / International Energy Outlook 2002 and 2007

Figure 2: Energy Consumption by Source, China,1980-2005 (Quadrillion Btu)



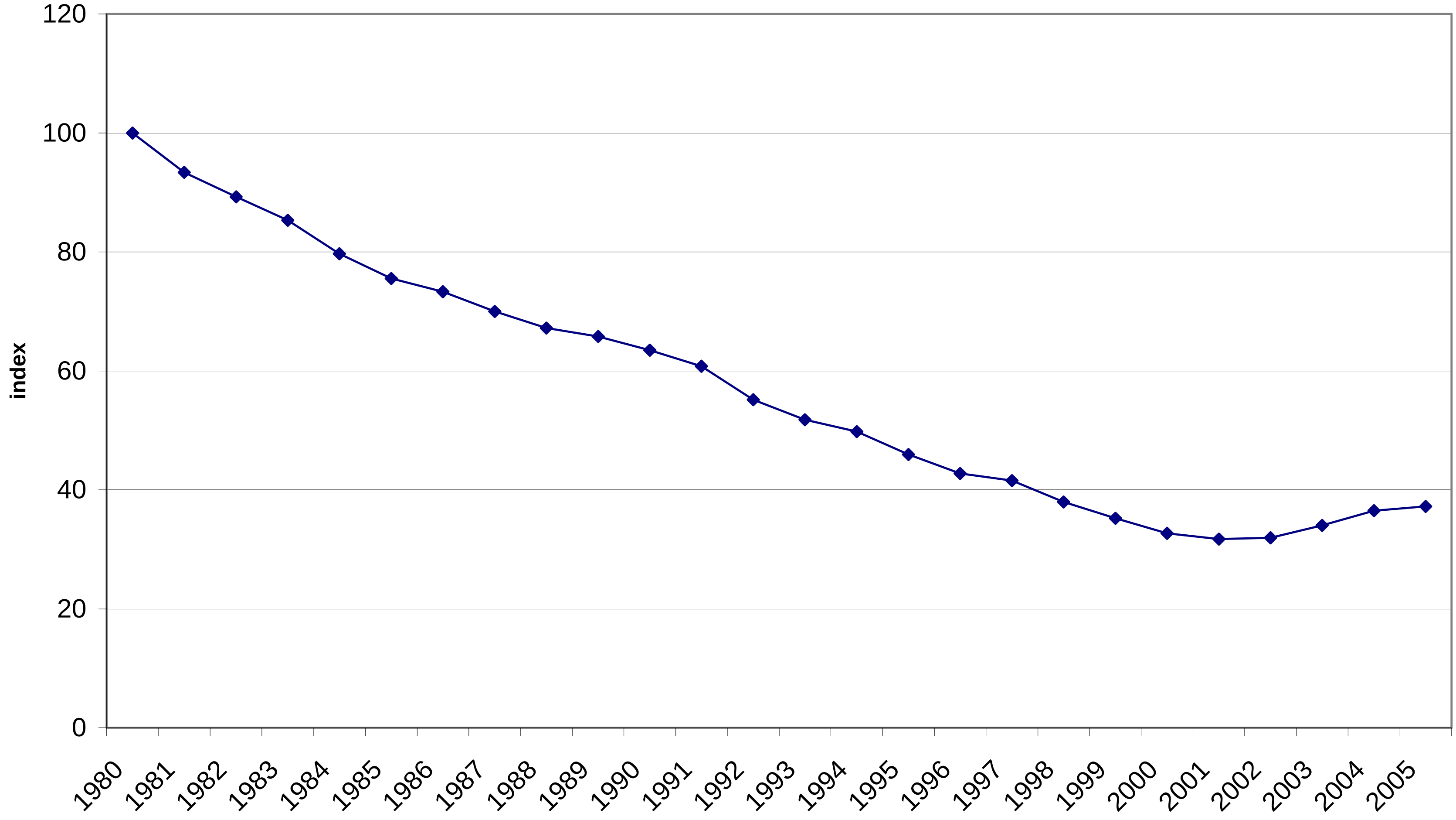
Source: Energy Information Administration, 2007

