CHALMERS | GÖTEBORG UNIVERSITY

Modelling Energy Systems and International Trade in CO_2 Emission Quotas

The Kyoto Protocol and Beyond

Tobias A. Persson

Department of Physical Resource Theory
Chalmers University of Technology
Göteborg University
Göteborg, Sweden 2002

AKADEMISK AVHANDLING FÖR FILOSOFIE LICENTIATEXAMEN
I MILJÖVETENSKAP MED INRIKTNING MOT FYSISK RESURSTEORI

Modelling Energy Systems and International Trade in CO_2 Emission Quotas –

The Kyoto Protocol and Beyond

Tobias A. Persson

Department of Physical Resource Theory
Chalmers University of Technology and Göteborg University
Göteborg, Sweden 2002

Modelling Energy Systems and International Trade in CO_2 emission Quotas – The Kyoto Protocol and Beyond
Tobias A. Persson

Department of Physical Resource Theory
Chalmers University of Technology and Göteborg University
SE-412 96 Göteborg
Sweden
Telephone +46(0)31-772 1000
Fax +46(0)31-772 3150
http://www.frt.fy.chalmers.se

Printed at Physics and Engineering Physics
Göteborg, Sweden 2002

Modelling Energy Systems and International Trade in CO_2 Emission Quotas – The Kyoto Protocol and Beyond

Tobias A. Persson
Department of Physical Resource Theory
Chalmers University of Technology and Göteborg University

Abstract

A transformation of the energy system in the 21st century is required if the CO_2 concentration in the atmosphere should be stabilized at a level that would prevent dangerous anthropogenic interference with the climate system. The industrialized countries have emitted most of the anthropogenic CO_2 released to the atmosphere since the beginning of the industrial era and still account for roughly two thirds of global fossil fuel related CO_2 emissions. Industrial country CO_2 emissions on a per capita basis are roughly five to ten times higher than those of developing countries.

However, a global atmospheric CO_2 concentration target of 450 ppm, if adopted would require that global average per capita CO_2 emissions by the end of this century have to be comparable to those of developing countries today. The industrialized countries would have to reduce their emissions substantially and the emissions in developing countries could not follow a business-as-usual scenario. The transformation of the energy system and abatement of CO_2 emissions would need to occur in industrialized and developing countries.

Energy-economy models have been developed to analyze of international trading in CO_2 emission permits. The thesis consists of three papers. The cost of meeting the Kyoto Protocol is estimated in the first paper. The Kyoto Protocol, which defines quantitative greenhouse gas emission commitments for industrialized countries over the period 2008-2012, is the first international agreement setting quantitative goals for abatement of CO_2 emissions from energy systems. The Protocol allows the creation of systems for trade in emission permits whereby countries exceeding their target levels can remain in compliance by purchasing surplus permits from other developed countries. However, a huge carbon surplus, which has been christened hot air, has been created in Russia and Ukraine since 1990 primarily because of the contraction of their economies. The current Unites States administration has repudiated the Protocol under which The U.S. was expected to be a large purchaser of CO_2 emission permits. The CO_2 emission permit price could thus be expected to drop substantially were the U.S. to stay out of the Protocol.

The second paper summarizes a model illuminating the technological and economical possibilities for abatement of CO_2 emissions from the energy system in India. An allocation of tradable emission allowances is suggested showing that there could be economic incentives for India to early join a protocol that requires reduction in global CO_2 emission. The same allocation approach is used in the third paper, which models the economic incentives for other developing regions to accept the allocation of emission rights.

Keywords: climate policy, Kyoto Protocol, trade, India, energy, carbon dioxide, hot air, allocation, energy economics, technological change

Technological growth is not only regarded as the ultimate problem solver but is also seen as determining our life styles, our social organizations, and our value system. Such technological determinism seems to be a consequence of the high status of science in our public life – as compared to philosophy, art, or religion – and of the fact that scientists have generally failed to deal with human values in significant ways. This has led most people to believe that technology determines the nature of our value system and our social relations, rather than recognizing that it is the other way round; that our values and social relations determine the nature of our technology.

The Turning Point, F. Capra, 1982

List of papers

This thesis is based on the following appended papers:

I **The cost of meeting the Kyoto Protocol –**
Dealing with the carbon surplus in Russia and Ukraine
Persson T.A. and Azar C., 2002. Working paper.

II **Energy and CO_2 mitigation strategies for India -**
allocation of emission permits and revenues from emission trading
Persson T.A. and Azar C., 2001. Submitted for publication in Energy the International Journal.

III **Allocation of emission rights – economic incentives for early emission reductions of CO_2 in developing regions**
Persson T.A., 2002. Work in progress.

Table of contents

1. INTRODUCTION

Energy use is central to contemporary industrial societies. During the industrialisation of the Western world, individual opportunities have increased. For example, in the middle of the nineteenth century the steam engine took over from hydro as the most important power source (Freeman and Perez, 1988). The steam engine was initially developed by Newcomen to pump up water from mines but a more important implication was that it made it possible to locate industries in areas where water was not accessible. The range of options when it come to mobility also increased since the steam engine made the development of railways and steamships possible. Today the availability of affordable energy supply allows many, but not all, people in industrialised countries to enjoy comfortable mobility and productivity.

Unfortunately industrialization has increased the impact on the environment. Societal interaction with nature is characterised by an exchange of energy and materials, and by manipulation (Holmberg and Karlsson, 1992). As noted in Agenda 21 much of the world energy is currently supplied and used in ways that could not be sustained if technologies were to remain constant and if overall quantities were to increase substantially (UN, 1992). The United Nations Framework Convention on Climate Change (UNFCCC, 1992) addresses the link between energy from fossil fuels and climate change.

The pre-industrial atmospheric CO_2 concentration was approximately 280 ppm. The combustion of fossil fuels and deforestation have raised this level to around 370 ppm during just one hundred years. According to IPCC a continuation on reliance of fossil fuels without any efforts to abate CO_2 emissions is expected to increase the global average equilibrium temperature 1.4 to 5.8^{o}C by the end of the century (IPCC, 2001). For comparison, during the last ice age the average equilibrium temperature was 5^{o}C lower than today.

The concern about the climate change triggered the international negotiations that led to the United Nations Framework Convention on Climate Change (UNFCCC, 1992). The convention calls for a 'stabilization of greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.' However, the meaning of 'dangerous' remains to be determined since (I) the degree of harm from any level of climate change is subject to uncertainties and (II) the extent to which any level of risk is 'acceptable' or 'dangerous' is a political, not a scientific judgement (Azar and Schneider, 2002).

A range of stabilization targets are being discussed. Azar and Rodhe (1997) suggest a stabilization target below 400 ppm CO_2. The Swedish government suggests a 550 ppm stabilization target (CO_2 equivalent), which roughly corresponds to 450 ppm CO_2. The present global average per capita CO_2 emissions are approximately 1.1 tC yr^{-1}. Global per capita CO_2 emissions by 2100 would for instance have to be reduced to 0.2-0.4 tC yr^{-1} if a 450 ppm stabilization target is adopted.

Stabilization targets around 450 ppm would have dramatic implications for the energy system, as they would require that emissions of CO_2 would have to be reduced in the same time as the energy demand increases. According to IIASA/WEC scenarios (Nakićenović *et al.*, 1998), the global GDP is estimated to increase by 2.8 to 3.7 times between year 2000 and 2050 and by 7.7 to 11.2 times between 2000 and 2100. This implies that the resulting primary energy demand would increase by 1.5 to 2.5 times that of the present by 2050 and by 2 to 4.5 times the present by the end of this century.

Thus, reducing CO_2 emissions to the levels necessary to stabilize atmospheric concentrations at a level that would prevent dangerous anthropogenic interference with the climate system will require that energy is used much more efficiently and that new energy supply, conversion and end use technologies diffuse into the energy system (Figure 1).

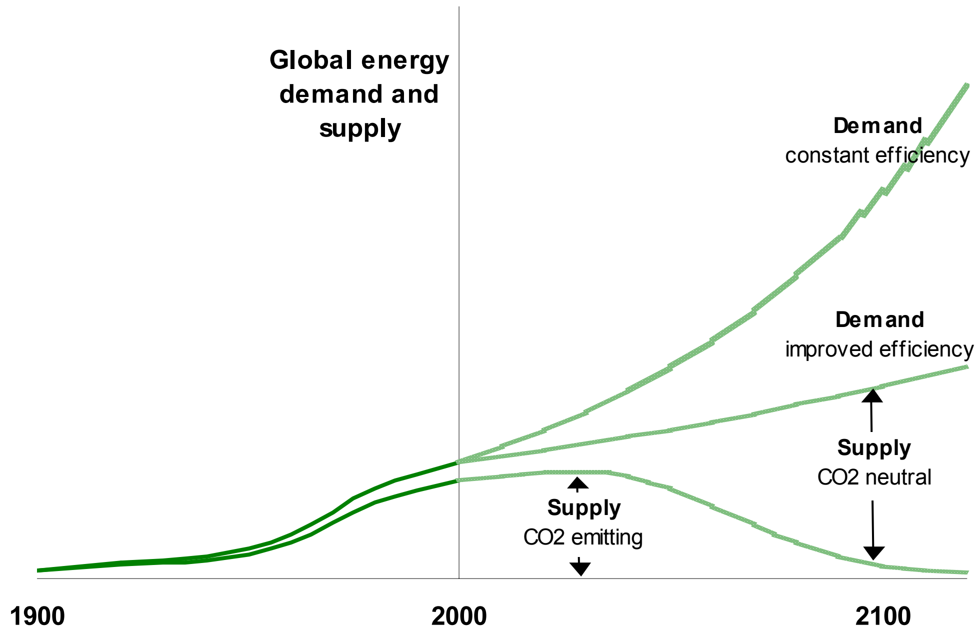

Figure 1. The simultaneous growth of energy services and a phase out of CO_2 emitting technologies will demand a growth of CO_2 neutral energy supply technologies as well as technologies that increase the efficiency of energy use. The figure is reconstructed from B.A. Andersson (2001).

Many governments, and society in general remain hesitant to take even precautionary action. The industrialised economies seem to have become locked into fossil fuel-based technological systems through a path-dependent process, driven by technological and institutional returns to scale, *a carbon lock-in* (Unruh, 2000; Dosi, 1997; Wright, 1997). The lock-in arises essentially as a result of the dynamics of large technological systems like energy generation, distribution and end-use. These large systems have to be seen as complex systems embedded in a conditioning social context of public and private institutions and cannot be seen as a set of discrete technological artefacts.

India, and other countries attempting to increase industrialization, must recognize that stabilization of atmospheric CO_2 concentrations at around 450 ppm requires energy systems with low CO_2 emissions.

However, India appears to becoming increasingly coal dependent. The first major step towards a planned development of Indian coal industry occurred when the National Coal Development Corporation (NCDC) was formed in 1956. The most recent draft from Tata Energy Research Institute on an integrated energy strategy for India, which takes into account the imperative of sustainable development, environmental protection and energy security, assumes that India's coal use will triple from today until 2046 (TERI, 2002).

This introduction to the appended papers is structured as follows: in section 2 the aims of the papers are summarised. Brief summaries of the appended papers are presented in section 3. Finally, in section 4, the main conclusions are given.

2. METHODOLOGY AND AIMS OF APPENDED PAPERS

In Paper 1, costs of meeting the Kyoto Protocol are estimated. The 1997 Kyoto Protocol to the UN Framework Convention of Climate Change contains legally binding emission reduction targets for six greenhouse gases (GHG) to be met by 2008 to 2012 by developed countries, the so-called Annex 1 parties. An energy economy model has been used. The model is based on a global energy model, GET 1.0 (Azar *et al*., 2000). C. Azar and K. Lindgren have modified this model to only include Western Europe. T.A. Persson has regionalized the model to include five Annex 1 regions and the rest of the world. The model is used to estimate the cost of meeting the Kyoto Protocol[1] with trading of emission permits could be affected by the withdrawal of the U.S. from the Protocol and by the dominance of the Former Soviet Union as seller of emission permits. The analysis also includes how early negotiations and agreement on more stringent targets in subsequent commitment periods could affect abatement policies and permit prices during

[1] Earlier studied have also presented estimates of meeting the Kyoto targets, both with and without use of the flexible mechanisms (see e.g. Weyant, 1999).

the first commitment period (2008-2012). Earlier modelling studies have disregarded the effects of early agreements of subsequent commitments in their cost estimates.

Paper 2, examines the energy system in India under a stringent long-term CO_2 abatement target scenario. To be able to meet atmospheric CO_2 stabilization targets in the range of 400-500 ppm, India is an important country since about one sixth of the world population lives in the country and due to the likely rapid economic development (which is presently highly correlated to more coal demand). The aim of the paper is twofold:

(I) To demonstrate and analyse different ways for the energy system in India to meet stringent CO_2 targets during this century.
(II) To suggest and analyse an allocation of emission quotas that would offer economic incentives for early emission reductions of CO_2 in India.

The model used is a modification of the GET 1.0 model. T.A. Persson has included two regions, India and the rest of the world.

Paper 3 explores the economic incentives for four developing regions (Centrally Planned Asia including China, South Asia including India, Latin America and Africa) to accept the allocation of emission allowances presented in Paper 2. Comparisons are made with business-as-usual CO_2 emission scenarios from the literature. The aims of this working paper are to suggest an allocation of emission quotas, to estimate when business-as-usual emissions for the developing regions reach the suggested emission allowances, and to estimate regional economic implications following the allocation of emission quotas. For the economic analysis, a regionalized version of the GET 1.0 model (Grahn, 2002) has been used.

3. MAIN RESULTS OF PAPERS

3.1 The cost of meeting the Kyoto Protocol – Paper 1

The industrialized countries with binding reduction targets, the Annex 1 parties, can reduce their emissions domestically or use the flexible mechanisms:

(I) *Emissions trading*, which enables Annex 1 countries to buy and sell emission reductions among themselves.

(II) *Joint Implementation (JI)*, under which one Annex 1 country may receive an emission credit for performing an emissions-cutting project in another Annex 1 country.

(III) *The Clean Development Mechanism (CDM)*, similar to JI but for projects undertaken in developing countries, which have no binding targets.

These mechanisms allow individual countries to reduce their emissions domestically or to buy emission permits or carry out joint projects with other countries. If the international permit price is lower than the domestic marginal abatement cost, countries may instead of reducing emissions domestically, buy permits from the international market. This means that a lower overall cost for the first commitment period is achieved.

The Kyoto targets are referenced to emissions in 1990 (some countries have other base years). However, emissions in Eastern Europe, Russia and Ukraine decreased dramatically after the base year, largely because of economic upheaval following the demise of central planning (Victor *et al.*, 2001; Mastepanov *et al.*, 2001). This has created a huge carbon surplus, conventionally known as hot air, in Russia, Ukraine and several countries in the Eastern Europe.

The current U.S. administration has repudiated the Kyoto Protocol under which the U.S. was expected to be a large purchaser of CO_2 emission permits. A consequence is that the permit price is estimated to be substantially lower. In fact, the model results suggest that the aggregated emission target in the Kyoto Protocol could be met even if no abatement policies are carried out in the Annex 1 countries and without U.S. as a buyer. Thus, the permit price could actually drop to zero. The lower permit price would discourage investments in alternative technologies.

It is possible, however, that the permit price will not collapse totally even if the size of hot air is more than the amount of CO_2 that has to be abated in other Annex 1 countries. The Russian Federation and Ukraine are responsible for almost all hot air. The Annex 1 Former Soviet Union could act as oligopolists, withholding emission permits thus forcing up the permit price and hence maximizing their revenues to billions of US$ yr^{-1}.

A number of countries could, however, find it unacceptable to transfer billions of dollars with no overall reduction in emissions. This suggests several strategies that would lead to actual emission reductions, including:

- Do not buy emission permits from Russia and Ukraine.
- Carry out joint implementation projects in Russia and Ukraine where actual reduction would take place.
- Develop the so called Green Investment Scheme[2] in particular one needs to make sure that the revenues are actually re-invested into real abatement projects in Russia and Ukraine.
- Negotiate and agree on more stringent targets for subsequent commitment periods. This would create incentives for early abatement and banking of emission permits in all regions.
- Work to convince the U.S. to rejoin the Kyoto Protocol.

3.2 Energy and CO_2 mitigation strategies for India – Paper 2

> '*The idea that developing countries like India and China must share the blame for heating up the earth and destabilising its climate ... is an excellent example of environmental colonialism.*' (Agarwal and Narain, 1991).

The unilateral focus on industrialised countries in the Kyoto Protocol was one of the prime reasons that George W. Bush invoked in 2001 when he stated that the U.S. would not ratify the Protocol. However, it was formally recognised in Article 3.1 of the Rio de Janeiro conference in 1992 that the developed and developing countries have 'common but different responsibilities'. It must be kept in mind that it is the industrialised countries that have emitted most of the CO_2 in the past, they still account for roughly two thirds of the emissions, and their emissions on a per capita basis are roughly five to ten times higher than the levels prevailing in most developing countries. For instance, annual per capita CO_2 emissions in the U.S. and EU in 1998 were 5.6 tC and 2.6 tC, respectively, which can be compared to 0.3 tC in India and 0.7 tC in China (Marland *et al.*, 2001).

An energy economic model was used to examine strategies for India in meeting stringent CO_2 targets during this century in Paper 2. The total energy demand for India in the model is set exogenously and estimated to grow from 11 EJ yr^{-1} in 1990 to 52 EJ yr^{-1} by the end of this century, whereas GDP is assumed to grow by a factor of 55. India's energy system in the modelled reference scenario would be totally dominated of coal supply without restrictions on CO_2 emissions. By the end of this century, India's per capita emission in the reference scenario, without any carbon mitigation policies, is estimated to be almost the same as the average per capita emission of the world today

[2] One option that could make trading with hot air politically acceptable is the so-called 'Green Investment Scheme' - GIS (Mastepanov *et al.*, 2001; Moe *et al.*, 2001; Averchenkov and Berdin, 2001). Then the revenues the Former Soviet Union makes by trading hot air are re-invested into emission reduction projects and the resulting emission reductions should be more than the amount of units sold.

(1.1 ton C capita^{-1} yr^{-1}). The population is, however, assumed to have grown to 1.6 billion, so the emissions in absolute terms are about a quarter of the present total global carbon dioxide emissions from combustion of fossil fuels. Thus, stringent atmospheric CO_2 stabilization targets could not be met without carbon abatement policies in India.

Four scenarios for India are presented that are compatible with a global CO_2 atmospheric stabilization target of 450 ppm. During the first half of the century, fossil fuels remain important in all abatement scenarios. Oil is used in the transportation sector, natural gas is used in electricity production, and coal is used for electricity, heat and process heat. The coal is domestic, but oil and natural gas would need to be imported. However, many renewable energy supply alternatives could expand in India in the coming decades, particularly wind power and modern use of biomass.

During the second half of the century, the modeling analysis indicates that India could choose between a high dependence on solar hydrogen or to sequester the CO_2 from fossil fuel combustion (alternatively a combination of them).

An allocation approach based on contraction and convergence (Meyer, 2000) is suggested in the Paper. The allowances are assumed to follow a linear trend from their present per capita level for industrial regions and the per capita emission by 2012 for developing regions towards an equal per capita allocation by 2050. The per capita emission allowances are then assumed to follow the per capita emission profile towards the stabilization target.

The economic incentives for India to accept the suggested allocation approach are estimated. Economic benefits from trading permits could be high during the first half of this century, while the benefits are smaller during the second half. Thus, the suggested allocation approach could provide an incentive for an early involvement of India in a protocol.

3.3 Allocation of emission quotas as an economic incentive for early emission reductions in developing countries – Paper 3

Several studies, including Paper 2 about India, conclude that stringent atmospheric CO_2 stabilization targets could not be met without carbon abatement policies in developing countries (Kinzig and Kammen, 1998; Nakićenović *et al.*, 1998; IPCC, 2000; Bolin and Kheshgi, 2001; Wigley, 1997). The Paper 3 analysis imposes the same contraction and convergence approach as in the India paper. Regional business-as-usual CO_2 emission scenarios from the literature are compared with the suggested emission allowances. The analysis indicates that business-as-usual emissions for Centrally Planned Asia including China (CPA), Latin America (LAM) and South Asia including India (SAS) reach their emission allowances for a stabilization of the atmospheric CO_2 concentration at 350, 450, or 550 ppm during the coming decades. Business-as-usual emissions for CPA reach the assumed emission allowances by 2010-2040. LAM and SAS reach the assumed allowances a few decades later than CPA while the business-as-usual emissions for Africa reach their allowances during the second half of the century. However, some countries, for example South Africa, have per capita emission levels already today that are comparable to those of industrialised countries or more developed regions.

Thus, a stringent atmospheric stabilization target could not be met without abatement of the CO_2 emissions in developing countries.

The economic incentives for the developing regions to accept the suggested allocation approach are estimated. As for India, it is indicated that the economic benefits with trading permits could be high during the first half of this century, while the benefits are smaller during the second half. However, one exception exists, the CPA is buying emission permits during almost the whole century. The suggested allocation approach could, thus, be used as an incentive for an early involvement of most developing countries in a Protocol for emission reductions. An early involvement of developing countries would also imply that the overall cost of meeting the stringent targets would be lowered, as the permit price on CO_2 decreases.

4. MAIN CONCLUSIONS

Energy system models and modelling methodologies are tools that can inform energy policy decisions. Energy economic models have been used and developed in the work displayed in this thesis to analyse different ways for the energy system in India to meet stringent CO_2 targets during this century and to analyse international trade in CO_2 emission quotas.

The results show that there exist technological options to abate CO_2 emissions to per capita levels by the end of this century, which is lower than today in India. In the long-term, solar energy and/or CO_2 sequestration could be the most important options for the abatement of emissions.

On the other hand, the industrialised countries have emitted most and still emit most of the CO_2. Therefore, they have the responsibility to act first.

The Kyoto Protocol contains legally binding greenhouse gas (GHG) emission reduction targets for developed countries to be met by 2008-2012. However, the integrity of the Protocol is threatened by hot air and the U.S. decision to opt out. In fact, the aggregate Kyoto Protocol emission target could be met in the absence of U.S. participation even if no abatement policies are carried out in the other countries. Thus, the permit price could actually drop to zero.

Policy makers who are concerned about climate change must thus work for real emission reductions in the Kyoto Protocol. They also have to work for a future Protocol that includes the developing countries. A stringent atmospheric CO_2 stabilization target could not be met without carbon abatement policies in developing countries. However, in the initial phase the industrial countries should bear the main costs of developing countries joining the protocol. An economic incentive for early participation of developing countries could be a generous allocation of emission allowances, perhaps along the lines sketched in Paper 2 and 3.

ACKNOWLEDGEMENTS

My first experience of academic research was at the Chalmers department of Environmental Physics. It was a time of new experiences and discussions. I am grateful to professor Eva Selin Lindgren for giving me the chance to be at the department. I would also like to thank Dr Jan Isakson for introducing me to the research field and to Sara Jarnhäll, Peter Molnár, Johan Bohman, and the others at the department for help and interesting discussions.

The fates determined that I should move one floor up in the Physics building and begin my Ph.D. studies. The department of Physical Resource Theory provided a place where my interests in industrial metabolism and the environment could develop. The two and half years I have been at the department have been the most interesting and enjoyable in my life.

I express my gratitude to all persons who have been of importance for the accomplishment of this thesis.

I first thank my main supervisor, professor Christian Azar, for being an excellent guide in the research field. You have supported me, been a good listener and helped me with the writing. I am especially thankful that you have the ability to ask me the hard questions that force me to do better work.

Kristian Lindgren, I am grateful to you for our discussions about modelling and for always being a good listener. My thanks also to our department head, John Holmberg, for his unflagging support. Sten Karlsson, you have taught me many things. Johan Swahn, I really appreciate our discussions about research and the importance of individual development.

Jessica Johansson, I must thank you for your advice and letting me know your experiences of being a Ph.D. student at the department. In addition there are others that have made the time a joyful experience. Wathanyu Amatayakul, Björn Andersson, Göran Berndes, Anders Eriksson, Karl-Erik Eriksson, Fredrik Fredriksson, Daniel Johansson, Peter Jönsson, Jenny Hanell, Eija Hyttinen, Tomas Kåberger, Ulrika Lundqvist, Bernhard Mehlig, Peter Nordin, Jonas Nässen, and Krister Wolf. I thank you all for ongoing help and discussions.

I thank Gunnar Larsson, Dean Abrahamson, Robert Ayres, Sujata Gupta, and N.H. Ravindranath for their help and discussions in my research.

I am grateful for the encouragement from my parents Rolf and Solveig Persson. I would also like to send a thought to sensei, my grandfather Nils, without whom I would not be the person I am today. I hope your spirit can visit my licentiate presentation.

Finally, I would like to thank Camilla for emotional support and unending patience. Without you, the life would not be so joyful.

REFERENCES

Agarwal A. and Narain S., 1991. Global warming in an unequal World. Centre for Science and Environment, New Delhi.

Andersson B.A., 2001. Material constraints on technology evolution: The case of scarce metals and emerging energy technologies. PhD Thesis, Physical Resource Theory, Chalmers University of Technology and Göteborg University, Göteborg.

Averchenkov A. and Berdin, V., 2001. Strategic Environmental Assessment of Kyoto Protocol by Russian Federation. Delivering Kyoto: Could Europe do it? Royal Institute of International Affairs, London.

Azar C. and Rodhe H., 1997. Targets for stabilization of atmospheric CO_2. Science, 276, 1818-1819.

Azar C., K. Lindgren and B.A. Andersson, 2000. Hydrogen or methanol in the transportation sector?, Department of Pysical Resource Theory, Chalmers University of Technology and Göteborg University, Göteborg.

Azar C. and Schneider S.H., 2001. Are uncertainties in climate and energy systems a justification for stronger near term mitigation policies? Paper prepared for a Pew Center meeting on timing of climate policies, Washington October 11-12.

Bolin B. and H.S. Kheshgi, 2001. On strategies for reducing greenhouse gas emissions, Proceedings of the National Academy of Sciences, 98, 4850-4854.

Capra F., 1982. The turning point. Flamingo, an Imprint of HarperCollins Publishers.

Dosi G., 1997. Opportunities, incentives and the collective patterns of technological change. The Economic Journal, 107, 1530-1547.

Freeman C. and Perez C., 1988. Structural crises of adjustment, business cycles and investment behaviour. Technical Change and Economic Theory, London: Printer, 38-66.

Grahn M., 2002. Regionalisation of the Global Energy System Model. Work in progress.

Holmberg J. and Karlsson S., 1992. On designing socio-ecological indicators. In: society and environment: A Swedish research perspective, eds. U. Svedin and B. Hägerhäll Aniansson, pp. 89-106. Kluwer Academic Publisher, Dordrecht.

IPCC, 2000. Emissions scenarios, Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge UK.

IPCC, 2001. Climate Change 2001. Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge UK.

Kinzig A.P. and Kammen D.M., 1998. National trajectories of carbon emissions: analysis of proposals to foster the transition to low-carbon economies. Global Environmental Change, 8, 183-208.

Marland G., Boden T.A. and Andres R. J., 2001. Global, Regional, and National Fossil Fuel CO2 Emissions. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

Mastepanov A., Pluzhnikov O., Berdin V. and Gavrilov V., 2001. Post-Kyoto energy strategy of the Russian Federation, outlooks and prerequisites of the Kyoto mechanisms implementation in the country. Climate Policy 1, 125-133.

Meyer A., 2000. Contraction and convergence: The global solution to climate change. Schumacher Briefing No. 5, Greenbooks for the Schumacher Society, Bristol, USA.

Moe A., Tangen K., Stern J., Grubb M., Berdin V., Sugiyama T. and Korppoo A., 2001. A Green Investment Scheme: Achieving environmental benefits from trading with surplus quotas. Climate Strategies: http://www.climate-strategies.org/.

Nakićenović N., Grübler A. and McDonald A., 1998. Global Energy Perspectives, IIASA & WEC, Cambridge University Press, Cambridge UK.
TERI, 2002. Defining an intergrated energy strategy for India – a document for discussion, debate and action. Tata Energy Research Institute, New Delhi, India. ISBN: 81-85419-96-5.
UN, 1992. United Nations. Earth Summit Agenda 21: The United Nations Programme of Action from Rio, New York.
UNFCCC, 1992. United Nations Framework Convention on Climate Change. Available at www.unfccc.de.
Unruh G.C., 2000. Understanding carbon lock-in. Energy Policy, 28, 817-830.
Victor D.G., Nakićenović N. and Victor N., 2001. The Kyoto Protocol emission allocations: windfall surpluses for Russia and Ukraine. Climate Policy, 3, 263-277.
Weyant J. ed., 1999. The cost of the Kyoto Protocol: A multi-model evaluation. Special Issue of The Energy Journal.
Wigley T.M.L., 1997. Implications of recent CO_2 emission-limitation proposals for stabilization of atmospheric concentrations, Nature, 390, 267-270.
Wright G., 1997. Towards a more historical approach to technological change. The Economic Journal, 107, 1560-1566.

PAPER 1

The cost of meeting the Kyoto Protocol –
Dealing with the carbon surplus in Russia and Ukraine

Tobias A. Persson and Christian Azar
Department of Physical Resource Theory,
Chalmers University of Technology/Göteborg University,
412 96 Göteborg,
Sweden;
Email: frttp@fy.chalmers.se

ABSTRACT

The cost of meeting the Kyoto Protocol is estimated with an energy-economic optimization model. Special focus is on the Russian and Ukrainian so called hot air and the possible implication of the U.S. decision to withdraw from the Protocol. It is found that the carbon permit price drops substantially due to the withdrawal of the U.S. from the Protocol. In fact, the aggregated emission target in the Kyoto Protocol could be met in the absence of U.S. participation even if no abatement policies are carried out in the other countries. Thus, the permit price could actually drop to zero. However, Russia and Ukraine could be the dominant sellers of emission permits and by withholding their carbon surplus from the market they can increase the permit price. We estimate that Russia and Ukraine can maximize their revenues to a few billion US$ by acting as oligopolists. Clearly no climate benefits would result from trading emission permits that do not correspond to real reductions in CO_2 emissions. EU countries, and to a maybe lesser extent Japan, Canada and Australia, are not likely to be supportive of paying billions of dollars that do not result in emission reductions. One way of dealing with the Russian and Ukrainian surplus is to negotiate more stringent targets for subsequent commitment periods early, and to allow banking. The carbon surplus could then be used as an argument in favor of more stringent subsequent targets for Russia and Ukraine, and they would then get incentives to bank their permits for future use. Our model suggests that, under these conditions, early action takes place and that banking does take place in Russia and Ukraine.

1. INTRODUCTION

The 1997 Kyoto Protocol to the UN Framework convention of climate change (UNFCCC, 1992) contains legally binding greenhouse gas (GHG) emission reduction targets for developed countries, the so-called Annex 1 parties. The Protocol allows the creation of systems for emissions trading in which countries exceeding their target levels can remain in compliance by purchasing surplus permits from other Annex 1 countries (Article 17). This option was highly debated during the negotiations, partly since it can allow trading with no 'real' emission reductions.

The Protocol requires the Russian Federation and Ukraine to stabilize their emissions at their 1990 levels. However, during the last decade a 400 MtC yr^{-1} carbon surplus (normally referred to as hot air) has been created in these countries because their GHG emissions have dropped by 39 percent between 1990 and 1998. The main reason for this reduction is the economic disarray, which followed the collapse of the Soviet Union and central planning (Victor *et al.*, 2001). Experts from the Russian Government estimates that about 60-70 percent of the emission reductions in the energy sector during the last decade were attributed to economic decline, about 8-12 percent to initiation of institutional reforms in the energy sector and the rest due to wider use of natural gas and structural changes in the economy (Mastepanov *et al.*, 2001), although it is not clear how they estimated these numbers.

Estimates of the marginal cost of meeting the Kyoto Protocol domestically in Annex 1 countries range between marginal abatement costs close to zero and as high as 1200 US\$ tC^{-1} (see for example the special issue of the Energy Journal, May 1999, which reports cost of compliance to the Kyoto Protocol for twelve different models affiliated to the Energy Modelling Forum, Weyant (1999)). Most studies that allow trading end up with a permit price in the range 20-150 US\$ tC^{-1}. However, the permit prices are expected to be sharply lower due to the withdrawal of the U.S. from the Kyoto Protocol (see e.g., Nordhaus, 2001), because the demand for emission allowances would be reduced without U.S. participation. The revenues to Russia and Ukraine associated with the sales of the emission allowances would similarly decrease. There is concern that the price will collapse to very low levels, since it is possible that the required CO_2 reduction during the first commitment period, 2008-2012, would be less than or at least close to the carbon surplus in Russia, Ukraine, and Eastern Europe.

There appear to be several ways of prevent a large permit price collapse, including:

- Russia and the Ukraine can act as oligopolists, they are in some sense price makers and not price takers. Their goal would be to maximise their revenues from selling of emissions allowances or reduce the future cost by banking all or some of their carbon surplus.

- All EU countries may not find it politically acceptable were the Kyoto commitments to be met by trading with hot air.[1]
- The incentives for not selling and buying emission permits may increase if the second commitment period is negotiated before the first commitment period begins.
- The price would not drop if the U.S. were to rejoin the Protocol before 2008.

The aim of this paper is fourfold:

1. Estimate the carbon permit price with and without Annex 1 trading with U.S. ratifying the Protocol.
2. Estimate the carbon permit price with competitive Annex 1 trading without the U.S. ratifying the Protocol.
3. Estimate the carbon permit price without the U.S. ratifying the Protocol and with Annex 1 Former Soviet Union acting as oligopolists.
4. Analyse how early negotiations and agreement on more stringent targets in the subsequent commitment periods could affect abatement policies and permit prices during the first commitment period.

A global energy-economic optimisation model (linear programming) with six regions, EU, A1-FSU (Annex 1 Former Soviet Union, i.e., Estonia, Latvia, Lithuania, Russia and Ukraine), REU (Rest of Annex 1 Europe), PAOC (Pacific OECD and Canada), USA and ROW (the rest of the World), has been developed and used to carry out the analysis. Only emissions of carbon dioxide (CO_2) from combustion of fossil fuels are taken under consideration, the most important human cause of global warming.

The paper is structured as follows: in section 2 the present energy situation in A1-FSU is summarised. In section 3 our method and model is presented. The resulting

[1] One option that could make trading with hot air politically acceptable is the so-called 'Green Investment Scheme' - GIS (Mastepanov *et al.*, 2001; Moe *et al.*, 2001; Averchenkov and Berdin, 2001). Then the revenues the Former Soviet Union makes by trading hot air are re-invested into emission reduction projects and the resulting emission reductions should be more than the amount of units sold. The first official political commitment on GIS by the Russian government was announced at COP 6-bis in Bonn. The Russian Ministry of Energy has since then also supported GIS. It should, however, be recognised that projects implemented jointly in Russia and Ukraine would have more stringent requirements on emission reductions than GIS. The GIS can be seen as a mixture of emissions trading and joint implementation, with less stringent requirements and influence on the project than what would normally be the case in joint implementation projects.

scenarios with abatement cost estimations and potential A1-FSU revenues from trading are presented in section 4. In section 5, a sensitivity analysis is presented and finally some conclusions are given in section 6.

2. A1- FSU ENERGY SITUATION

The energy sector is responsible for a dominant part of the GHG emissions in Russia and Ukraine. According to the Russian second national communication (UNFCCC, 2000), fossil fuel combustion causes 98.6 percent of the total Russian anthropogenic CO_2 emission, while CO_2 contributes 77 percent to the total GHG emissions. The energy sector would have to play a major role if Russia were to meet stringent GHG abatement targets.

Total secondary energy use was 4.4 EJ yr^{-1} in Ukraine and 20.8 EJ yr^{-1} in Russia (IEA, 2001), and 6.0 and 27.5 EJ yr^{-1}, in 1995 and 1992 respectively (see Figure 1). Natural gas provides about half primary energy demand. The other Annex 1 countries in A1-FSU on the other hand are more dependent on other energy sources. Estonia and Latvia are more dependent on oil and Lithuania on nuclear power.

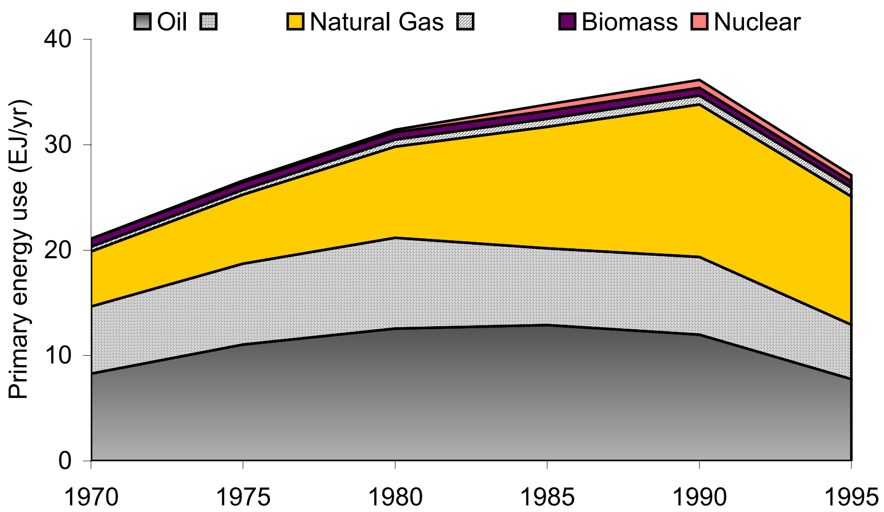

Figure 1. Estimated historic primary energy use in Annex 1 Former Soviet Union countries, i.e., Estonia, Latvia, Lithuania, Russia and Ukraine.
Source: Data from IEA (2001).

Historically, the energy intensity, defined as primary energy supply divided by GDP, in the Soviet Union was very high in comparison to other industrialised countries and it rose even further in the 1990s[2] (when economic output fell faster than energy use). One reason explaining why energy use fell faster than economic output in the 1990s is that it takes time for economic agents to adjust their behaviour to new price signals, not only because of capital stock turnover, but also because consumers often do not have an accurate knowledge of their energy use, or the technical capacity to reduce the use. Energy intensity in FSU (measured as primary energy per GDP) was 59 MJ US$$^{-1}$ in 1990, and it increased by one third until 1995 (81 MJ US$$^{-1}$). For comparison, the energy intensity in 1995 was approximately 8 MJ US$$^{-1}$ in the EU, and 12 MJ US$$^{-1}$ in the U.S. (IEA, 2001). Energy intensity was, however, lower in Former Soviet Union in ppp GDP numbers, 30 MJ US$$_{ppp}^{-1}$ in 1990 and 41 MJ US$$_{ppp}^{-1}$ in 1995.

Despite the drop in energy use in the 1990s there is a need for investment in new equipment. According to Hill (1999) a significant proportion of the power generation equipment is obsolescent. In 1996, for example, 21.5 GW of fossil fuel capacity was operating beyond its working lifetime in Russia, and this is expecting to increase to some 55 GW (almost one fourth of the total installed capacity) by 2005.

The A1-FSU region is well endowed with fossil fuel resources. Most of these are located in the Russian Federation. A large share of the total export earnings and government revenues are dependent on exports of these resources. Russia produces roughly 15 EJ of oil and 22 EJ of natural gas annually, with approximately 10 EJ of oil and 7 EJ of natural gas being exported, generating export revenues about 40-50 billion (10^9) US$ yr^{-1}.

3. METHODOLOGY

A global linear programming (LP) energy-economy optimisation model has been developed for the analysis (Persson *et al*. 2002:a; Azar *et al*. 2002). The model has six regions, EU, PAOC (Pacific OECD and Canada), A1-FSU (Annex 1 Former Soviet Union), REU (Rest of Annex 1 Europe), USA and ROW (the Rest Of the World). The model is composed of three different parts: the supply side, the demand side, and the energy technology system. Energy supply potentials, maximum expansion rates, and the CO_2-emission limitations are all exogenously set. The LP model minimizes the total energy system cost, based on costs for fuel, capital and a discount rate of 5 percent yr^{-1} in together with vehicle technology cost for the transportation sector.

[2] It should be recognised that GDP numbers for Soviet Union (during the communist era) are very difficult to estimate.

3.1 REFERENCE ENERGY DEMAND

The energy demand in the reference scenarios is derived from linear extrapolations of historic trends for EU, PAOC and the USA. We have used IEA World Energy Statistics and Balances for the historic trend analysis (IEA, 2001). Demand is divided into three main categories: the demand for electricity, demand for heat and process heat, and demand for transportation fuels. For each region, we carried out an analysis of how the demand of the three categories has developed since the 1960 (see Figure 2 for the EU and the U.S., and Persson *et al.,* 2002:a, for a background paper). A strong linear relation between energy use and time was found for electricity and transportation fuels and we have extrapolated these trends into the future. The resulting equations are used as reference energy demand scenarios in the model. The heat and process heat demand is assumed to be the same as the present demand.

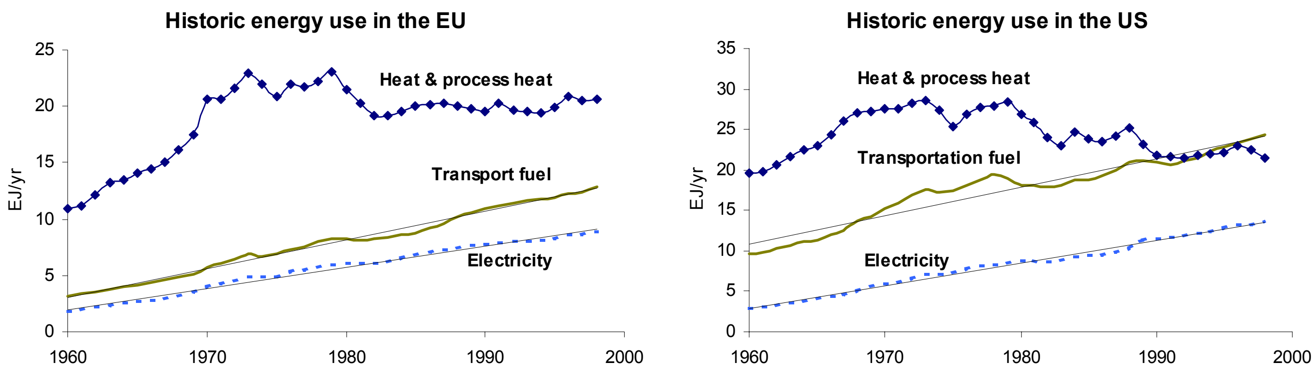

Figure 2. Historic energy use in the EU-15 and the U.S.. For the EU, the future electricity and transportation fuel demand is assumed to follow the linear historic extrapolation (the correlation coefficient r^2 is 0.99 for both electricity and transport fuel) while the heat demand is assumed to be constant, 18.5 EJ yr^{-1}, in the reference demand scenario. For the U.S., the future electricity and transportation fuel demand is assumed to follow the linear historic extrapolation (the correlation coefficient r^2 is 0.99 for electricity and 0.93 for transport fuel) while the heat demand is assumed to be constant, 20.5 EJ yr^{-1}, in the reference demand scenario.