Figure 3: Chinese GDP growth in PPP



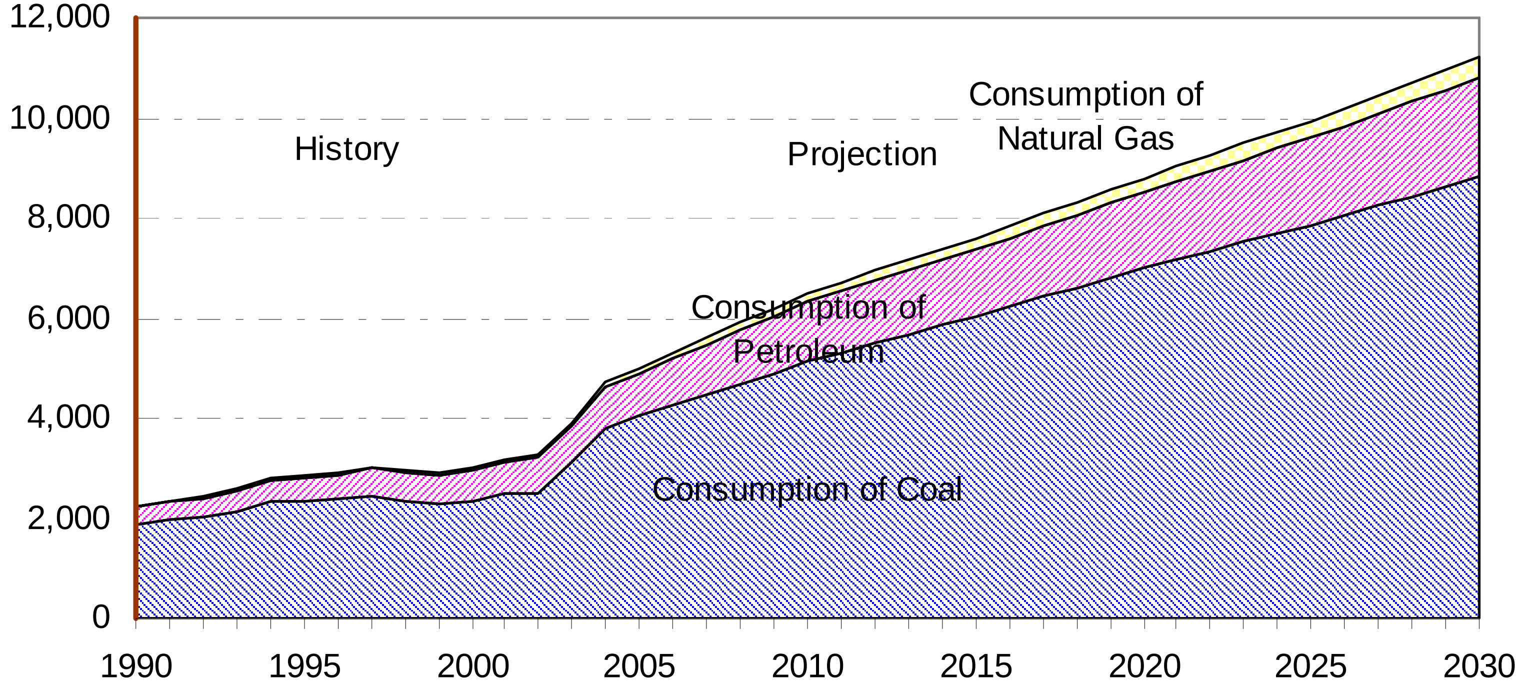
Source: IMF World Economic Outlook Database April; 2008

Figure 4: Energy (1000 BTU) per Unit of GDP (PPP) (1980=100)



Source: Energy Information Administration World Energy Outlook

Figure 5: Projections of CO2 Emissions by Fuel Type, China, 1990-2030
(Million Metric Tons Carbon Dioxide)