Energy demand for A1-FSU and REU are assumed to follow the assumed GDP growth. The size of the carbon surplus is based on assumptions about future changes of energy demand, economic recovery relative to 2008-2012, structural changes in the economy, and energy supply choices. According to Mastepanov *et al.* (2001), the energy saving potential through institutional and technological measures in Russia is more than 14 EJ yr^{-1} by 2010 and 38 EJ yr^{-1} by 2020. And according to Horn (1999), the energy demand in Ukraine by 2010 is in the range 2.8-4.4 EJ yr^{-1}. Jochem (2000) estimates the economic energy efficiency potentials in 2010 for Russia and Ukraine to 8.3-11.7 EJ yr^{-1}.

GDP in A1-FSU is assumed to grow by 3.5 percent yr^{-1}, energy intensity is assumed to decline at 1 percent yr^{-1} (i.e., the demand grows by 2.5 percent yr^{-1}) in the reference scenario. However, due to the uncertainties related to the demand we have done a sensitivity analysis of how our results will be affected by adopting a different reference demand scenarios for A1-FSU. The energy demand in REU is assumed to grow by 1.5 percent yr^{-1} in the reference scenario.

3.2 ENERGY DEMAND IN THE ABATEMENT SCENARIOS ADJUSTMENT TO A CARBON TAX

The permit price is defined as being equal to the carbon tax required to reach the Kyoto target. The tax is introduced by 2006, increases by 5 percent yr^{-1} until 2020, and thereafter remains constant.

The model can make three energy sector adjustments in response to a carbon tax:

(i) Decreasing energy intensity
(ii) Switching fuel
(iii) Sequestering CO_2

Our model is linear programming model, with exogenously specified energy demand levels. In order to introduce a price-demand feedback, we have assumed that the energy drops as a function of the carbon tax by 2010. The relation is based on the energy demand/carbon tax relation implicit in the Annual Energy Outlook 2002 study (EIA, 2002). In this study, a short-term energy demand price elasticity parameter, -0.25 is used, i.e., for a 1% increase in the price of energy, there is a corresponding decrease in energy demand of 0.25%. This translates into a 13% drop in energy demand below reference scenario for a carbon tax equal to 200 US\$ tC^{-1} in the U.S. by 2010. We have used these relations as a basis for our study. When the tax increases, we have assumed a decoupling factor that increases linearly from zero to 13% when the tax is 200 US\$ tC^{-1}. EU, REU and PAOC are assumed to have the same decoupling factor as the U.S., while the decoupling is assumed to be stronger in the A1-FSU. For a tax of 200 US\$ tC^{-1}, the reference energy demand in A1-FSU is assumed to be reduced by 25%.

CO_2 emissions can be reduced by switching primary fuel to non-carbon emitting energy sources such as wind, biomass and hydro, and/or shifting from fuels with high carbon-to-energy ratios (such as coal) to fossil fuels with lower carbon-to-energy ratios (such as natural gas).

3.3 ENERGY SUPPLY POTENTIALS

The primary energy supply potentials are region specific and based on literature values (see Masters *et al.*, 1990; Johansson *et al.*, 1993; Moreira and Pool, 1993; Sørensen, 1995; Rogner 1997; EWEA, 1999). Maximum rates of growth in each primary energy source are set exogenously for all technologies. Nuclear power output is assumed to be phased out at 1 percent yr^{-1} of the 2000 capacity beginning in 2010. Wind power and solar PV are allowed to grow by a maximum 20 percent yr^{-1} (note that this is less than actual growth rates experienced for both technologies).

4. RESULTS

4.1 NO KYOTO – REFERENCE SCENARIO

The estimated cost of reducing CO_2 emissions to meet the Kyoto commitments is critically dependent upon the reference scenario. The higher the growth rates of emissions in the reference case the greater the cost of meeting the Kyoto targets.

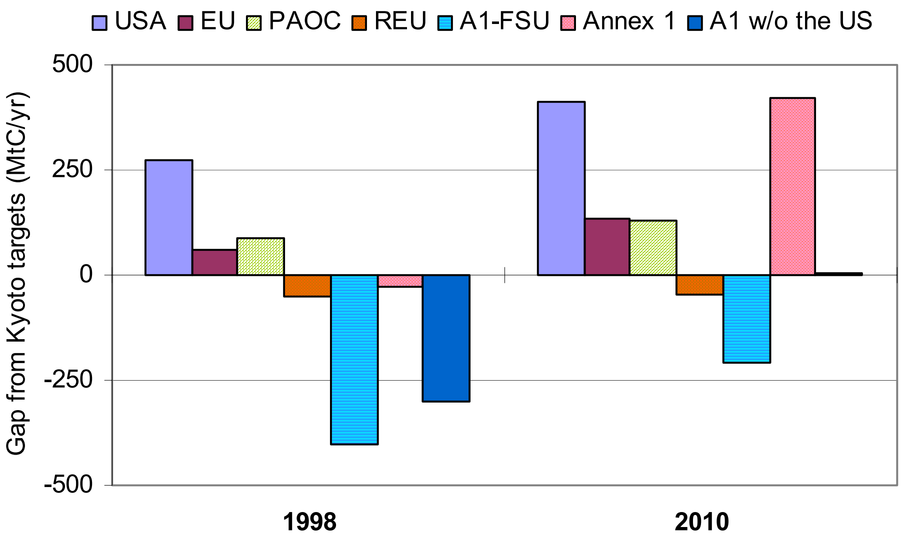

Figure 3. Absolute gap between CO_2 emissions and the Kyoto commitments in 1998 and 2010. 1998 data are taken from Marland *et al.* (2001), while 2010 numbers are based on our modelled reference scenario. Annex 1 is the gap from the aggregated Kyoto commitment and A1 w/o the U.S. refers to the gap from the aggregated commitment without U.S. participation. It can thus be seen that the Kyoto Protocol (without U.S. participation) is met in our reference scenario in the aggregate, and that this is due to the hot air in Russia, Ukraine and to a much minor extent the Eastern Europe.

There is a significant gap between 1998 CO_2 emissions, the modelled 2010 emissions, and the Kyoto commitments, Figure 3. The carbon surplus in Annex 1 Former Soviet Union that our model generates with the reference energy demand scenario we presented in Section 3 is about 220 MtC yr^{-1}. The surplus includes Marrakech sinks and emissions from the energy system. These estimates of the tradable amounts of CO_2 emission permits are in line with other estimates: generally, it is estimated that A1-FSU need to use about 70-90 percent of the allocated emission quota (Mastepanov *et al.*, 2001; Victor *et al.*, 2001; EIA, 2001; Grubb *et al.*, 2001).

Worth to note in Figure 3 is that the aggregated emissions in year 1998 with U.S. participation are almost equal to the Kyoto targets, i.e., the reduction of 5 percent from base year to 2010, is perhaps better describes as a stabilization target from 1998-2010 (since the targets were actually negotiated in Dec. 1997, and not in 1990). It may here also be noted that the U.S. reduction target from 1998 to 2010 is almost 16 percent (included all Kyoto greenhouse gases), i.e., much more than the 7 percent number that is refers to the 1990-2010. Modelled reference emissions have increased in all our regions by 2010. The carbon surplus in the Economies in Transition (REU and A1-FSU) has decreased while the other Annex 1 countries are even further away from their commitments. In our reference scenario, EU has to reduce the emission by 135 MtC yr^{-1}, PAOC by 130 MtC yr^{-1}, and the U.S. by 410 MtC yr^{-1} by 2010. The fifth Annex 1 region in our model, REU, is like A1-FSU a potential seller of emission permits by 2010. In our scenario the CO_2 emissions are 45 MtC yr^{-1} less than their allowances in 2010. Thus, the aggregated gap between the Kyoto commitment and the reference scenario emissions by 2010 is approximately 410 MtC yr^{-1} with the U.S. in the Protocol and around zero MtC yr^{-1} without the USA, i.e., the Kyoto commitments are meet without any real emission reductions.

4.2 KYOTO NO TRADING

EU, Japan, Canada, Australia, and the other Annex 1 countries can meet their targets either by reducing their emissions domestically or by using the flexible mechanisms (CDM-Clean Development Mechanism, JI-Joint Implementation, and trade in emission permits).

In the no trading case, each Annex 1 region must individually meet its emissions targets without any use of the flexible mechanisms, Table 2. In our scenarios, compliance is generally met by substituting natural gas and wind power for coal in the production of electricity and by substituting biomass for coal in the production of heat and process heat. The carbon tax is required to reach levels where these technologies become economically competitive.

Table 2. Emissions mitigation relative to reference emissions, and emissions taxes required meeting the emission reduction requirements in the Kyoto Protocol by 2010 (sinks included).

Region	Emissions mitigation relative to reference to meet Kyoto commitment targets MtC yr^{-1}	Marginal abatement cost to achieve compliance without trading(1) US\$ tC^{-1}
USA	410	200
EU	135	100
PAOC	130	125
REU	-45	—
FSU	-220	—

(1) We have rounded the required carbon tax to the nearest multiple of 25 USD tC^{-1} in order to avoid the impression that the estimations are exact numbers without uncertainties.

4.3 KYOTO COMPETITIVE TRADING – WITH THE U.S.

A potentially less costly way of meeting the Kyoto Protocol targets is through the use of the flexible mechanisms. The basic idea behind these mechanisms is that they allow each country to reduce their emission domestically or to buy emission permits, or to carry out joint projects with other countries. If the international permit price is lower than the domestic marginal abatement cost, countries may instead of reducing emissions domestically, buy permits from the international market. This means that a lower overall cost could be achieved.[3]

In an Annex 1 trading regime, a country may only emit more carbon dioxide than their allocated emissions rights if another Annex 1 country is willing to sell the corresponding number of permits, thereby forcing the selling region to reduce its domestic emissions below the required commitment. This is modelled as if a common carbon tax were applied to all Annex 1 regions to meet the aggregated Annex 1 emissions target.

We further assume the trading market to be competitive, i.e., suppliers of permits are numerous and no single permit seller can affect the price received by withholding permits from the market or demand a price over the optimum where the demand and supply for permits reach each other.

[3] On the other hand, the lower abatement cost could also result in less effort being put into developing new and more advanced technologies that are required to meet subsequent more stringent abatement targets. Too much focus on near-term cost-efficiency might thus lead to higher costs of meeting future targets, or the possibility that stringent future targets are considered too costly to be accepted (see Andersson and Azar, 2002; Persson 2002).

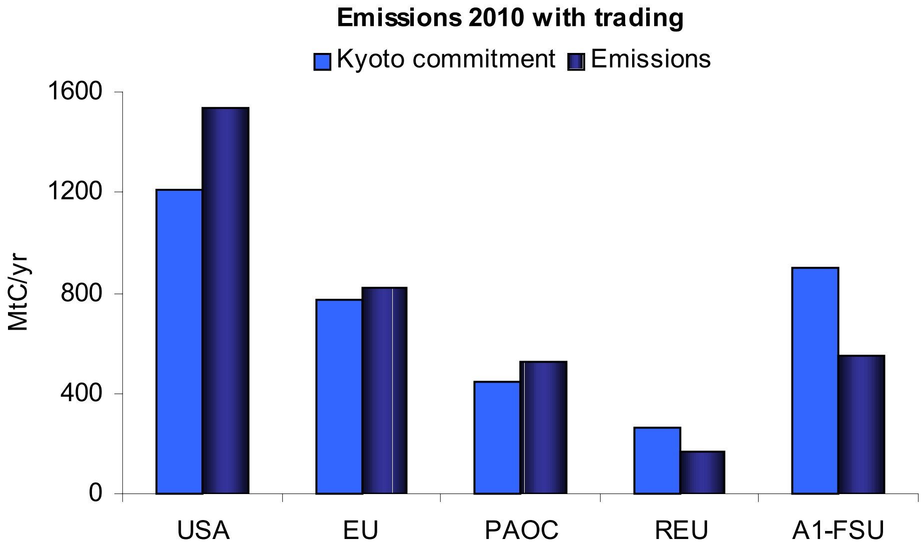

Figure 4. Annex 1 CO_2 emissions in 2010 by region and Kyoto commitments – competitive Kyoto Protocol trading with the USA. Annex1 FSU and REU sell emission permits, i.e., their emissions are lower than the Kyoto commitment, while the USA, EU and PAOC buy emission permits.

Marginal abatement costs are lower in EU, PAOC and USA with Annex 1 trading than in the no trading scenario. The permit price to bring the aggregated Annex 1 emissions into compliance with the Kyoto commitments is estimated to be around 70 US\$ tC^{-1}. However, this number is not directly comparable to the marginal abatement costs in Table 2, since the total amount of carbon abated is higher in the no trading case than in the trading case (in the no trading case all countries meet their targets and A1-FSU and REU are 265 MtC yr^{-1} from their target). In the no trading scenario, CO_2 emitters like the EU undertake emissions mitigation options available only within the countries and, hence, arguments that you should not buy hot air from Russia and Ukraine cannot be challenged on the grounds that this is not a cost-effective strategy. This observation is particularly important in the case where the U.S. does not participate in the Protocol.

However, with the modelled Annex 1 full trading scenario, regions are included that have mitigation options with lower costs than the EU (especially the carbon surplus in Economies in Transition), thereby the marginal cost to meet the EU commitment is lowered. A transfer of emission permits from the countries in economic transition to the modern industrialised countries, especially from A1-FSU to the U.S. would be required, Figure 4. The U.S., for example, would have to purchase approximately 325 MtC $yr^{-1}$of permits by 2010.

The A1-FSU revenues from this trading are close to the present revenues from the export of natural gas and oil. Annex 1 Former Soviet Union sells in this scenario about 350 MtC yr^{-1}, generating revenues about 25 billion US\$ yr^{-1}.

4.4 KYOTO COMPETITIVE TRADING - WITHOUT THE U.S.

As in the previous section, trading markets are assumed to be competitive, but the U.S. is assumed not to ratify the Protocol.

The U.S. decision to opt out from the Kyoto Protocol, results in a situation where the largest potential buyer of emission permits has disappeared. A lower demand for permits results in a lower price. In Figure 5, we show our modelling results for the total emissions in 2010 for each region and compared to the Kyoto commitment for each region. In our reference scenario, total emissions in 2010 for the Annex 1 region (without the U.S.) is roughly as large as the Kyoto target and therefore the required carbon tax, or the permit price, drops to close to zero US\$ tC^{-1}. The transfer of emission permits goes from the Economies in Transition to the EU and PAOC, which would have to reduce their emissions by approximately 265 MtC yr^{-1} from the reference emissions during the first commitment period.

The revenues from trading would decrease close to zero in the Russian Federation and Ukraine as a result of the decrease in permit price.

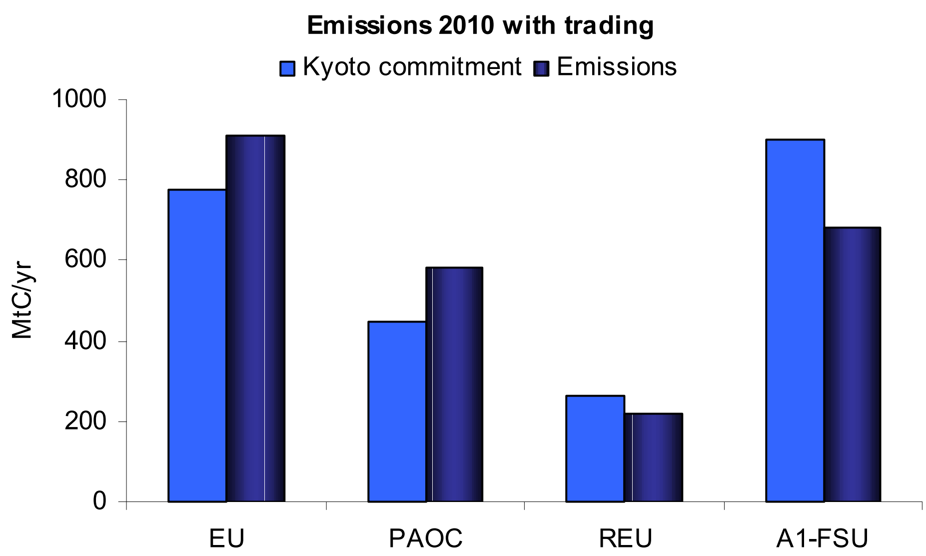

Figure 5. Annex 1 CO_2 emissions in 2010 by region and Kyoto commitments – competitive Kyoto Protocol trading without the USA. REU and A1-FSU sells emission permits to the EU and PAOC.

4.5 KYOTO WITHOUT THE U.S. – A1-FSU AS OLIGOPOLISTS

Russia and Ukraine, can be expected to be the dominant sellers of emission permits in 2010, as previously shown. Thus, Russia and Ukraine have strong incentives to act as oligopolists were the U.S. does not participate and permit prices fall (since Russia and Ukraine belong to the same region in the model we have modelled a monopolistic scenario). A1-FSU countries could then choose to sell less CO_2 emission rights than in the competitive trading situation and thus increase the permit price from zero US$ tC^{-1}.

The potential revenues for A1-FSU are very sensitive to the permit price given that all regions should comply with the Kyoto Protocol and that A1-FSU acts so as to maximize its revenues, Figure 6. The figure also shows the amount of CO_2 emission rights traded. If no CO_2 abatement policies are implemented in A1-FSU, these countries can sell the difference between their reference CO_2 emissions and their commitment, i.e., the hot air, about 220 MtC yr^{-1}, but then the price of the permits would basically drop to zero (this is the competitive scenario presented in the previous section, and could materialize if the governments in Russia and Ukraine would allocate emission rights freely to companies in these countries and if they would be allowed to sell these rights internationally without any restrictions). The scenario shows that A1-FSU is maximizing the revenues when the permit price is around 45 US$ tC^{-1} and they would sell approximately 140 MtC yr^{-1}. The revenues end up at approximately 6.3 billion US$ yr^{-1} from 2008 until 2012. This is about 15% of the revenues to the present Russian national budget.

It should be noted that this scenario would bring about real reductions in the remaining Kyoto regions. Total emissions in the Annex-1 region (without the U.S.) would be 80 MtC yr^{-1} lower than the target.

Finally, it may also be noted that if the permit price increases to 75 US$ tC^{-1}, then EU, PAOC and the rest of Europe would, in our model, not have any economic incentives to buy permits from A1-FSU.

It is assumed that the A1-FSU countries will act to maximize their revenues during the first commitment period, and future commitment periods are not considered.

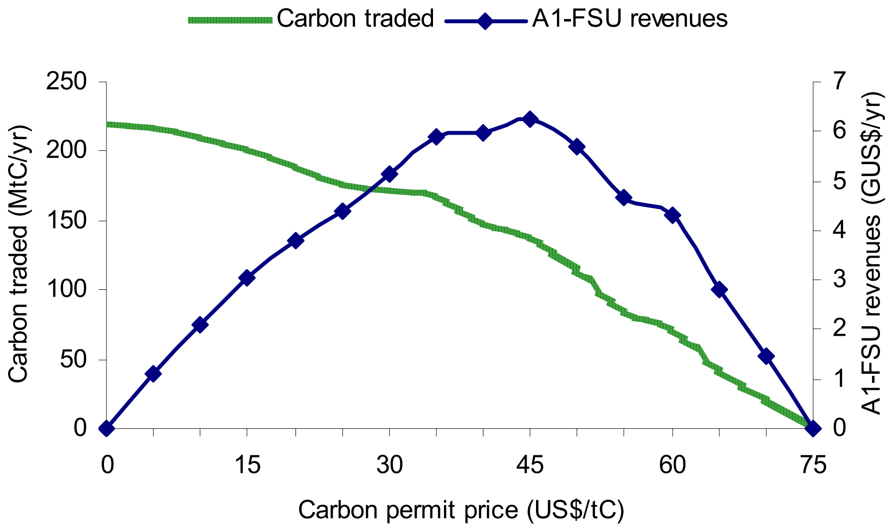

Figure 6. Annex-1 Former Soviet Union revenues from trading in GUS$ yr^{-1} (doted line) and the amount CO_2 traded in MtC yr^{-1} (no dots) as a function of the carbon dioxide permit price. A1-FSU sets the permit price at 45 US$ tC^{-1}, total revenues will be maximized at 6.3 billion US$ yr^{-1} (right axis), and a total of 140 MtC yr^{-1} (left axis) will be sold. Not that around 80 MtC yr^{-1} can be banked in this case for future commitment periods, but we have not considered the value of this.

4.6 THE IMPACT ON TRADE AND PERMIT PRICES OF EARLY DESSISSIONS ON SUBSEQUENT COMMITMENT PERIOD TARGETS

In this section, we analyse if negotiations and decisions about future emission allowances (Assigned Amount Units, AAUs) could prevent the permit price from collapsing to zero during the first commitment period. It is assumed that banking of the assigned amount units is allowed and that the allowances are allocated according to a contraction and convergence approach. All people are assumed to have equal amounts of emission permits by 2050, i.e., the emissions converge to an equal per capita emission profile. Per capita emissions of 0.7 tC $capita^{-1}$ yr^{-1} are allowed in 2050. Before 2050, each Annex 1 region is allocated per capita emissions allowances that follow a linear trend from their Kyoto target towards the equal per capita allocation by 2050 (the U.S. allowances follows a linear trend 15% above their 1990 levels in 2012). In Figure 7, we show our prescribed allocation of emission rights for the different regions on a per capita basis, and it is seen that the U.S. has the toughest challenge in the long term (despite the generous distribution by the first commitment year).

A1-FSU countries, for example, should reduce their emissions by approximately 2.3 percent yr^{-1} during the 2020's, 2.9 percent yr^{-1} in the 2030's and so forth under this scenario. It can be argued that these reduction targets might be too stringent. But, if we shall stabilize the climate, the CO_2 emissions might have to be reduced to per capita levels prevailing in the less developed countries today by the end of this century (Azar and Rodhe, 1997). This means that the total emissions in the Former Soviet Union might have to be reduced by 50 percent until 2050 (for a more detailed discussion about allocation of emission permits see Persson and Azar, 2002; Persson, 2002). Population estimates are taken from UN World Population Prospects, median variant (UN, 2000).

Tow scenarios are compared, Figure 7. The first scenario, christened *surprise*, assumes that emissions until 2012 follow the CO_2 emission profile in the competitive trading scenario (see Section 4.4). The total cost to bring the aggregated emissions into compliance with the first commitment period targets is minimized assuming no oligopolists tendencies and, hence, the permit price falls to basically zero. After the first commitment period, the aggregated emissions are assumed to be in compliance with the subsequent period emission allowances.

The second scenario, designated as *early agreement*, assumes that the regions are aware of the future emissions allowances before the first commitment period begins. The total cost to bring the aggregated emissions in compliance with the allowances in this case is minimized for the first and second commitment period.

The same energy demand is imposed in both scenarios (since subsequent commitment periods is analysed, the previously used carbon tax/decoupling relation is not useable) and banking of emission permits is allowed. It is recognized that both the *surprise* and the *early agreement* scenario are extreme variants. In the real world, agreements have to be made earlier than 2010, but the extreme variants clarify the benefits of early decisions.

Figure 7, shows the development of the different regions per capita emissions for the two scenarios. Due to the knowledge about the more stringent emissions targets during the second period, the per capita emissions by 2010 are lower in the *early agreement* scenario. The EU is still not in compliance with their emission commitments domestically. However, the purchases from trading by 2010 are reduced from 135 MtC yr^{-1} to about 10 MtC yr^{-1} in the EU, see Figure 8. PAOC is in compliance with the Kyoto commitments in the *early agreement* scenario. Thus, the aggregate abatement of emissions is more than required in the Kyoto Protocol. It may also be noted that the U.S. starts to abate emissions already during the Kyoto period.

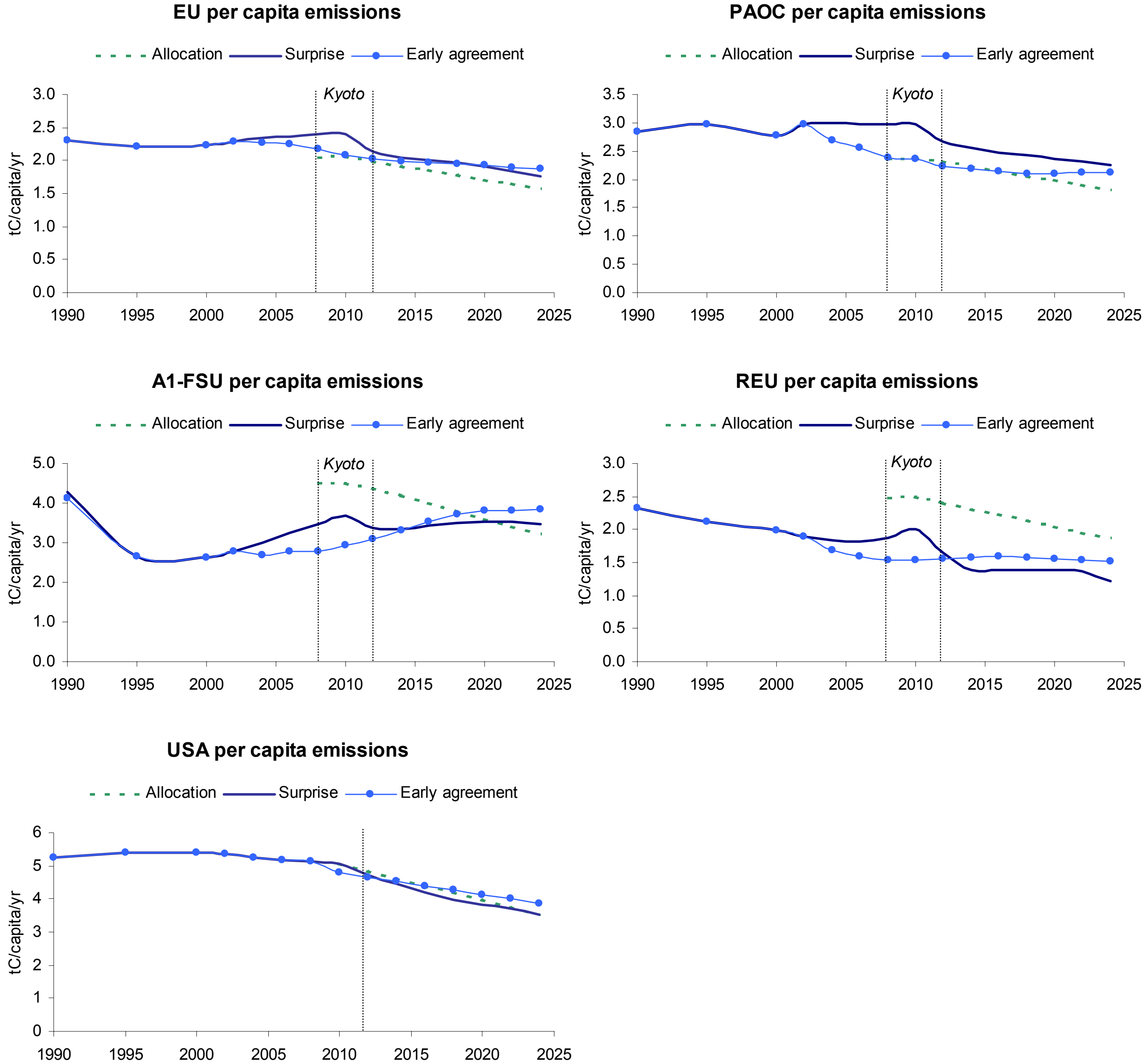

Figure 7. The effect of negotiation timing of the second commitment period on the CO_2 per capita emissions in the regions. In the *surprise* scenario (first scenario), the Kyoto commitments are met with the lowest permit price. Adjustments to the emission allowances in the second commitment period begin in 2012. In the *early agreement* scenario (second scenario), the Kyoto commitments and the second period commitments are meet with the lowest permit price. The allocation of emission allowances in the second commitment period is based on a contraction and convergence approach presented in Section 3.4. The U.S. is assumed to have emission targets in the second commitment period.

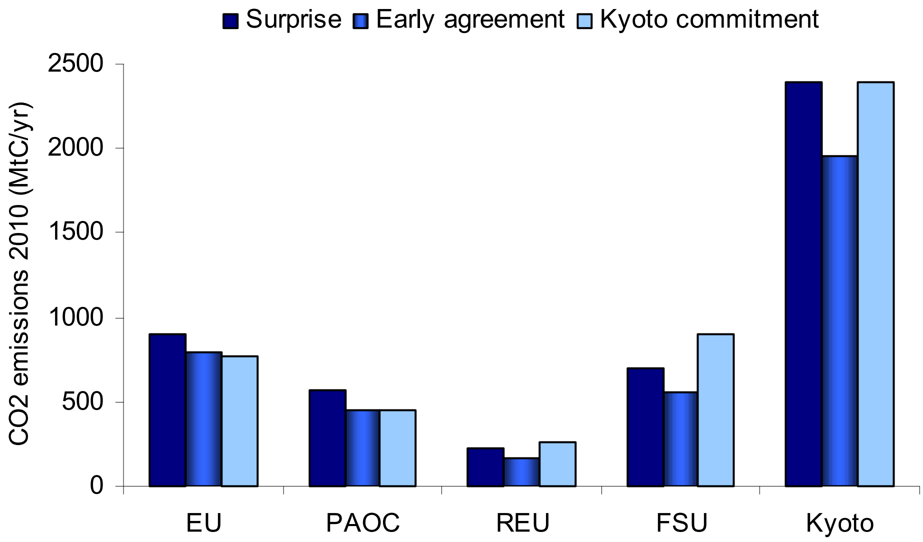

Figure 8. CO_2 emissions by 2010 for each region and Kyoto commitments – competitive trading without the USA. The aggregated abatement of emissions is more than required in the Kyoto Protocol when the future emission allowance is known before the first commitment period.

Knowledge about future emission commitments could thus be an incentive to reduce the emissions during the first commitment period in all regions since all regions benefit from acting early so that they are in a better position to meet more stringent later targets. Even Russia and Ukraine have incentives to act, and thereby avoid selling permits at too a low price. The same is evident for the U.S., even if they only join the protocol after 2012. If agreements on future assigned amounts units are delayed (the *surprise* scenario), countries may be reluctant to reduce their emissions now since that could be turned into an argument in favour of more stringent subsequent emission reductions targets. If, on the other hand, decisions about future abatement targets are made soon, and banking is allowed, governments can act now without being concerned that lower emissions in the first commitment period (2008-2012) would be used as an argument to reduce that countries assigned amount unit. In the model, abatement takes place in the model by 2008-2012 even in the absence of CO_2 taxes, since this additional cost is more than compensated by the economic benefits of having lower emissions for the subsequent more stringent commitment periods. In the real world, however, carbon taxes would be needed so as to make sure that emissions are brought down to desirable levels[4]. It is then

[4] One might argue that this would not be enough if all actors knew very well what their assigned amount units for subsequent periods are. However, perfect foresight does not exist in the real world. It should also be recognized that even if early agreements on future targets were reached, there could still be uncertainty as to whether governments would actually implement them. Pressure from large companies, political parties or voters could of course change the picture. A current interesting case can be found in Sweden. The government has decided to close down the remaining nuclear reactor at Barsebäck next year. However, at the same time, 10 MUS$ are invested in the plant and this may come to be used as a very strong argument against phasing out the reactor.

easier to be in compliance with the commitments in the subsequent period. In the *early agreement* scenario, we estimate that the required marginal abatement cost is around 130 US$ tC^{-1} in 2010. The marginal abatement cost increases, by 2020 it is estimated to be about 215 US$ tC^{-1} in the *early agreement* scenario which could be compared with 340 US$ tC^{-1} in the *surprise* scenario. For Russia and Ukraine, knowledge about the subsequent commitment periods would offer incentives to bank emission allowances.

5. SENSITIVITY ANALYSIS

Because of the substantial amounts of uncertainty that surround scenario studies, we have performed a sensitivity analysis in order to identify the sensitivity of our results with respect to different parameters and assumptions, such as the size of hot air, maximum expansion rates of primary energy supply technologies, and the contribution of nuclear power. In this section, we offer a brief summary of the results from our sensitivity analysis. For each result section except for the last, we have changed the decoupling factor of energy demand from GDP in Annex 1 Former Soviet Union from 1 percent to 0.5 percent yr^{-1}, allowed an expansion of the nuclear power supply, and increased or decreased the exogenously set maximum expansion rates on primary energy supply by 20 percent.

Table 3. Emission mitigation and marginal abatement costs required to meet the Kyoto target (Marrakech sinks included).

Region	Emissions mitigation relative to reference to meet Kyoto commitment targets MtC yr^{-1}	Marginal abatement cost to achieve compliance			
		Domestically US$ tC^{-1}	Trading US$ tC^{-1}	Trading w/o the U.S. US$ tC^{-1}	A1-FSU oligopoly US$ tC^{-1}
EU	131 – 184	75 – 125			
USA	414 – 574	175 – 225			
PAOC	125 – 160	100 – 150			
FSU	-220 – -32	0			
REU	-72 – -45	0			
Annex-1[1]	413 – 812		60 – 75		
Kyoto[2]	155 – 238			0 – 25	40 – 60

(1) Annex-1: the aggregated emission gap from the Kyoto commitment for all Annex-1 countries.
(2) Kyoto: the aggregated emission gap from the Kyoto commitment for Annex-1 countries without the U.S. participation.

The marginal abatement costs are dependent on the emissions in the reference scenario. Generally, the amount of CO_2 that must be abated increases with higher energy demand in A1-FSU, and with a reduction of the maximum allowable expansion rates (high expansion rates allows a faster substitution of natural gas for coal), Table 3. The marginal abatement cost of meeting the Kyoto commitments in our sensitivity analysis is most dependent on the assumed maximum allowable expansion rates of the primary energy supply.

The sensitivity analysis indicates that the marginal abatement cost to meet the Kyoto targets domestically is higher in the USA than in the EU and PAOC. An allowed expansion of the nuclear power output does not affect significantly the marginal abatement cost in the EU and U.S., while, the marginal abatement cost decreases by 25% in PAOC.

Russia and Ukraine have strong incentives in all scenarios to act as oligopolists were the U.S. does not participate. The optimal permit price for A1-FSU ranges from 40-60 US$ tC^{-1}, while the PAOC, REU and EU buy 85-165 MtC yr^{-1} during the first commitment period. The corresponding revenues from the trading range from 4 to 11 GUS$ yr^{-1}.

6. CONCLUSIONS

This paper has analysed the economics of the Kyoto Protocol. These key issues have been examined: (i) the impact on the expected marginal cost of meeting the Kyoto protocol greenhouse gas emission targets of the U.S. decision to withdraw from the protocol, (ii) strategies that Annex 1 Former Soviet Union (mainly Russia and Ukraine) may employ to raise revenues from the sales of its emission rights, and (iii) how early decisions on allocation of emission rights for subsequent abatement periods may affect strategies to meet the Kyoto protocol targets.

The permit price with the U.S. in the Kyoto Protocol is estimated to be 50-100 US$ tC^{-1} and the total revenues to the Former Soviet Union during 2008-2012 amount to about 25 billion US$ yr^{-1}. However, should the U.S. remain outside the Protocol the permit price is expected to be much lower (since the overall reduction requirement drops by perhaps as much as 400 MtC yr^{-1}). The permit price without the U.S. in the Protocol could actually approach zero (the overall target is met by transferring excess emission rights in Russia and Ukraine to non-complying countries/regions). Under the assumption of a faster economic recovery than in the base case in Russia/Ukraine, the amount of hot air would decrease and actual emission abatement would become necessary, and the marginal abatement cost might rise to perhaps 25 US$ tC^{-1}. The Russian and Ukrainian potential revenues from the trading could be eliminated or greatly reduced due to the withdrawal of the U.S. from the Protocol.

Russia and Ukraine could, however, restrict the supply of emission permits and thus increase the permit price and their revenues. Annex 1 Former Soviet Union could, with oligopoly tactics, increase the price to around 50 ± 10 US$ tC^{-1} and their revenues to 4-11 billion US$ yr^{-1}.

Two distinct futures can be envisioned, neither, of which is neither attractive nor likely. First, the permit price drops to near zero levels and the Kyoto Protocol would be met to a very large extent through the purchase of hot air from Russia/Ukraine. This is hardly an attractive future for EU or FSU.

The possibility that the Kyoto Protocol could be met almost entirely through the purchase of hot air is, or at least could be seen, as a nightmare for all governments, scientists and environmental organizations. Not only would this scenario mean that nothing real is being about climate change. It also means that the credibility of emission trading strategies as part of any international efforts to deal with the climate problem would drop to zero.

The second alternative, which might at first sight seem a reasonable strategy for governments in the Annex 1 FSU, would be to hold back substantial amounts of CO_2 emission rights so as to increase the permit price and increase their revenues. This would perhaps be attractive for Russia and Ukraine but less so for governments in the remaining Annex 1 countries. For policy makers that are concerned about climate change, transferring billions of dollars without net emission reductions is not likely to be acceptable, and an alternative strategy has to be developed. There are several strategies that would make sure that real abatement efforts are carried out, and these need to be looked at more carefully.

- Do not to buy emission permits (assigned amount units, AAUs) from Russia or the Ukraine. Clearly, the targets for the EU can be met without the use of flexible mechanisms (as our modelling efforts and many others show), and this would send a clear signal to the world that climate mitigation and economic development are compatible.
- Carry out joint implementation projects in Russia where actual reductions would take place.
- Develop the so-called Green Investment Scheme, which is a middle form between joint implementation and emissions trading. The scheme has been proposed by Russia and deserves more attention before it could be considered an acceptable strategy. In particular, one needs to make sure that the revenues are actually re-invested into real abatement projects. But once such controls are put in place, one might be much closer to joint implementation projects.
- Negotiate more stringent targets for subsequent commitment periods. This would create incentives for early abatement and banking of the

hot air in all regions, including the U.S. (early abatement would be in interesting option if they were given targets beyond Kyoto). We illustrate the potential for this option, and show that under stringent targets, the U.S. starts to abate emissions already during the Kyoto commitment period even if they do not have any commitments for this period.

- Work to convince (through the use of both carrots and sticks) the U.S. to rejoin the treaty.

Governments in Russia and Ukraine are aware that there are strong demands in Europe and elsewhere that Kyoto leads to 'real' emission reductions. For this reasons, there is a fair chance that constructive solutions to the problem that CO_2 prices might drop to very low levels will be found and accepted.

Acknowledgements

Financial support from the Swedish Energy Agency is gratefully acknowledged. We would also like to thank Kristian Lindgren for contributions to the development of the model and reference scenarios. Dean Abrahamson is gratefully acknowledged for comments on early manuscript.

References

Andersson B.A. and C. Azar, 2002. The cost of cost-efficiency. Work in progress.

Averchenkov A. and Berdin, V., 2001. Strategic Environmental Assessment of Kyoto Protocol by Russian Federation. Delivering Kyoto: Could Europe do it? Royal Institute of International Affairs, London.

Azar C. and Rodhe H., 1997. Targets for stabilization of atmospheric CO_2. Science, 276, 1818-1819.

Azar C., K. Lindgren and B. Andersson, 2002. Global energy scenarios meeting stringent CO_2 constraints. Cost-effective fuel choices in the transportation sector. Submitted for publication.

EIA, 2001. International Energy Outlook 2001. Energy Information Administration, DOE/EIA-0484, Washington, DC.

EIA, 2002. Assumptions to the Annual Energy Outlook 2002. Energy Information Administration, DOE/EIA-0554(2002), Washington, DC.

EWEA, 1999. Achieving 10% of world power from wind by 2020: a blueprint. Renewable Energy World, 2, 40-61.

Grubb M., Hourcade J-H. and Oberthur S., 2001. Keeping Kyoto – A study of approaches to maintaining the Kyoto Protocol on Climate Change, Climate Strategies report.

Hill M.R., 1999. Carbon dioxide emissions from the Russian Federation – Problems and choices. Energy & Environment, 10, 51-78.

Horn M., 1999. Energy demand until 2010 in Ukraine. Energy Policy 27, 713-726.
IEA, 2001. World Energy Statistics and Balances. International Energy Agency, Paris.
Jochem E., 2000. Energy end-use efficiency. World Energy Assessment, Energy and the challenge of sustainability, UNDP, New York.
Johansson T.B., Kelly H., Reddy A.K. and Williams R.H., 1993. A Renewable-Intensive Global Energy Scenario, Renewable Energy: Sources for fuels and electricity, Ed by T.B. Johansson *et. al*, Island Press.
Mastepanov A., Pluzhnikov, O., Berdin, V. and Gavrilov V., 2001. Post-Kyoto energy strategy of the Russian Federation, outlooks and prerequisites of the Kyoto mechanisms implementation in the country. Climate Policy 1, 125-133.
Masters C.D., Root D.H. and Attanasi E.D., 1990. World Oil And Gas Resources: Future Production Realities, Annu. Rev. Energy Environ. 15: 23-51.
Moe A., Tangen K., Stern J., Grubb M., Berdin V., Sugiyama T. and Korppoo A., 2001. A Green Investment Scheme: Achieving environmental benefits from trading with surplus quotas. Climate Strategies: http://www.climate-strategies.org/.
Moreira J.R. and Poole A.D., 1993. Hydropower and its constraints, Renewable Energy: Sources for fuels and electricity, Ed by T.B. Johansson *et. al*, Island Press.
Nordhaus W.D., 2001. Global warming economics. Science, 294, 1283-1284.
Persson T.A. and Azar C., 2002. Energy and CO_2 mitigation strategies for India - allocation of emission permits and revenues from emission trading, submitted for publication in Energy the international journal.
Persson T.A., 2002. Allocation of emission rights and an economic incentive for early emission reductions of CO_2 in developing regions. Work in progress.
Persson T.A., Azar C., and Lindgren K., 2002:a. Energy scenarios for five Annex 1 regions – Kyoto and beyond. Working paper.
Persson T.A., 2002. Emission trading and technological change: Global energy scenarios meeting the Kyoto commitments. Work in progress.
Rogner H-H , 1997. An assessment of World hydrocarbon resources, Ann. Rev. Energy Environ, 22:217-62.
Sørensen B., 1995. History of, and recent progress in, wind-energy utilization, Annual Review of Energy and environ, vol 20.
UN, 2000. World Population Prospects. United Nations Population Division. Available at http://esa.un.org/unpp/
UNFCCC, 1992. United Nations Framework Convention on Climate Change. Available at www.unfccc.de.
UNFCCC, 2000. Second national communication of the Russian Federation, UN, FCCC/IDR.2/RUS (Framework Convention on Climate Change).
Victor, D.G., Nakicenovic, N. and Victor N., 2001. The Kyoto Protocol emission allocations: windfall surpluses for Russia and Ukraine. Climate Policy, 3, 263-277.
Weyant J. ed., 1999. The cost of the Kyoto Protocol: A multi-model evaluation. Special Issue of The Energy Journal.