Source: Energy Information Administration / International Energy Outlook 2007

Figure 6: Global Carbon Dioxide Emissions from Fossil Fuels 1990 and 2030

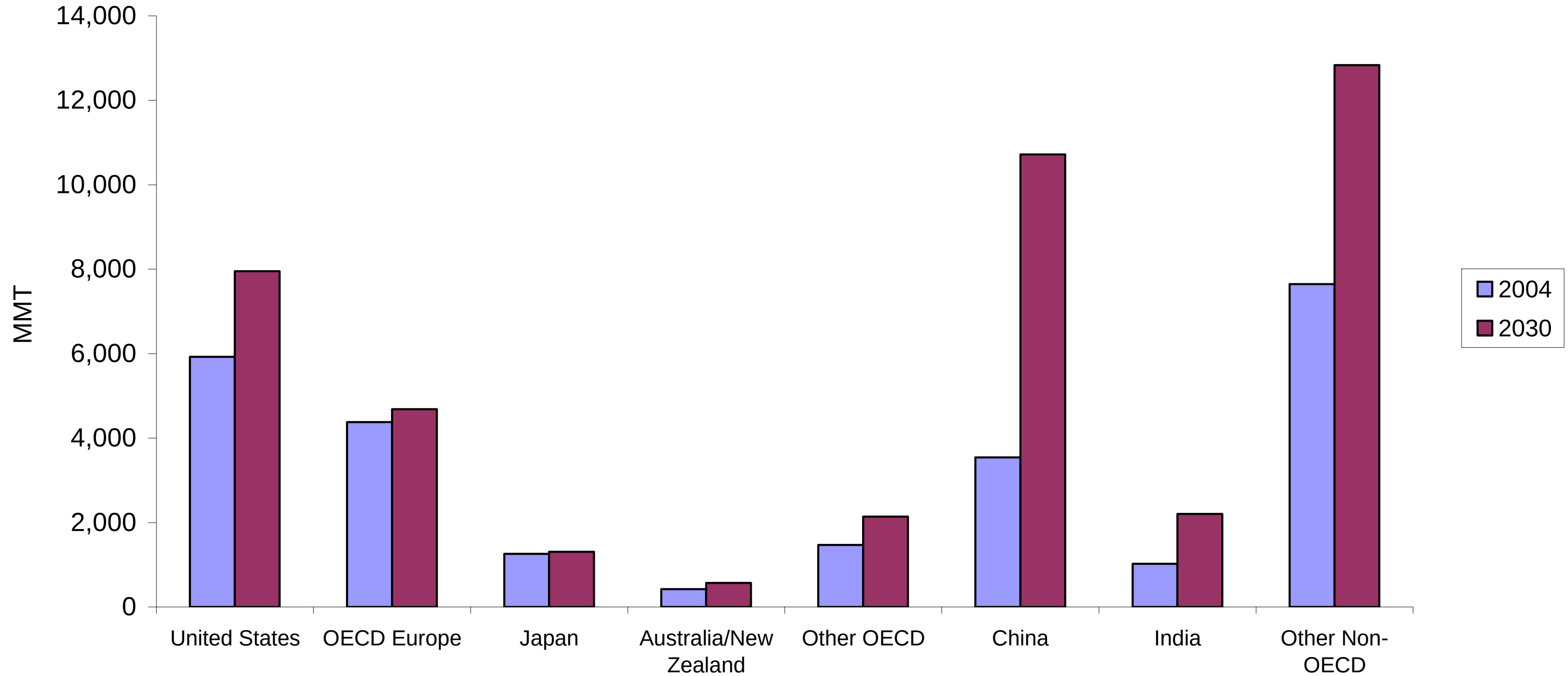
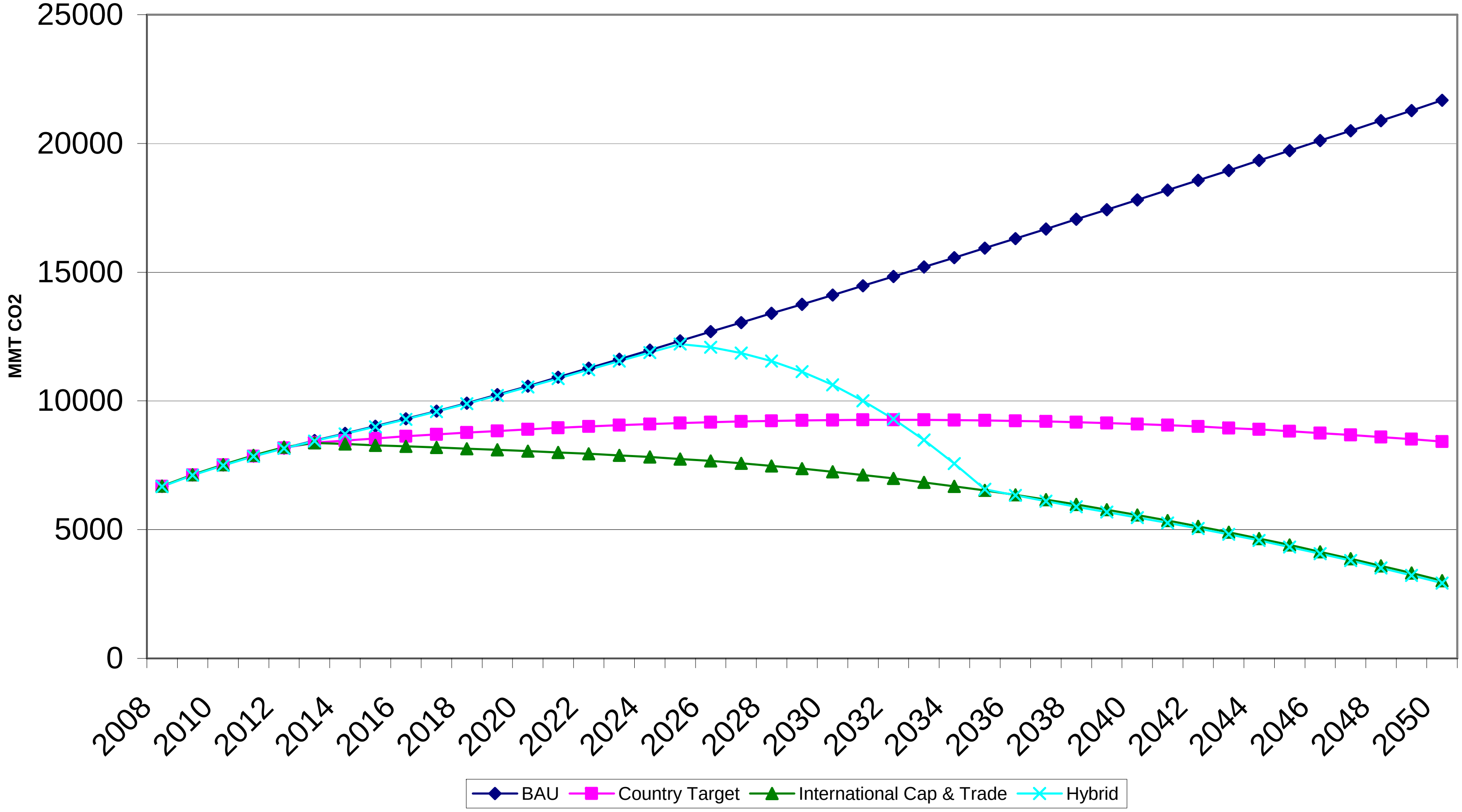