PAPER 2

Energy and CO_2 mitigation strategies for India - allocation of emission permits and revenues from emission trading

Tobias A. Persson and Christian Azar
Department of Physical Resource Theory,
Chalmers University of Technology/Göteborg University,
412 96 Göteborg,
Sweden;
Email: frttp@fy.chalmers.se

ABSTRACT

The present carbon dioxide emissions in India are 0.3 ton C capita^{-1}, but might increase, 5 times until the end of the century if the dependence on coal continues. In this paper we present four alternative carbon abatement scenarios for India throughout the century, which relies heavily on either coal, natural gas, solar or nuclear power. Carbon sequestration plays an important role in the two fossil fuel based scenarios. All abatement scenarios have the same emission profile and are derived by a global energy economic optimization model with an atmospheric CO_2 stabilization target of 450 ppm. We also show that the additional annual energy systems cost is only a few percent of the annual GDP. However, with a global system of trading in carbon emissions permits and an equal per capita allocation by 2050, Indian revenues from selling excess permits is likely to be higher than the costs of changing the energy system most of the time of this century. For instance, we estimate the revenues from these sales at 6% of the GDP while the extra energy system cost is 3% of the GDP by 2050.

1. INTRODUCTION

In July 1997, the US senate adopted a resolution stating the US would not accept any binding CO_2 emission reduction targets under the UN Framework convention on climate change, unless developing countries also adopted policies to limit their own emissions. The resolution was adopted by 95 votes in favor, and zero against. Still, in Kyoto in December that very year, the Kyoto protocol was adopted calling for emission reductions in the industrialized countries (including the former eastern bloc), but not in the South. The US administration accepted this, but Clinton could not put forward the Kyoto protocol to the congress because of the firm opposition in the senate.

The unilateral focus on industrialized countries in the Kyoto protocol was also one of the prime reasons that George W. Bush invoked when stating that the US would withdraw from Kyoto. But it should be kept in mind that it is the industrialized countries that have emitted most of the CO_2 in the past, they still account for roughly two thirds of global fossil fuel related CO_2 emissions, and emissions on a per capita basis are roughly five to ten times higher than the levels that prevail in developing countries. For instance, the annual per capita energy use and carbon emission in India were around 15 GJ and 0.29 ton C, respectively, in 1998, which can be compared with the final energy use and carbon emission in the United States 223 GJ $capita^{-1}$ yr^{-1} and 5.6 ton C $capita^{-1}$ yr^{-1} [1] respectively.

However, it should also be made clear that also many developing countries must soon begin to reduce their CO_2 emissions if we are to stabilize the climate. If for instance, a global atmospheric CO_2 concentration target of 450 ppm is adopted, global carbon emissions must reduced to levels comparable to those that prevail in India today.

The predicted economic and population growth for India in the future is expected to increase the demand for energy. Recent business as usual scenarios for India suggest that carbon emissions might increase almost fivefold over the next 40 years [2].

The aim of this article is

- to demonstrate and analyse different ways for the energy system in India to meet stringent CO_2 targets during this century and
- to suggest and analyse an allocation of emission quotas that would offer economic incentives for India to join the protocol.

We assume that the atmospheric CO_2 shall be stabilized at 450 ppm (a little bit higher than the recommendation in Azar & Rodhe [3]). It can be argued that 450 ppm might be a too high stabilization target for CO_2. If other greenhouse gases are included, 450 ppm CO_2 is roughly equivalent to a stabilization target of 550 ppm CO_2-equivalents, which would lead to a global average equilibrium temperature increase in the range of 1.5-4.5^oC according to IPCC [4]. A global temperature increase by 4.5^oC is approaching the changes that occur during the transition from an ice age to an interglacial, and is likely to cause potentially very hazardous climatic changes, but if the climate sensitivity is below the best guess sensitivity of 2.5 ^oC, a 450 ppm target might be acceptable. At present it is far too early to express any firm opinion about which stabilisation target we should opt for.

Climate policy is an evolving process in which new information and changes in value judgements continuously reshape our decisions on how much to reduce the emissions. We have chosen 450 ppm for the sake of illustration, since it might be a reasonable target. A lower stabilization target might have to be implemented if the sensitivity of the climate is in the higher range of what we expect at present.

A global energy model with two regions, India and the rest of the world, is developed and used to carry out the analysis. We first develop a reference scenario in which no carbon abatement takes place. We then develop a cost-efficient emission reduction scenario towards the 450 ppm. In this scenario, carbon sequestration from coal and solar hydrogen play prominent roles. We also analyse three alternative abatement scenarios for India (in these alternative cases the emission trajectory for India is equivalent to that in scenario 1, but we have made different assumptions about the availability of natural gas, the acceptability of nuclear power and the possibilities to apply carbon sequestration technologies).

Thus, we have developed in total five scenarios for India, four of which are abatement scenarios meeting a global 450 ppm target.

(I) **Natural gas future with carbon sequestration**. Decarbonisation of fossil fuel is allowed as an option to reduce the carbon dioxide emissions. Low transportation cost on natural gas, high natural gas supply potential (30 000 EJ instead of 10 000 EJ), and restrictions on the use of nuclear power.

(II) **Coal future with carbon sequestration**. Decarbonisation of fossil fuels is allowed, but the transportation cost for natural gas is higher. There is also restriction on the use of nuclear power.

(III) **Solar future**. Decarbonisation of fossil fuel is not allowed. Limited supply of nuclear power.

(IV) **Nuclear future**. Decarbonisation of fossil fuel is not allowed. Low cost and higher limits (10 times the original) on the assumed maximum potential supply of nuclear power.

The paper is structured as follows: in section 2 our method and model is presented. In section 3 and 4, we develop an energy demand scenario and present the energy supply potentials in the scenarios. The resulting scenarios are summarized in section 5. The energy system cost for these scenarios is presented in section 6. Then, in section 7, we also analyse the revenues India can obtain by selling emission permits assuming that emissions allowances are allocated on a per capita basis in the World by 2050 and onwards. Some conclusions are given in section 8. In the Appendix some technical characteristics are presented.

2. METHODOLOGY

A global linear programming (LP) energy-economy optimization model (originally developed by Azar *et al.* [5]) has been separated into two regions, India and the rest of the World, and modified to suit the conditions in India. The model is composed of three different parts: the supply side, the demand side, and the energy technology system. Energy supply potentials, maximum expansion rates, energy demand, and the CO_2-emission limitations are all exogenously given. The LP model minimizes the total energy system cost, i.e. for India and the rest of the world combined, based on costs for fuel, capital and a discount rate of 5% together with propulsion technology cost for the transportation sector and operation and maintenance cost for electricity generation.

One disadvantage of an economic optimisation model like this is as Shukla *et al.* [6] argues it poorly reflects actual consumer behaviour, it overestimates the impact of the single cheapest alternative and it can neither account for investor preferences like risk mitigation or financial guarantees, nor ensure energy security without input from the modeller.

3. ENERGY DEMAND

The energy demand in the model is divided into four main sectors: transportation, industry (including the service sector), agriculture and households. The main sectors are divided into sub-sectors. Energy use in each sector is driven by overall GDP growth and a decoupling factor related to structural changes and to energy intensity changes within each sector. We have assumed that the Indian GDP grows (in market exchange rates) by around 6% yr^{-1} over the period 1990-2010 and then by 3.8% yr^{-1} in the 2020s, 3.4% yr^{-1} in the 2030s, 3.2% yr^{-1} in the 2040s and then 3% yr^{-1} throughout the rest of the century. This implies that GDP grows by a factor of 55 and that the Indian per capita income equals 11000 US$ $capita^{-1}$ yr^{-1} (in 1990 market exchange dollars) by the end of the century. The assumed growth rate levels correspond well with the assumptions made for the period 1990-2020/30 by Sathaye *et al*. [7], Shukla [2], Fisher-Vanden *et al*. [8] and TERI [9] .

Finally, it should be stated clearly that our end use energy scenarios should not be seen as attempts to predict the actual use of energy in the future. Rather, the scenarios may be seen as plausible levels for the future energy demand. Actual values may well be a factor of two lower or higher depending on growth rates, policies regarding energy efficiency, environmental problems (including climate change) and structural changes in the economy. An increase in the growth rate with one percentage unit corresponds to as much as an increase in the end use by the end of this century by factor three. We have chosen these levels as inputs into an attempt to analyze what the Indian energy supply may come to look like under stringent CO_2 constraints.

3.1 Energy demand - the transport sector

The commercial energy use in the transportation sector (personal and freight combined) has grown by around 5.1% per year on average over the period 1970-1998, from 0.46 EJ yr^{-1} to 1.75 EJ yr^{-1} [10]. Most of this energy is used for road transport, both freight and passenger transportation have shifted towards roads. The share of the passenger transport on road has increased from 62% in 1980/81 to 83% in 1993/94 [11]. In the same time, the total personal transportation increased from 573 billion pkm to 1811 billion pkm, a growth rate of 8.1% yr^{-1}. Freight transportation has shown the same tendency. In 1980/81, 38% of the 257 billion ton-kilometers (tkm) took place on road, while the corresponding numbers in 1993/94 were 58% of a total of 607 billion tkm.

The energy demand scenario for transportation is separated into passenger and freight transportation. The total personal travel demand are projected by using the historic relationship between GDP_{ppp} per capita and the pkm per capita in Japan, India is assumed to follow this trend (the conversion from our assumed scenario for GDP market exchange rate to ppp is made by using GDP_{PPP} relation assumed in the IIASA/WECs scenarios [12]. We used Japan as a reference country since the population density is high in both countries. This results in an average growth rate for the per capita travel demand of 1.6% per year in India during this century and the predicted personal travel demand by the end of this century is almost $12 \cdot 10^{12}$ pkm (Figure 1). In order to satisfy an increasing travel demand a shift towards faster travel modes is assumed. We have used the model presented in Schafer [13] and Schafer and Victor [14, 15] to estimate the shifts between different transportation modes. Since cars are faster than rail transportation, the major shift in India is towards more road transportation. By the end of this century, the number of cars per km^2 in India is less than in Japan today.

Two-wheelers, which constituted more than 67% of the total number of vehicles in 1993 [11], are included in the scenario but not as a separate travel mode because of lack of adequate data. But as mentioned in Bose [16], two wheelers are only driven 13.5 km per day with an average of 1.5 passenger per vehicle in cities. Using these estimates together with the numbers of two wheelers in 1993/94, i.e. 8.3 million, we find that two wheelers represent only 3% of the total passenger km or 4% of the energy use (assuming a fuel efficiency of 0.8 MJ km^{-1} for a 2-wheeled 2 stroke engine according to [16]).

The resulting personal transport energy demand is given by the transportation volumes multiplied by the energy efficiency for each mode over the century. Fuel consumption in cars drops by 43% (or roughly 1% yr^{-1}), busses by 56%, aircrafts by

59%, and trains by 50% [5]. Under these assumptions, total energy use for personal transportation reaches approximately 9.5 EJ yr^{-1} by the end of this century.

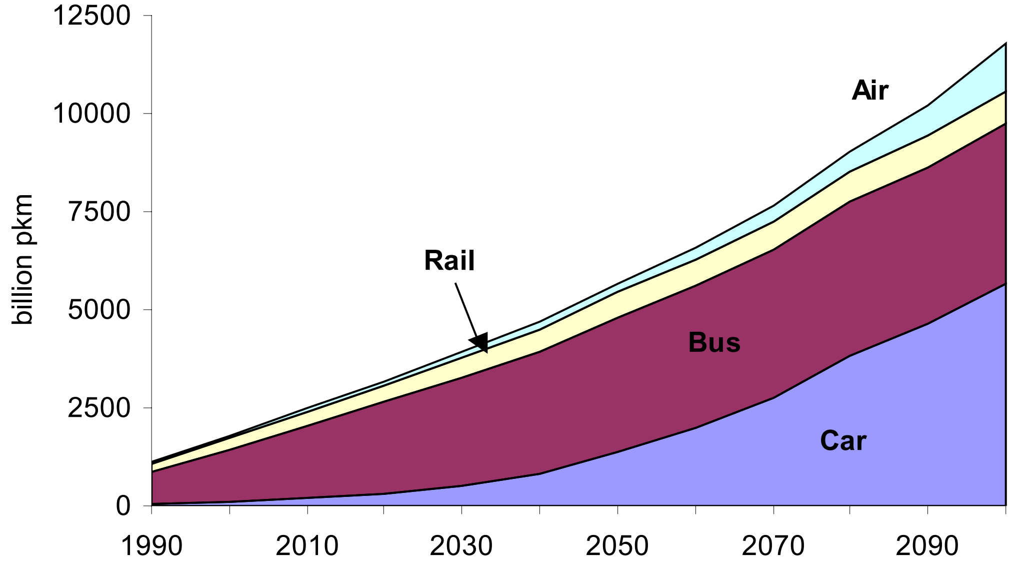

Figure 1. Personal travel demand, separated into different modes.

The freight travel demand is obtained as the product of the following factors: energy intensities (MJ tkm^{-1}), freight activity intensities (tkm GDP^{-1}) and economic growth (GDP). Energy intensity changes both as a function of assumed improvements in fuel efficiency and modal changes towards more road transportation. We assume that the elasticity of the freight activity intensity with respect to GDP_{ppp} is –0.3. This means that the freight activity intensity drops by 62% from 0.5 tkm GDP^{-1} at present to 0.19 tkm GDP^{-1} by the end of this century, which can be compared with the OECD-Pacific, where the activity in 1990 was about 0.24 tkm GDP^{-1} and the GDP $capita^{-1}$ was almost the same as our assumed level for India in the year 2100.

The total energy demand for both freight and personal transportation is approximately 15 EJ yr^{-1} by the end of this century, 5 EJ yr^{-1} of which is for freight transportation.

Finally, it should be noted that further improvements in fuel efficiency could be obtained in the model through a shift towards fuel cells if energy prices rise as a consequence of carbon abatement policies. This applies both to personal and freight transportation.

3.2 Energy demand - the household sector

The present use of energy is different in rural and urban areas, with modern energy carriers such as liquefied petroleum gas (LPG) and electricity being more common in urban areas, while non-commercial biomass is still the most common energy carrier in rural areas. Often, urbanization leads to shifts in the use of energy carriers. These carrier shifts are stimulated by an increased household income and availability of convenient energy carriers such as LPG and electricity [17, 18].

There have been several studies investigating rural energy use, for example Reddy *et al.* [19], Ravindranath and Ramakrishna [20], Saxena [21], Sinha *et al.* [22], Pannu *et al.* [23], Gupta and Ravindranath [18] and Ravindranath and Hall [24]. Biomass in the form of firewood, twigs, leaves, dung and agriculture residues are the most important energy carriers. The biomass is thus used in an inefficient way and therefore the primary energy demand is relatively high. The main end use is cooking. We assume that people living in rural areas climb the energy ladder, i.e. shift from non-commercial biomass such as cattle dung, crop residues or firewood, to gaseous fuels (kerosene, LPG) and possibly electricity, when income levels grow [17]. In our end use scenario, we have assumed that the energy demand for kerosene, biomass (dung, firewood, biogas) and fossil gas (LPG, natural gas) is exogenously given and based on cooking energy requirements for each type of stove. At present, energy use in rural areas amount to 8.2 GJ firewood, dung cakes and crop residues, 0.1 GJ electricity, 0.3 GJ kerosene, and 0.02 GJ LPG per capita and year [25, 26]. By 2100, the annual per capita energy use of kerosene, gas and biomass (improved biomass stoves) for cooking are 0, 1.3 and 0.5 GJ, respectively.

In urban areas, the use of commercial energy carriers is already widespread in households [27, 28, 29]. Approximately 1.1 GJ firewood and chips, 0.4 GJ electricity, 0.6 GJ kerosene, and 0.5 GJ LPG was used per capita in 1993 [25]. Because of this use of more energy efficient energy carriers, the yearly per capita energy use in urban households is approximately 40% of the corresponding energy use in rural households. As in the rural end use scenario, we assume the use of kerosene, gas and biomass is based on the energy ladder idea and is exogenously given. The energy use is 0, 1.1 and 0.1 GJ per capita and year by 2100 for kerosene, gas and biomass, respectively. This direct residential fuel demand might be considered low but it corresponds to the present per capita levels in countries such as Saudi Arabia, Hong Kong and Singapore [10].

There has been a significant growth in the number of households with access to electricity, from 26% in urban areas in 1981 to 76% in 1991 [26]. According to the same source, 31% of the rural households had access to electricity in 1991.

We assume that the ratio household electricity use to GDP declines by 1% per year. By the end of this century, electricity dominates household energy use in both urban and rural households with a demand of 8.5 GJ $capita^{-1}$ yr^{-1}. This per capita electricity demand is in the same range as the household electricity demand today in Saudi Arabia, United Arab Emirates and Singapore.

The total household energy demand is assumed to grow to 10 GJ $capita^{-1}$ yr^{-1} by the end of this century, less than the average in the European Union today (30 GJ per capita and year [10]).

3.3 Energy demand - the agricultural sector

The energy demand for the agricultural sector includes fuel and electricity for irrigation and machineries. TERI [26] reports that the cultivated area has been rather stable for decades, around 143 million ha [26], and around 37% of this area is irrigated today. At present (1998), a total 0.37 EJ yr^{-1} of electricity is used for irrigation (around 85% of the electricity for irrigation is grid supplied and the rest is from decentralized diesel generators). This corresponds to 27% of the total electricity end use in India (including decentralized electricity). TERI [26] has claimed that as much as 97% of the cultivated area can be irrigated. We assume that the cultivated area remains stable at 143 million ha and that the share that is irrigated grows linearly to 80% in year 2050, and remain constant thereafter. We also assume that the energy for irrigation comes from electricity and an average energy requirement of 6 GJ_{el} ha^{-1} yr^{-1} over the entire irrigated area (based on values from TERI [26]). This results in a final electricity use for irrigation equal to 0.66 EJ yr^{-1}.

With industrialization, the relative importance of agriculture can be expected to fall and therefore we assume that growth in the agricultural sector will be less than the overall GDP growth. We assume that the fuel use for machinery grows by 1.5 percentage units per year less than overall GDP growth. During the last decades of this century, the fuel demand reaches fuel use levels per ha that prevail in present day Swedish agriculture.

3.4 Energy demand - industries

The energy use in industries has grown rapidly, on average by 6% yr^{-1} from 1980 until 1998. Today (1998), it is the sector that uses most commercial energy, almost 4.4 EJ yr^{-1}.

However, comparisons with industrialised energy use in OECD countries reveal that there is a significant potential for energy efficiency improvements in many industries in India (see Table 1). We assume the future industry energy demand for this century will decouple by 2% yr^{-1} from GDP. This is due in part to the above mentioned potential for energy efficiency improvements and to the fact that structural changes towards less energy intensive industries are likely to take place. In Figure 2, we depict industrial energy use in India (*our scenario*) and the OECD countries (*actual historical values*) as a function of overall GDP levels. It can be seen that the energy use in Indian industries (in our scenario) is below the levels that prevailed in OECD countries (for the same GDP level), this results from our assumption that technological improvement will drive further improvements in energy efficiency over time.

The electricity share of the energy use in the industries is supposed to increase. Today (1998), electricity accounts for 14% of the final energy use in Indian industries, which can be compared with 28% in Denmark, 27% in the United States and 27% in Japan [10]. We assume that the electricity share of the industrial energy use develops linearly to 30% in year 2050 in our scenario and that this share remains constant at that level thereafter.

Table 1. Energy use in GJ to produce one ton of steel, aluminium, cement and printing and writing paper in India compared to modern energy efficient plants in the world.

	India	Modern
Steel (GJ ton^{-1})	35[a, b]	17.5[a, b, c]
Aluminium (GJ ton^{-1})	60[d]	45
Cement (GJ ton^{-1})	4.2[d, e]	3.3[d, e]
Paper (GJ ton^{-1})	15-40[d, f]	8-20[f, g]

(a) [30];
(b) [31];
(c) World wide average 24 GJ ton^{-1} according to de Beer *et al.* [32];
(d) [26]
(e) Values are for dry processes.
(f) Values are for primary energy, assuming heat is generated from boilers with an efficiency of 90%, and all electricity is generated in power plants with an efficiency of 33%.
(g) [33].

.

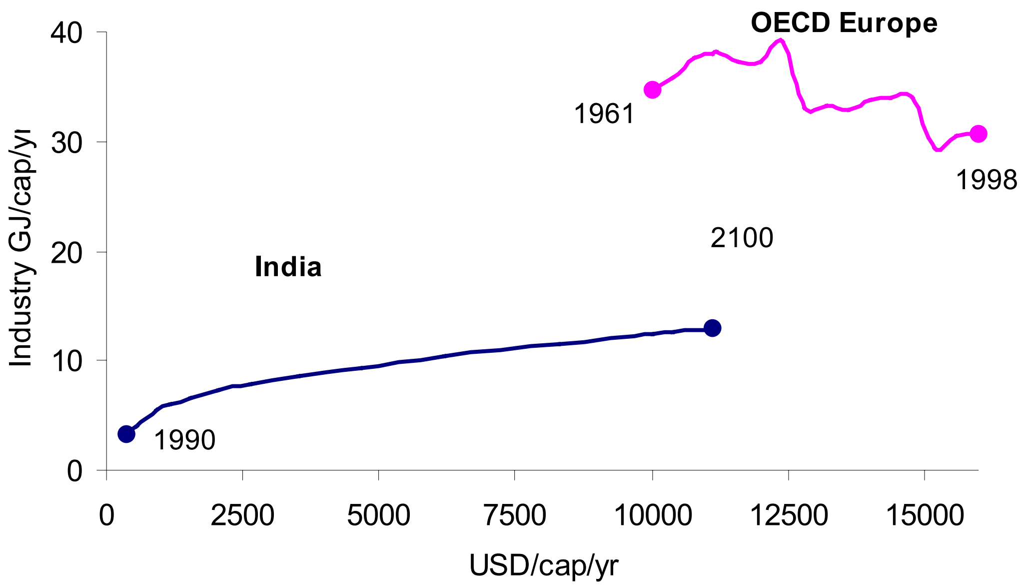

Figure 2. GDP income in USD $capita^{-1}$ versus industrial energy use per capita. The values from India are from our scenario, while the OECD Europe values are historic values taken from IEA [10].