Figure 7: China CO2 Emissions from Energy



Source: Gcubed model in McKibbin and Wilcoxen (2008)

Figure 8: China GDP Change from Emissions Reduction

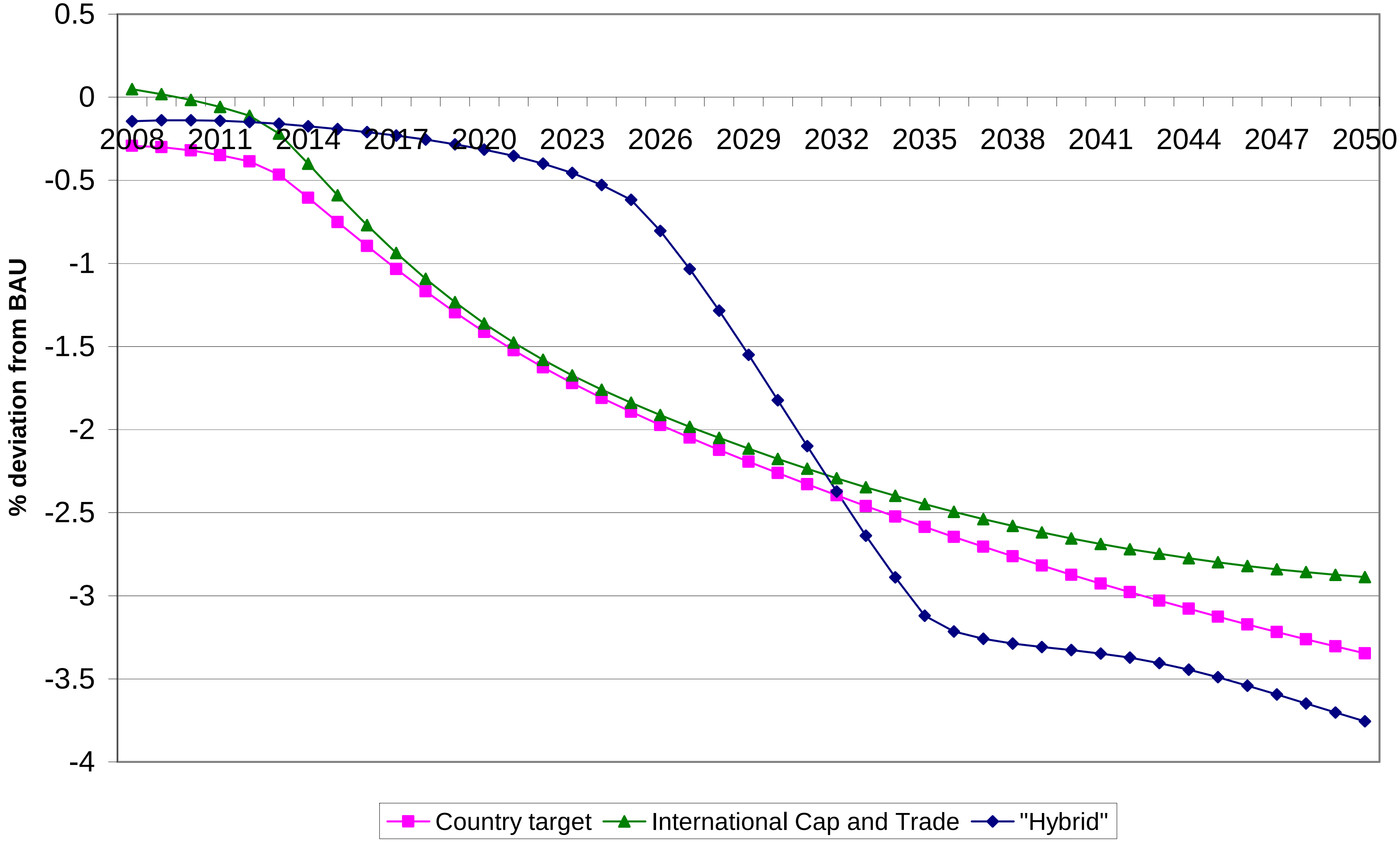