3.5 Total energy demand

Table 2 summarizes and compares the per capita GDP, travel demand, and commercial energy demand, and the freight activity with European Union values for 1990. By the end of this century, India has not (in our scenario) reached energy and GDP per capita levels that prevail in Western Europe today. But because of its large, and growing population the total energy demand in India is roughly twice the final energy use in EU today.

In our scenario, the total energy demand is assumed to grow from 11 EJ yr^{-1} in 1990 to 52 EJ yr^{-1} in the end of this century (Figure 3). Energy use grows by a factor of five during the period, whereas GDP grows by a factor of 55, i.e. energy decouples from GDP by 2.3 % yr^{-1} on average.

In comparison to IIASA-WECs scenarios [12], the overall energy demand in our scenarios develops rather modestly. By year 2100, the yearly direct fuel and electricity demand per capita are 9.3 GJ and 12.8 GJ respectively, which can be compared with 38.9 GJ and 16.4 GJ for SAS (South Asia) in the IIASA-WECs A1 scenario (high growth, ample oil and gas availability), and 19.8 GJ and 9.8 GJ in the C1 scenario (ecologically driven, renewables and nuclear phase out) respectively. The energy demand in the transportation sector is also almost the same in our scenario as in the IIASA-WEC A1 and C1 scenarios. By 2100 the per capita energy demand for transportation is about 9.0 GJ as can be compared to around 9.8 in both the IIASA/WEC scenarios.

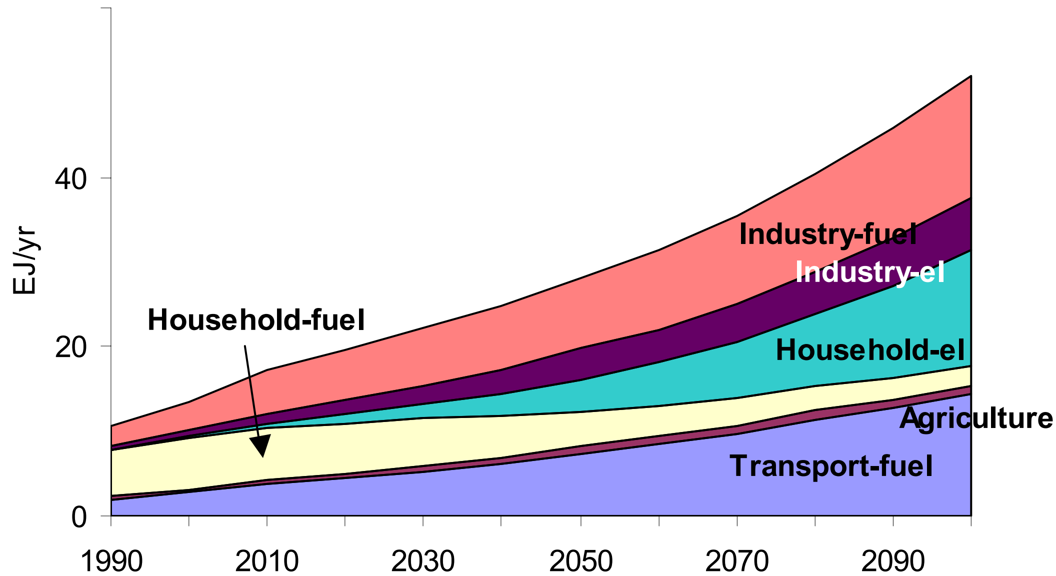

Figure 3. Scenario for the energy demand in India, separated into different sectors.

Table 2. Comparison between India and European Union in per capita GDP, travel demand, and energy demand, and freight transport intensity. The 2100 levels for India is from our energy demand scenario.

	India		EU
	1990[(a)]	2100	1990[(b)]
GDP USD/cap	380	11 000	18 500
Pkm cap^{-1}	1 300	9400	11 000
Tkm GDP^{-1}	0.5	0.19	0.25
Tfuel GJ cap^{-1}	1.3	9.0	30.0
HH-el GJ cap^{-1}	0.1	8.5	5.3
HH-fuel GJ cap^{-1}	6.5 [(c)]	1.4	20.3
Ind-el GJ cap^{-1}	0.5	3.9	11.9
Ind-fuel GJ cap^{-1}	2.6	9.1	32.1
Agri-el GJ cap^{-1}	0.2	0.4	0.3
Agri-fuel GJ cap^{-1}	0.0	0.3	2.1

a) Sources: [10, 26]; TERI, 1999.
b) Sources: [10, 5].
c) Includes both commercial and traditional biomass fuels.

4. ENERGY SUPPLY POTENTIALS

At present, (1998) annual primary energy supply is 16.9 EJ of which 8.2 EJ is bioenergy, 6.7 EJ coal, 0.8 EJ is natural gas and 0.8 EJ is oil (see Figure 4). The energy supply has grown by 3.5% yr^{-1} on average since 1980 and electricity generation has increased by 4.4% yr^{-1} since 1990 [10].

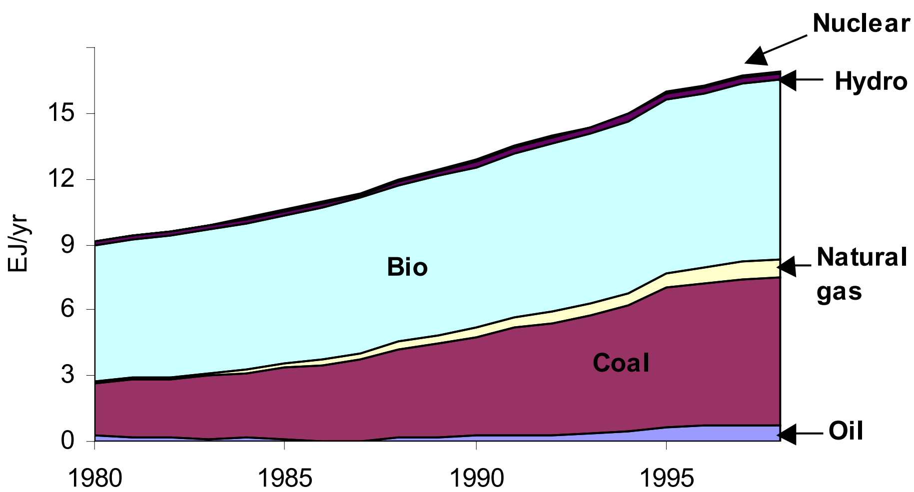

Figure 4. Primary energy supply in India from 1980 to 1998. Source: [10].

India is relatively well endowed with both renewable and fossil energy resources. Table 3 summarizes the assumed domestic energy potentials for India. Approximately 7% (2200 EJ) of the proven coal reserves of the World are located in

India [26], which means that the per capita coal reserve is lower than the World average. The estimated coal resource up to a depth of 1200 m is 5700 EJ [26]. Domestic oil and natural gas reserves are more scarce, 34 EJ and 27 EJ, respectively [26]. Today, around 50% of the oil is imported, while in 1997 all consumed natural gas was domestic. In the future, India is likely to be more dependent on imports of both oil and natural gas. The dependence on imports raises questions of energy security. For example, some are concerned that the import of natural gas by pipeline via Pakistan is too risky since it would, at least indirectly, give Pakistan some political power over India. Pakistan cut, e.g., threaten to raise prices or cut of supplies in the event of escalating conflicts in Kashmir. Sen [34], e.g., has argued that a pipeline in the deep sea outside Pakistani territorial water may be the only feasible solution over the next couple of decades. On the other hand, a pipeline through Pakistan will also increase mutual dependence which might reduce risks of war and conflict since both would have more too loose from such events.

Carbon neutral energy sources considered in this paper are biomass, hydropower, wind-, solar-, and nuclear power. Biomass supply potentials are discussed below. The importance of hydropower for electricity generation has declined, from 44 percent in 1960 to 25 percent in 1995 [6]. Today, 15 percent of the estimated hydropower potential of 84000 MW is exploited, and another 5900 MW is under development [26]. We assume that social and environmental considerations limit the potential of hydropower to what is presently in use or under development, i.e. roughly 20000 MW.

Table 3. Domestic energy supply potential for India, characterised by limited maximum total extraction over the time period 1990-2130 for fossil fuels and limited annual energy supply of biomass, hydropower, wind power and solar electricity.

Energy source	Potential
Coal (EJ)	10 000
Oil (EJ)	50
Gas (EJ)	35
Biomass (EJ yr^{-1})	10
Hydro (EJ yr^{-1})	0.4
Wind [(a)] (EJ yr^{-1})	0.4
Solar [(a)] (W m^{-2})	200

(a) Wind and solar electricity contribute together with less than 30% of the electricity.

The potential for wind power is estimated in varies between range at 20000 MW [26] and 45000 MW [35]. The potential for solar energy is 200 W m^{-2} [26]. However, because of the intermittent nature of solar and wind power, wind and solar electricity combined are limited upwards to a maximum of 30% of the total electricity supply. It is possible to overcome intermittency problems by producing hydrogen from wind and solar energy, and in that case the contribution from solar energy can be much larger than the entire Indian energy supply at present.

India has reserves of both uranium and thorium for nuclear electricity generation. The uranium reserve in India is 34000 tonnes, but only 44% is economically exploitable [26]. 32% of the global thorium reserve is found in the country. Present generating capacity of nuclear power in India is 2280 MW, owned by the government operator – Nuclear Power Corporation (NPC), mostly in pressurized heavy water rectors (PHWRs). Four 220 MW nuclear reactors are under construction and the work on two 500 MW units have just started. Two more 220 MW reactors, one 500 MW reactor, and two 1 000 MW reactors from Russia are awaiting approval. India's Department of Atomic Energy (DAE) are also planning the construction of ten 500 MW PHWRs, four 500 MW fast breeder reactors and five 1000 MW LWRs [36].

4.1 Biomass potential in India

Biomass is of growing interest as a commercial energy source because of potential economic and environmental benefits. Biomass can be carbon neutral if the harvest does not exceed the annual increment and the combustion is complete (see Schlamdinger *et al.* [37], Schlamadinger *et al.* [38] for a more complete discussions of the link between biomass energy and changes in biospheric carbon stocks). To the extent that fossil fuels are replaced, the use of sustainably generated biomass implies a net reduction of CO_2 emissions [39].

The major categories of biomass for energy use are (i) residues (and by-flows) from the food and material sectors, and organic municipal waste, and (ii) dedicated energy crop plantations. We have included plantations and electricity generation from the sugarcane industry into the model as possible sources for modern biomass fuels. Traditional biomass use is exogenously given to the model and free of charge. Traditional biomass is assumed to be collected from the same sources as today, i.e. from public and private lands [21]. It is estimated that each year, about 200 million tons of fuelwood, 100 million tons of dung cakes and 100 million tons of agriculture residues are consumed as fuels in rural areas [26].

The highest potential of all possible sources for commercial biomass production has probably been short-rotatation, intensive-culture plantations of trees. Land availability for dedicated plantations is thus a critical issue. In India, the major factor that determines land availability is the demand for land for food production, which in turn is driven by population and income growth. It can be noted that the agricultural area in India has remained stable over the past decades despite an increase in the total production of food. Partly for this reason, India has succeeded in halting deforestation [24]. The most important factor behind all this has been a significant increase in grain productivity. The overall food grain productivity in India is rather low, 1.27 t ha^{-1} yr^{-1} during 1990/91, which can be compared with a global average grain production of 2.7 t ha^{-1} yr^{-1} [40]. This suggests that further increases in yields are possible. Whether that will free land depends on a number of factors, e.g., international market prices for grain and possible alternative uses.

Sudha and Ravindranath [40] estimate conservatively the land availability for biomass energy plantations to 43 million ha in India. This is on land not suitable for agriculture or pasture practice. Assume an average yield of 10 ton DM ha^{-1} yr^{-1} we get 430 million tonne DM yr^{-1}, which is equivalently to roughly 8 EJ yr^{-1}.

Further, cogeneration in sugar cane mils could generate a potential electricity supply of 0.45 EJ yr^{-1} (using technological parameters from Carpentieri *et al.* [42].

We set a maximum potential supply of bioenergy equal to 10 EJ yr^{-1}.

5. ENERGY SCENARIOS FOR INDIA

5.1 Primary energy supply

Five scenarios based on the output from the model are presented in this article: one base case without any carbon abatement policy and four cases with atmospheric carbon emission restrictions where the global atmospheric CO_2 concentration shall be stabilized at 450 ppm. We only present the scenarios for India in this paper. Global energy scenarios based on the globally aggregated version of this model were originally presented in Azar *et al.* [5].

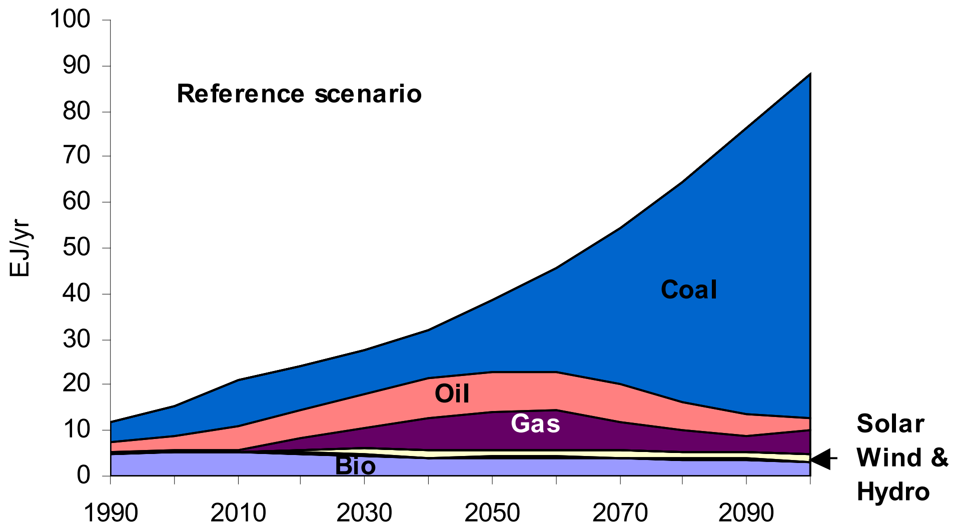

Figure 5. Reference scenario. In the absence of carbon abatement policies, the Indian energy system becomes even more dependent upon coal throughout the century.

The reference scenario is characterized by a dependence on coal as primary fuel in India, as can be seen in Figure 5. Carbon neutral energy sources, primarily biomass, wind and hydro, are used, but the relative share drops over time and reaches roughly 12% by the end of the century.

The abatement scenarios are generated in the following way. The model is run so that the atmospheric concentration of CO_2 is kept below 450 ppm and the exogenously specified energy demand should be met at the lowest possible cost. This results in a specific carbon emission trajectory for India, and the result is shown in Figure 6.

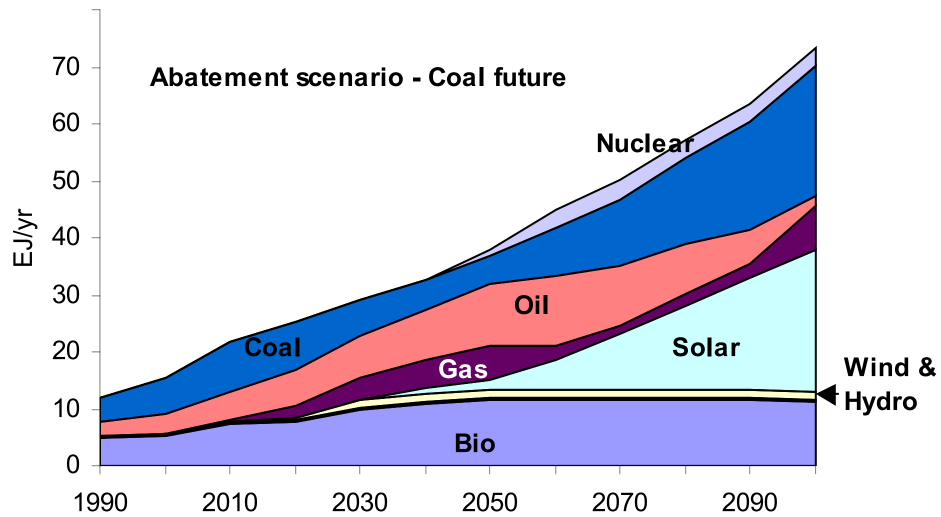

Figure 6. Carbon abatement scenario for India – Coal future. In this scenario, nuclear is maximised to 3 EJ/yr, and natural gas supplies are limited.

If carbon sequestration becomes a viable option, as is assumed in this scenario (see Figure 6), coal remains an important energy source throughout the century. The relative dependence on coal decreases, but in the scenarios where carbon sequestration is allowed, as in this one, the use of coal is actually five times higher by the end of the century than in 1990. But it should also be noted that biomass, and in particular solar, becomes very important energy sources over the century.

We now move on to explore alternative energy futures for India under stringent CO_2 targets. We assume that the carbon emission trajectory implicit in Figure 6 (and shown in Figure 14) should be satisfied for India, and either relax or sharpen some other constraints. In Figure 7, we show a natural gas scenario, in Figure 8 we show a solar scenario (in which decarbonization of fossil fuels is not allowed), and in Figure 9 we show an abatement scenario in which nuclear energy plays an important role.

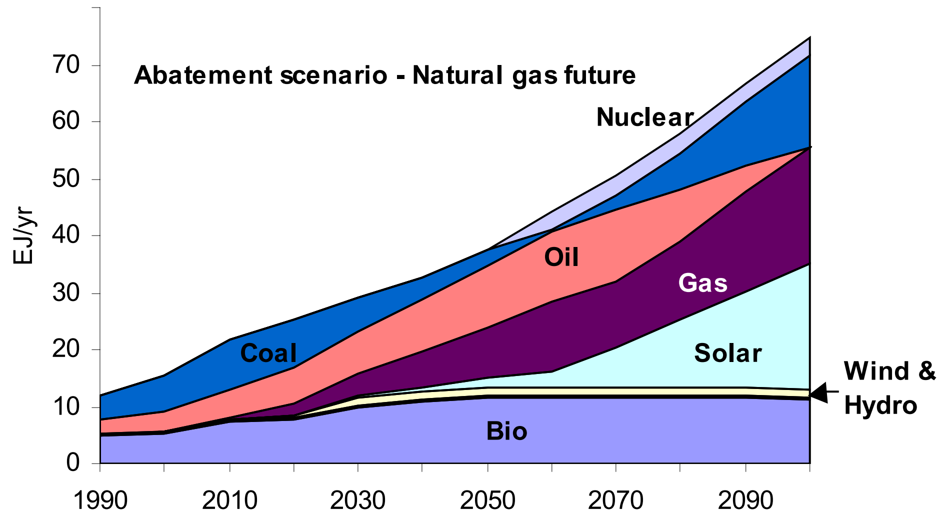

Figure 7. Carbon abatement scenario - Natural gas future. The cost of natural gas in India is lowered and the global supply potential is three times the original.

In the natural gas future scenario as in the coal future scenario, the energy system is dependent on fossil fuels. In the natural gas scenario, natural gas is plentiful and out competes coal during the middle of the century. However, scarcities eventually sets in and therefore coal returns towards the end of the century. Solar also plays an important role.

In the scenarios without carbon sequestration, coal is almost phased out by 2070-2090. Another general feature obtained in all carbon abatement scenarios is the increased dependence on solar energy mainly converted into hydrogen during the second half of the century.

In the solar future, solar energy technologies are introduced into the energy system a few decades earlier, 2010 instead of 2040-2050 in the other carbon abatement scenarios. The required solar supply is area demanding and reaches 60 000 km^2 in the solar scenario (assuming a solar influx of 250 W yr^{-1} m^{-2} and a conversion efficiency from solar energy into hydrogen of 10% and 15% from solar energy into electricity). This area can be compared with the size of the Thar desert, which is approximately 200 000 km^2. The solar derived hydrogen do not need to be domestically produced, one possibility would be to import hydrogen and electricity derived from solar energy from the neighboring countries around the Persian bay.

In the solar future, almost 70% of the primary energy comes from solar energy by the end of this century. In the same time, the efficiency of the energy system increases by for example more efficient engines.