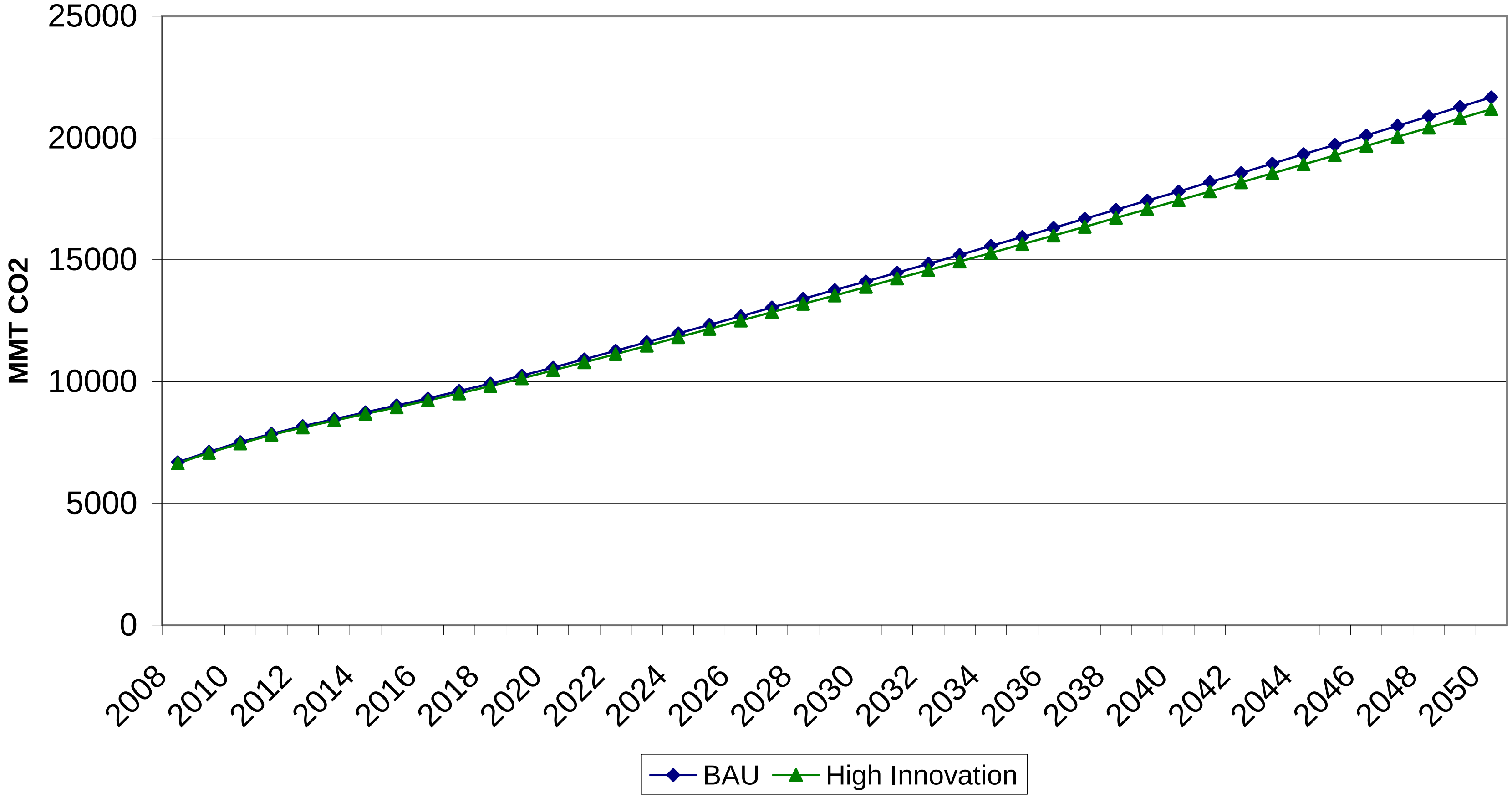


Figure 9: China CO2 Emissions from Energy Under Alternative Technology Assumptions



Source: Gcubed model in McKibbin and Wilcoxen (2008)

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