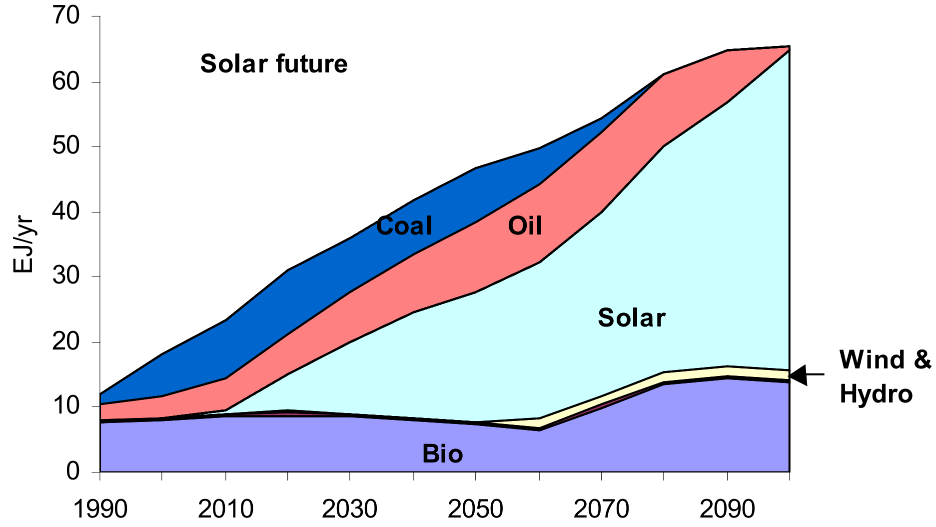

Figure 8. Carbon abatement scenario – solar future.

In the nuclear future, we do not allow carbon sequestration technologies, but we assume that the acceptability for nuclear power is much larger than in the earlier scenarios. A dominant feature is that a significant part of the solar energy is replaced by nuclear power. By the year 2100, nuclear power generates 33 EJ_{el} yr^{-1}, which is equal to the assumed maximum potential. This implies that there will be around 1000 reactors in India, assuming a 1000 MW capacity each.

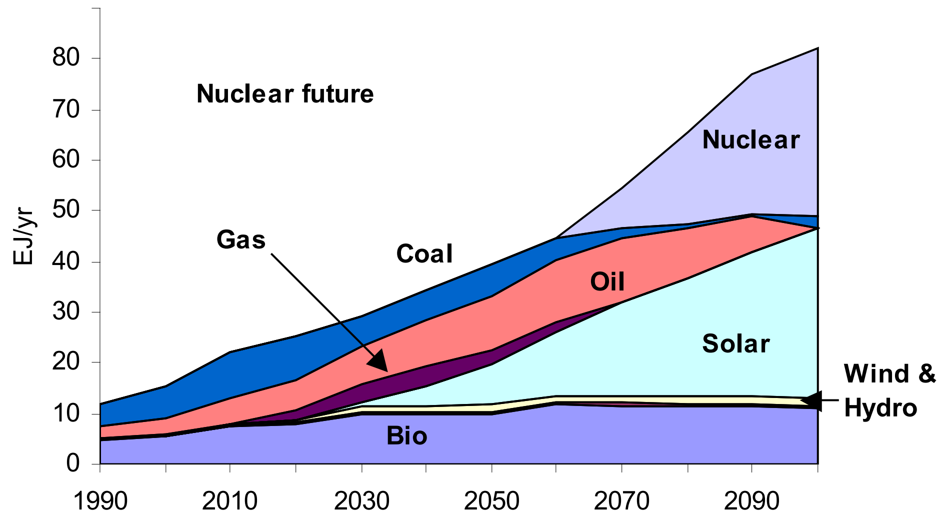

Figure 9. Carbon abatement scenario – Nuclear future

5.1.2 Transportation fuel

In the transportation sector, oil remains the only fuel except for electric use in trains until 2050-2070. By then a transition to methanol (used in internal combustion engines and derived from coal) is initiated in the reference scenario. In the abatement scenarios, hydrogen used in fuel cells is initiated around 2060-2070 (Figure 10 demonstrates the coal future). This transition away from oil is explained by the fact that we are running out of oil.

There are four alternatives fuels in the model, gasoline, natural gas, hydrogen and methanol (which is used as an example of a liquid hydrocarbon, but it could equally well have been e.g., ethanol). In the reference scenario methanol is chosen because the low cost of coal, which are used as feedstock for the methanol production, imply that there are no economic incentives to use the more efficient but also more expensive fuel cell technology. If internal combustion engines are used, methanol has an advantage over hydrogen since the storage costs for hydrogen vehicles is similar and the energy efficiency of the different fuels is roughly the same (in internal combustion engines).

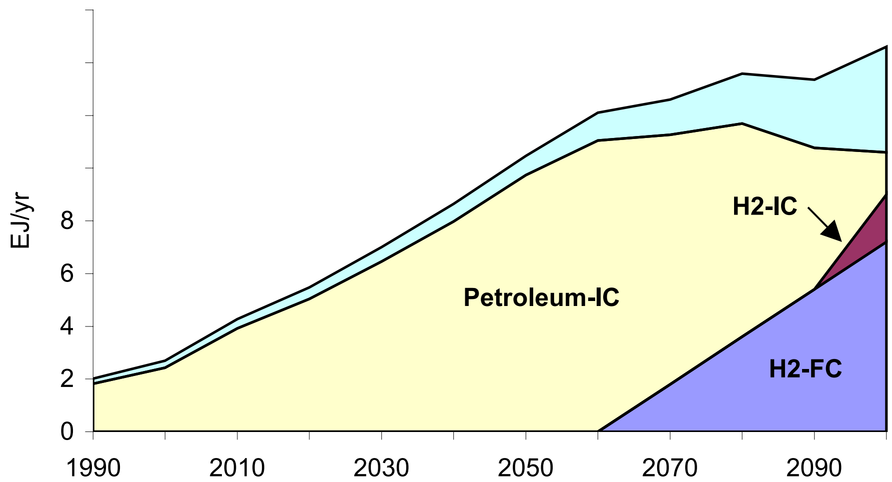

Figure 10. Use of transportation fuels in India in the solar scenario. There is a transition from petroleum fuel in internal combustion engines (IC) to hydrogen (H2) used in fuel cells (FC). The other carbon abatement scenarios look the same.

The transition towards hydrogen in the other abatement scenarios is explained by the fact that methanol can eventually only be produced from biomass since the use of coal would cause too large CO_2 emissions. The conversion from solid biomass into methanol is associated with substantial energy losses. The model suggests that it is more cost efficient to use the biomass for heat and process heat applications. The additional costs associated with storage, distribution and refueling of a gaseous fuel are not large enough to prevent hydrogen from becoming the dominant fuel in the transportation sector [5].

5.1.3 Electricity

Today, 75% of the electricity production in India is based on coal. The relative importance of coal for electricity generation drops in all carbon abatement scenarios (see Figure 11).

In the reference scenario, there is a minor transition towards natural gas during the coming decades, but during the second half of the century, there is a transition back to coal since natural gas becomes scarce. Even carbon neutral sources are used, hydro- and wind power.

In the carbon abatement scenarios, the electricity supply is even more diversified. During the first decades of this century, electricity generation from bagasse and wind power technologies are established and together with hydropower, coal, natural gas and a very small share of nuclear power they meet the exogenously specified electricity demand. By around 2050-2070 solar electricity enters the energy system in all carbon abatement scenarios. Nuclear power is phased out when the existing plants are retired, but the use starts again in the second half of this century. Nuclear power is especially important in the nuclear future, where it generates more than half of the electricity by the end of the century. During the last five decades of this century, hydrogen is also used as a source for electricity generation in most of the carbon constrained scenarios. Its importance increases fast, and by the last decade it is one of the most important fuels, producing around 25-35% yr^{-1} of the electricity in all abatement scenarios except the solar future scenario where the contribution is around 65% yr^{-1} of the electricity.

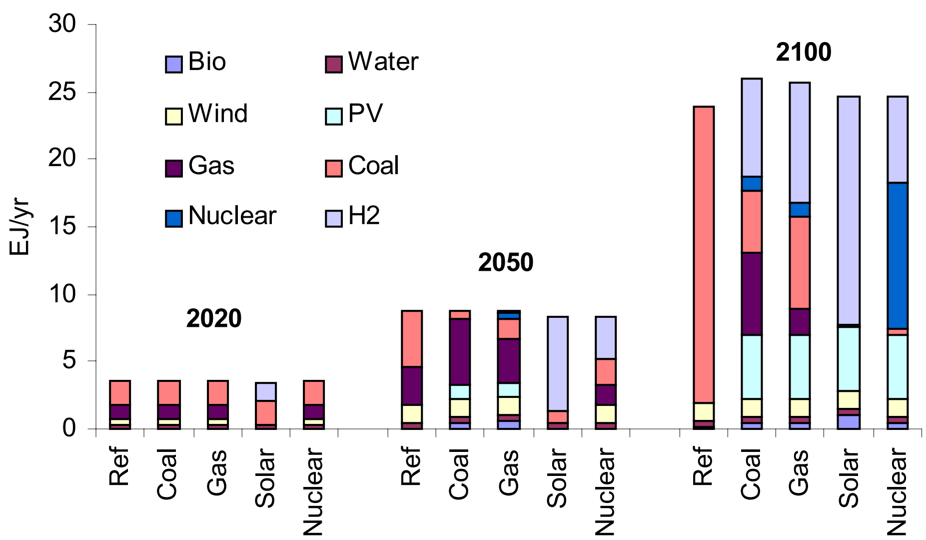

Figure 11. Electricity generation by source and scenario in 2020, 2050 and 2100.

5.1.4 Direct fuel use

Coal today is the most important energy source for direct fuel use and it continues to be so in the reference scenario where it is the dominant fuel during the whole period (see Figure 12).

Coal is also important in the carbon abatement scenarios, especially during the first half of the century. The relative share of the total direct fuel use is approximately 35% in the middle of the century in the nuclear future scenario, which can be compared with 10% in the solar future. In the other two scenarios the coal contributes with around 15-25% of the direct fuel by 2050. In the nuclear future scenario, it is more cost-efficient to reduce CO_2 emissions in the electricity sector (comparison to the situation in the other abatement scenarios) and therefore a higher share of the emissions stem from direct fuel use is in the nuclear scenario, and thus the coal use for direct fuel use is therefore higher in the nuclear future than in the solar future scenario. Other sources, e.g., biomass in all abatement scenarios, and natural gas in the natural gas future, are also important. During the coming decades, the importance of biomass as a source for direct fuel use grows. After 2040 biomass is the most important fuel for direct fuel use when carbon abatement policies are implemented and carbon sequestration are allowed. When carbon sequestration is not allowed hydrogen is the most important fuel during the second half of the century. By the end of the century from 25 to 55% yr^{-1} of the direct fuel comes from hydrogen. The small fraction represents the coal future scenario where the direct fuel is met by mainly (45% yr^{-1}) biomass and the high value represents the nuclear future where the use of hydrogen in the electricity system is lower than in the other scenarios and instead used as direct fuel.

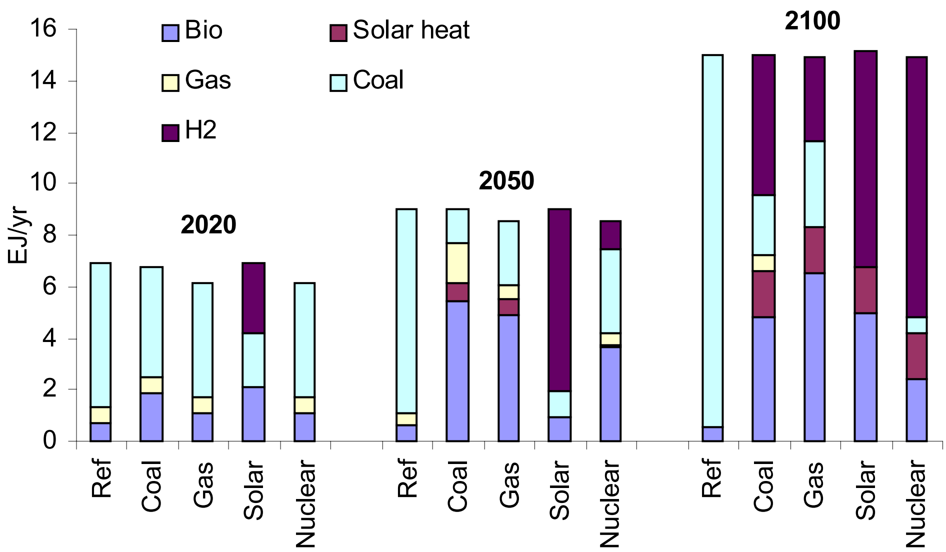

Figure 12. Secondary energy supply for direct fuel and heat by 2020, 2050 and 2100. Bio is both traditional and modern use of bioenergy.

.

6. CARBON REDUCTION COSTS

We have compared the energy system cost between the reference scenario and the abatement scenario (coal future), The emissions trajectory is obtained by implementing the carbon tax profile that will take the global energy model towards a 450 ppm target, and the emissions trajectories for the reference and the abatement scenario is shown in Figure 14.

The costs are higher in the abatement scenario since the model is forced to use technologies that are more expensive. Further, we have assumed that energy use in the reference scenario is optimal, which means that we have excluded so called no regrets and win-win options. This suggests that costs may be overestimated.

The annual extra cost for the abatement scenario is shown in Figure 13. The abatement cost varies between 0 and 4% yr^{-1} of the GDP in India, and it takes some 50 years before the abatement cost climbs above 1 % of GDP.

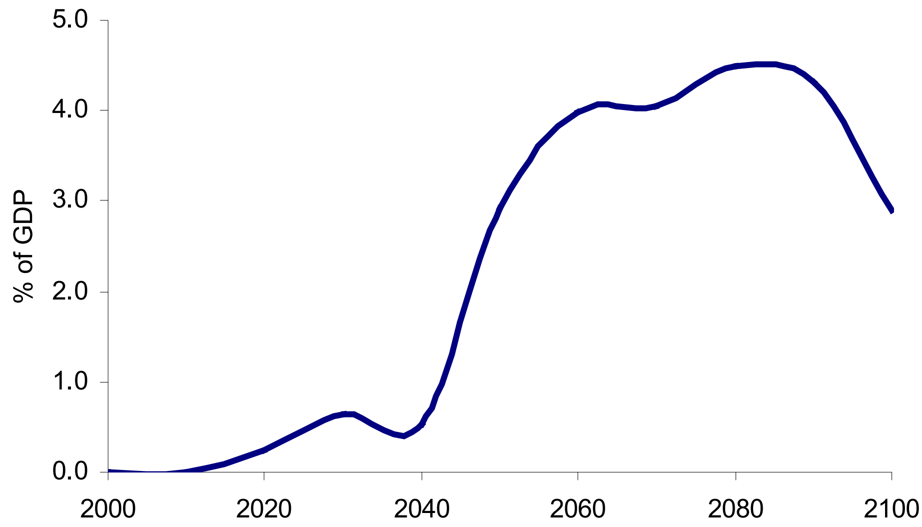

Figure 13. Abatement cost as percent of GDP in India.

The net present value cost of the abatement scenario is almost two thirds of the present GDP, 499 billion US$ (at 1990 prices and exchange rate). This is of course a high cost but comparisons with expected future GDP levels suggest that the costs might be manageable. As stated earlier GDP is expected to grow at a rather fast rate over the next century, and reach a level that is 55 times higher than in 1990 in the reference scenario. Now, with a cost that varies between 0-4%, GDP becomes 54 times higher in 2100 in the abatement scenario. And with a growth rate of 3% yr^{-1} GDP would become 55 times higher by August 2100. Thus, the cost amounts to a delay of roughly a year in achieving a very impressive GDP level. Similar observations can also be made as regards the costs of meeting stringent stabilization targets at the global level [43].

It should also be noted that none of these cost estimates include the benefits of emissions abatement, e.g., improved local air quality and avoided climatic changes. Further, a global treaty to reduce CO_2 emissions is likely to include emissions trading. The potential sales of these permits might, depending on how they are allocated among countries and over time, be large enough to cover the estimated costs. To this aspect, we turn below.

7. REVENUES FROM CARBON TRADING

In this section, we will analyze the potential economic benefits that India can derive by selling emission permits. Whether India will gain or not on this trade, depends on how the permits are allocated. In this paper, we will assume that emissions are allocated on a per capita basis, since this is probably the most equitable way of distributing permits, at least in the long term [44, 45, 46].

This equity criterion would probably be acceptable to the largest part of the human population. However, it is rather unlikely that allocations on a per capita basis will be implemented in the near term. For this reason, we have assumed that the equal per capita emission will be implemented by 2050 and from then on follow the per capita emission trajectory towards the 450 ppm stabilization target. Before that, each country is allocated per capita emissions allowances that follow a linear trend from their present level towards the equal per capita allocation by 2050.

This means that the allocation to EU is reduced from 2.4 ton C capita $^{-1}$ by 1990 to 0.9 ton C capita^{-1} by 2050 (2.5 % yr^{-1}), while the allocation to India is increased to 0.9 ton C capita^{-1} yr^{-1}. India is supposed to be a part of this process from 2020.

By the end of this century, the Indian per capita emission in the reference scenario is almost the same as the average per capita emission of the world today (1.1 ton C capita^{-1} yr^{-1}). But the population is assumed to have grown to 1.6 billion, so the emissions in absolute terms is 25% of the present total global carbon dioxide emissions from fossil fuels.

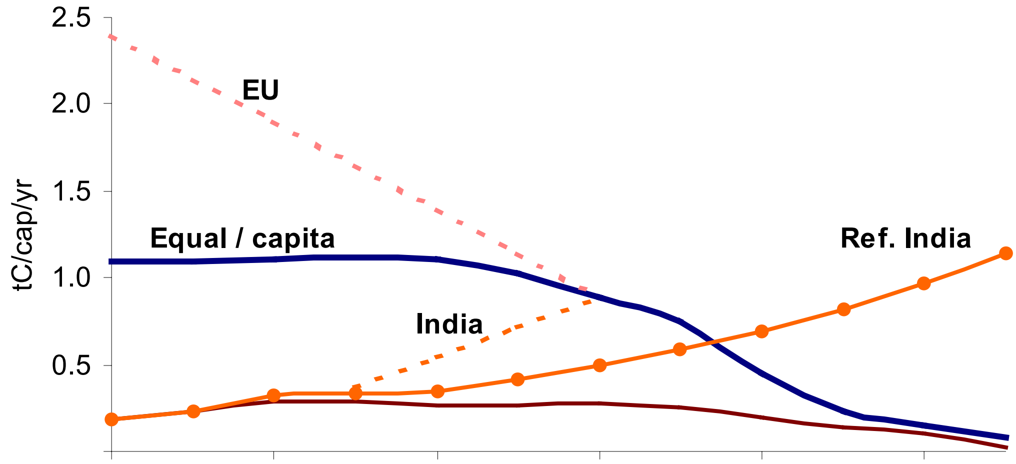

Figure 14. Carbon emissions per capita from fossil fuels. The equal per capita line is generated by the model, and represents a cost-effective emissions trajectory towards an atmospheric stabilization target of CO_2 concentration at 450 ppm. This profile is compared to the reference scenario and the abatement scenario (the coal future). We have assumed that emission allowances are allocated on an equal per capita basis from 2050. Between 2010/2020 and 2050, allowances are based on current emission levels, and drawn assumed to change linearly towards the equal per capita allocation by 2050 (see dashed lines for India and for EU).

In the same time as the emissions increase in the reference scenario, the permit price on carbon increases. By 2020, when India is supposed to take part of the process, the permit price is 60 US$ ton C^{-1}, by 2050 it is 260 US$ ton C^{-1}, and by the end of the century it is 1800 US$ ton C^{-1}. Of course these numbers are very uncertain (in particular the very high numbers towards the end of the century), and the main purpose with this exercise is to demonstrate that there might be substantial benefits for India to join a treaty that involve emissions trading, at least if permits are allocated on a per capita basis. It should also be noted that the flows of revenues to India are so large that one may wonder whether the richer countries will accept a distribution of emission permits that imply large transfers of income from the rich to the poor.

In the abatement scenario, India may actually sell emission permits throughout the century. Figure 14 shows the difference between the allocation and the actual emissions (in total over the next century as much as 39 Gton C are sold), and the revenues from this sale are substantial (see Figure 15). The revenue from the selling of emission permits increase up to 6% of the GDP by 2060. Thereafter the revenues decrease down to 1-1.5% by the end of the century.

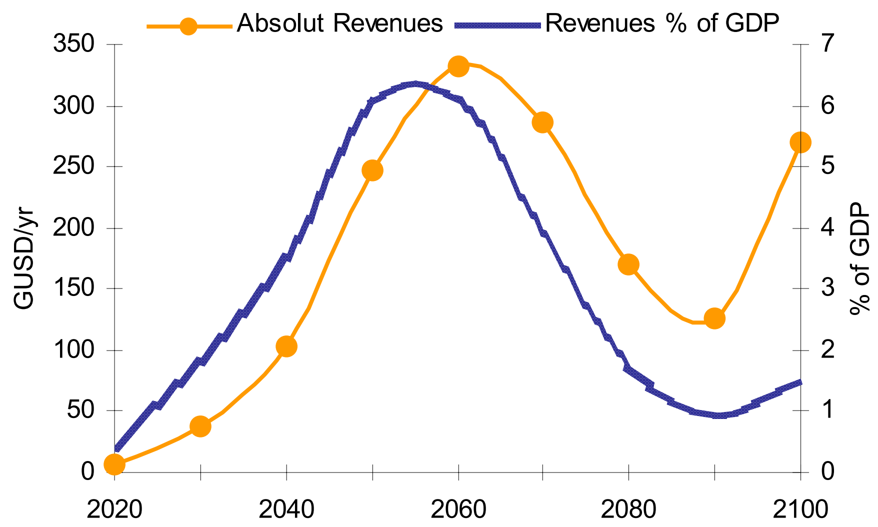

Figure 15. Revenues from selling emission permits in absolute values (GUSD) and as percent of GDP for the carbon abatement scenario.

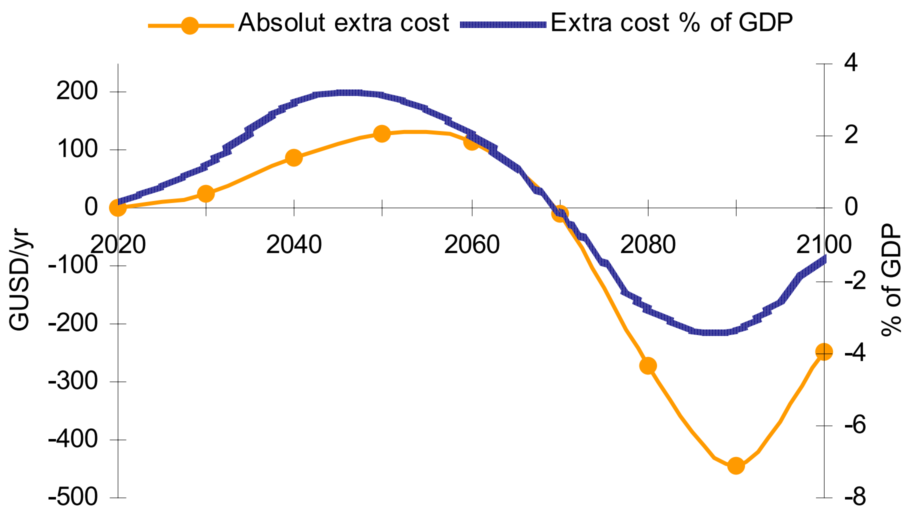

Figure 16. Net benefits (revenues from trading minus the extra energy system cost) as GUSD yr^{-1} and percent of GDP for the change of the energy system from the reference scenario to the carbon abatement scenario.

On the other hand the change of the energy system from the reference scenario to a carbon abatement scenario will increase the energy system cost (see Figure 16). By 2050 the revenues from the selling of emission permits are approximately 6% of the GDP while the extra energy system cost only is 2.9% of the GDP. By 2070, the extra cost for the change of the energy system is higher than the revenues from the selling of emission permits. The revenues are 3.9% of the GDP while the extra cost for the energy system is 4.1%, i.e. the extra cost is 0.2% of the GDP.

In absolute value, the revenues from selling of emission permits are 250 GUSD yr^{-1} by 2050, which could be compared to the extra energy system cost, 120 GUSD yr^{-1}. By then, the gain is 130 GUSD yr^{-1} or roughly three times the present Indian export revenues.

8. DISCUSSION AND CONCLUSIONS

In this paper we have presented four scenarios for India that are compatible with a global atmospheric stabilization target of 450 ppm. Based on assumptions on economic growth, decoupling factor, higher share of electricity in the industrial energy use, Zahavi´s law that each person travel about one hour each day, and steps up in the household energy ladder we ended up with an energy scenario demanding around 50 EJ per year in the end of this century. This is 20% higher than the energy use of the European Union today (1998 [10]). But per capita, the energy use in India by 2100 (in our scenario) is less than one third of the per capita energy use in the European Union today.

In our abatement scenarios, many renewable carbon neutral alternatives enter the energy system in the coming decades. First, wind power and modern use of biomass begin to contribute with a higher share than today. Commercial biomass mainly used as today primarily as direct fuel and, also in cogeneration applications (primarily bagasse).

By the middle of this century solar energy enters the energy system, in the form of electricity (e.g., from PV), heat or hydrogen.

In the second half of the century, decarbonization of fossil fuels is another alternative that is used to decrease the emissions of carbon dioxide to the atmosphere. Without decarbonization of fossil fuels, it is more difficult (costly) to restrict the emissions of CO_2.

However, during the first half of the century, fossil fuels remain important in all scenarios. Oil is used in the transportation sector, natural gas is used in electricity production (using efficient combined cycle gas turbines), and coal is used for electricity and as direct fuel. The coal is domestic, while there is need for importing oil and natural gas. A fast and large development of the natural gas use requires importation via pipelines from for example Iran, Turkmenistan or Oman, or as LNG, the latter of which being less costly but there are specific securities of supply issues that need to be addressed. It should be kept in mind that Europe imported natural gas from Soviet Union even during the critical days in the cold war.

Even if fossil fuels are used during the coming decades, it is cost efficient to initiate carbon abatement policies if we are to meet low stabilization targets.

Economic analyses, including ours, clearly show that the economic cost of stabilizing the atmospheric concentration of CO_2 will be lower if India and other developing countries adopted abatement targets under the United Nations Framework Convention on Climate Change already from the beginning. However, since it is the developed countries that have caused most of the emissions so far, we believe that these are the countries that should bear the main costs of India joining the protocol, at least during the initial phases. This could be done by offering a generous allocation of emissions allowances, perhaps along the lines sketched here. Under such a distribution, India has more to gain than to loose from adopting carbon abatement policies the coming decades.

Acknowledgements

Financial support from the Swedish Energy Agency is gratefully acknowledged. We would also like to thank D. Abrahamson, N.H. Ravindranath and S. Gupta for valuable discussions and comments.

References

[1] EIA. Emissions of greenhouse gases in the United States 1999, DOE/EIA-0573(99), Washington, 2000.
[2] Shukla P.R. The modelling of policy options for greenhouse gas mitigation in India. Ambio 1996;25:240-248.
[3] Azar C. and Rodhe H. Targets for stabilization of amospheric CO_2. Science 1997;276:1818-1819.
[4] Intergovernmental Panel on Climatic Change (IPCC). Climate Change 1995. The Science of Climate Change: Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. J T Houghton, L G Meira Filho, B A Callander, N Harris, A Kattenberg and K Maskell, (eds.). Cambridge UK: Cambridge University Press, 1996.
[5] Azar C., Lindgren K. and Andersson B. Hydrogen or methanol in the transportation sector? Physical Resource Theory Report. Available at www.frt.fy.chalmers.se, 2000.
[6] Shukla P.R., Ghosh D., Chandler W. and Logan J. Developing countries & global climate change: Electric power options in India, prepared for the Pew Center on Global Climate Change, 1999.
[7] Sathaye J., Monaehan P. and Sanskad A. Cost of reducing carbon emissions from the energy scenario: a comparison of China, India, and Brazil. Ambio 1996;25:240-248.

[8] Fisher-Vanden K.A., Shukla P.R., Edmonds J.A., Kim S.H. and Pitcher H.M. Carbon taxes and India. Energy Economics 1997;19:287-325.
[9] TERI Partnership for sustainable energy development Tata Energy Research Institute, New Delhi, 1998.
[10] IEA World Energy Statistics and Balances, International Energy Agency, 2000.
[11] Ramanathan R. and Parikh J.K. Transport sector in India: an analysis in the context of sustainable development. Transport Policy 1999;6:34-45.
[12] Nakićenović N., Grübler A. and McDonald A. Global Energy Perspectives. IIASA & WEC, Cambridge UK: Cambridge University Press, 1998.
[13] Schafer A. The global demand for motorized mobility. Transportation Res.-A 1998;32:455-477.
[14] Schafer A. and Victor D.G. Global passenger travel: implications for carbon dioxide emissions. Energy 1999;24:657-679.
[15] Schafer A. and Victor D.G. The future mobility of the world population. Transportation Res.-A 2000;34:171-205.
[16] Bose R.J. Automotive energy use and emissions control: a simulation model to analyse transport strategies. Energy Policy 1998;26:1001-1016.
[17] Reddy B.S. A multilogit model for fuel shifts in the domestic sector. Energy 1995;20:929-936.
[18] Gupta S. and Ravindranath N.H. Financial analysis of cooking energy options for India. Energy Conversion 1997;38:1869-1876.
[19] Reddy B.S., Parikh J.K. and Srinivasan P.V. Plantation programs through people's participation: a case study from India. Biomass and Bioenergy 1999;17:257-271.
[20] Ravindranath N.H. and Ramakrishna J. Energy options for cooking in India. Energy Policy 1997;25:63-75.
[21] Saxena N.C. The woodfuel scenario and policy issues in India, RWEDP report No 49, Bangkok, 1997.
[22] Sinha C., Sinha S. and Joshi V. Energy use in the rural areas of India: setting up a rural energy data base. Biomass and bioenergy 1998;14:489-503.
[23] Pannu C.J.S., Singh S., Singh M.P., Singh S. and Bhangoo B.S. Energy use pattern for a selected village in the cotton-belt of Punjab. Energy 1993;18:1113-1117.
[24] Ravindranath N.H. and Hall D.O. Biomass, energy, environment: a developing country perspective from India, New York: Oxford University Press, 1995.
[25] NSSO Energy used by Indian households. Department of Statistics, Government of India, Report No. 410, New Delhi, 1997.
[26] TERI Energy Data Directory & Yearbook: 1999/2000. Tata Energy Research Institute, New Delhi, 1999.
[27] Reddy A.K.N. and Reddy B.S. Substitution of energy carriers for cooking in Bangalore. Energy 1994;19:561-571.
[28] Kulkarni A., Sant G. and Krishnayya J.G. Urbanization in search of energy in three Indian cities. Energy 1994;19:549-560.
[29] Alam M., Sathaye J. and Barnes D. Urban household energy use in India: efficiency and policy implications. Energy Policy 1998;26:885-891.
[30] Jochem E. Energy end-use efficiency, Energy and the challenge of sustainability. World Energy Assessment, UNDP, New York, 2000.
[31] Choudhury R. and Bhaktavatsalam A.K. Energy inefficiency of Indian steel industry -scope for energy conservation. Energy Conversion and Management 1997;38:167-171.

[32] de Beer J., Worrell E. and Block K. Future technologies for energy-efficient iron and steel making. Annual Review of Energy and the Environment 1998;23:123-205.
[33] de Beer J., Worrell E. and Block K. Long-term energy-efficiency improvements in the paper and board industry. Energy 1998;23:21-42.
[34] Sen A. Natural gas imports into South Asia: a study in international relations. Energy Policy 2000;28:763-770.
[35] Mangotra A.K. Kyoto protocol and CDM – An Indian perspective on renewable energy. Conference Delivering Kyoto – Could Europe do it?, 1-2 October, London, 2001.
[36] Patri N. India's DAE plans for 17,000 MW of new nuclear capacity by 2020, Nucleonics Week 2000;41(16):11-11.
[37] Schlamadinger B., Grubb M., Azar C., Bauen A. and Berndes G. Carbon sinks and the CDM: could a bioenergy linkage offer a constructive compromise? Climate Policy 2001;1(3):411-417.
[38] Schlamadinger B., Grubb M., Azar C., Bauen A. and Berndes G. Carbon sinks and biomass energy production. a study of linkages, options and implications. Climate strategies network. www.climate-strategies.org, 2001.
[39] Hall D.O., Mynick H.E. and Williams R.H. Alternative roles for biomass in coping with greenhouse warming. Science & Global Security 1991;2:113-151.
[40] Sudha P. and Ravindranath N.H. Land availability and biomass production potential in India. Biomass & Bioenergy 1999;16:207-221.
[41] Kartha S. and Larson E.D. Bioenergy Primer: Modernised Biomass Energy for Sustainable Development. United Nations Development Program: New York, 2000.
[42] Carpentieri A.E., Larson E.D., and Woods J. Future biomass-based electricity supply in northeast Brazil. Biomass and Bioenergy 1993;4:149-173.
[43] Azar C. and Schneider S.H. Are the economic costs of stabilizing the atmosphere prohibitive? Submitted for publication 2001.
[44] Azar C. Economics and distribution in the greenhouse, Climatic Change 2000;47:233-238.
[45] Baer P., Harte J., Haya B., Herzog A.V., Holdren J., Hultman N.E., Kammen D.M., Norgaard R.B. and Raymond L. Equality and greenhouse gas responsibility. Science 2000;289:2287.
[46] Gupta S. and Bhandari P.M. An effective allocation criterion for CO_2 emissions. Energy Policy 1999;27:727-736.
[47] Larson E.D. Technology for electricity and fuels from biomass. Annual Review of Energy and the Environment 1993;18:567-630.
[48] Williams R.H., Larson E.D., Katofsky R.E. and Chen J. Methanol and hydrogen from biomass for transportation, Energy for Sustainable Development 1995;1(5):18-34.
[49] Ogden J.M., Steinbugler M.M. and Kreutz T.G. A comparison of hydrogen, methanol and gasoline as fuels for fuel cell vehicles: implications for vehicle design and infrastructure development. Journal of Power sources 1999;79:143-168.
[50] Larson E.D. and Marrison C.I. Economic scales for first generation biomass-gasifier/gas turbine combined cycles fuelled from energy plantations, Journal of engineering for gas turbines and power 1997;119:285-290.
[51] Gustavsson L. Energy efficiency and competitiveness of biomass-based energy systems. Energy 1997;22:959-967.
[52] Neij L. Cost dynamics of wind power. Energy 1999;24:375-389.
[55] Rajsekhar B., van Hulle F. and Jansen J.C. Indian wind energy program: performance and future directions. Energy Policy 1999;27:669-678.

[53] Naidu B.S.K. Indian scenario of renewable energy for sustainable development. Energy Policy 1996;24:575-581.
[54] Kapur T., Kandpal T.C. and Garg H.P. Electricity generation from rice husk in Indian rice mills: potential and financial viability. Biomass and Bioenergy 1998;14:573-583.

Appendix – Technology characteristics

As mentioned in section 2 learning curves is not implemented in the model, and therefore the original price estimation is important for the result. But, the aim of this paper is to show some possibilities and not the exact truth.

Modern technologies are implemented into the model. For example, in the transportation section there are possibilities to use traditional combustion engines as well as fuel cells. The transportation fuel for example can be petroleum, methanol, hydrogen or decarbonised fuels. There are two distinct ways for decarbonisation: (I) flue gas decarbonisation – fossil fuel is combusted the traditional way and the CO_2 is captured from the flue gas; (II) fuel gas decarbonisation – fossil fuel is transformed to produce hydrogen and CO_2 is obtained as a by-product. Table A.1 summarize several of the technical options used in the model with conversion efficiencies and capital costs.

Table A1. Conversion efficiencies and capital costs for different technologies used in the model.

Fuel	Conversion into hydrogen[(a)]		Conversion into methanol[(b)]		Power plant[(c)]		Heat plant[(d)]	
	Efficiency	Capital cost US\$ kW_{H2}^{-1}	efficiency	Capital cost US\$ kW_{MeOH}^{-1}	efficiency	Capital cost US\$ kW_{e}^{-1}	efficiency	Capital cost US\$ kW_{Th}^{-1}
Hydro	-	-	-	-	n.a	1000	-	-
Wind	-	-	-	-	n.a	600	-	-
Solar PV	-	-	-	-	n.a	1200	-	-
Solar heat	-	-	-	-	-	-	90%	400
Solar H_2	n.a	2000	-	-	-	-	-	-
Biomass	65%	1300	60%	1300	50%	1300	90%	300
Hydrogen	-	-	-	-	70%	1300	90%	100
Natural gas	85%	400	70%	500	60%	700	90%	100
Oil	75%	1000	-	-	50%	1000	90%	100
Coal	65%	1300	60%	1300	50%	1300	90%	300

(a) The conversion efficiency is defined as higher heating value of the energy contained in the product divided by the higher heating value of all energy inputs to the process assuming that all external energy requirements are provided using the same type of fuel as the feedstock. **Sources:** Conversion efficiencies are from Larson [47] and Williams *et al.* [48] capital costs are based on Ogden *et al.* [49]

(b) The conversion efficiency is defined as higher heating value of the energy contained in the product divided by the higher heating value of all energy inputs to the process assuming that all external energy requirements are provided using the same type of fuel as the feedstock. **Sources:** Conversion efficiencies are from Larson and Marrison [50] and Williams *et al.* [48].

(c) Note that these estimates are intended to reflect the efficiency and the costs of the technologies once they are mature. **Sources:** These estimates are based on various sources including Gustavsson [51], Neij [52], Larson and Marrisson [50], Shukla *et al.* [6], Rajsekhar *el al.* [53], Naidu [54] and Kapur *et al.* [55].

(d) **Sources:** Rounded from Gustavsson [51] for all fuels but hydrogen, witch we assume equal to natural gas.

PAPER 3

Allocation of emission rights – economic incentives for early emission reductions of CO_2 in developing regions

Tobias A. Persson

Department of Physical Resource Theory,

Chalmers University of Technology/Göteborg University,

SE-412 96 Göteborg, Sweden;

E-mail: frttp@fy.chalmers.se

ABSTRACT

Business-as-usual CO_2 emissions for four developing regions, Centrally Planned Asia including China, South Asia including India, Latin America and Africa, are compared to emission allowances that are allocated based on a contraction and convergence approach. CO_2 emission allowances are assumed to change linearly from present per capita emissions in industrial countries and from the projected 2012 per capita emissions in developing countries towards an equal per capita target by the year 2050 when allowable emissions are constrained to equal per capita emission trajectories leading to stabilization of atmospheric CO_2 concentrations at 350, 450, and 550 ppm, respectively. The economic impacts on the developing regions following this allocation of emission quotas are estimated through the use of a energy-economic system model.

1. INTRODUCTION

The industrialized countries have emitted most of the CO_2 in the past and still account for roughly two thirds of global fossil fuel related CO_2 emissions. Industrial country emissions on a per capita basis are roughly five to ten times higher than those of developing countries, Table 1. However, stabilizing the atmospheric concentration of CO_2 implies that carbon dioxide emissions per capita would have to fall below levels that prevail in India and Africa today. A 400 ppm target would for instance require that emissions by 2100 are equal to 0.2-0.4 tC capita^{-1} yr^{-1}.

Table 1. CO_2 per capita emissions in metric ton C in 1998. Values from G. Marland *et al.* (2001).

Region	Country	tC capita^{-1} yr^{-1}
Africa	Ethiopia	0.01
	Nigeria	0.20
	South Africa	2.38
Asia	China	0.68
	India	0.29
	Indonesia	0.31
Latin America	Brazil	0.49
	Chile	1.11
	Mexico	1.07

International negotiations about control of the emission of greenhouse gases (GHGs) have achieved little in terms of differentiation of future commitments and implementation mechanisms for a long-term stabilization of the atmospheric CO_2 emissions. No agreement has been reached on how allowable emissions should be allocated between countries on the long-term. Several allocation principles have been suggested and analysed (see for example by Gupta and Bhandari, 1999; Grübler and Nakićenović, 1994; Azar, 2000; Baer *et al.* 2000; Neumayer, 2000; Beckerman and Pasek, 1995; Berk and den Elzen, 2001; and Harvey, 1995; Torvanger and Ringius, 2000; Bolin and Kheshgi, 2001; Philibert, 2000).

Developing country representatives have argued that, given the high past emissions, the industrialised countries bear the primary responsibility for the climate problem and should therefore bear the brunt of emission reductions. This is formally recognised in Article 3.1 of the UNFCCC in Rio de Janeiro in 1992, which states that the developed and developing countries have ‘common but different responsibilities’ (Article 3.1, UNFCCC).

However, the senate in US adopted a resolution (S.RES. 98) in July 1997 with 95 votes in favour and zero against, stating that the US would not accept any binding reduction targets under the UN framework convention on climate change, unless meaningful developing country participation. The unilateral focus on industrialized countries was also one of the prime reasons that George W. Bush invoked when stating that the US would withdraw from the Kyoto Protocol.

The development of the international climate regime could (1) gradually expand the group of countries that have binding quantified emission limitations in the Kyoto Protocol or (2) define an evolution of emission allowances for all countries over a longer period, for example:

- allocation proportional to emissions in a specific base year (called *grandfathering*),
- allocation on an equal per capita basis without historical accountability, or
- allocation on an equal per capita basis with historical accountability.

Difference in base year emissions is basically regarded as justified or at least accepted with the grandfathering perspective. The second rule regards unequal per capita emissions as unjustified, but disregards historical inequalities in emissions. Like the second rule, the third rule take the equal per capita emission perspective, but it also takes into account differences in historical emissions.

The aim of this paper is twofold:

1) to suggest an allocation of emission quotas and estimate when developing regions business-as-usual emissions reach their emission allowances, and
2) to estimate the economic implications on the developing regions following this allocation of emission quotas.

This paper is structured as follows. In section 2 method and model are presented. Business-as-usual emission scenarios are compared with the suggested emission allowances in section 3. The energy system costs for scenarios stabilizing the atmospheric CO_2 concentration at 450 ppm are presented in section 4. Then, in section 5, the revenues the developing regions can obtain by selling emission permits are estimated assuming that emissions allowances are allocated on a per capita basis in the world by 2050 and onwards. Some conclusions are given in section 6.

2. METHODOLOGY

2.1 Allocation of emission permits

In this paper, future emissions allowances are assumed to be allocation according to a contraction and convergence (Meyer, 2000) approach. The allowances are assumed to follow a linear trend from their present per capita level for industrial regions and the per capita emission by 2012 for developing regions towards an equal per capita allocation by

2050. The per capita emission allowances are then assumed to follow the per capita emission profile towards the stabilization target. Only carbon dioxide is considered but the analysis could be extended to include other greenhouse gases.

2.2 Energy-economy model

The GET 1.1 global energy-economic model developed by Grahn (2002) is a regionalized version of the GET 1.0 (Azar *et al.*, 2000). The model is a linear programming model composed of three different parts: the primary energy supply, the final energy demand, and the energy conversion system. The energy demand is exogenous for three end-use sectors - transportation fuel, electricity and direct fuel. The energy technology system has two components: technologies for production of energy carriers and technologies for distribution and use of transportation fuels. All technologies have their own characteristics in terms of investment costs (the estimation of costs are intended to reflect the situation once the technologies are mature), lifetime, efficiency, and load factor, Appendix 1. The model is set up to meet the exogenous energy demands with the lowest energy system cost.

Future levels of population growth, GDP, electricity and direct fuel are assumed to follow the C1 scenario developed by IIASA/WEC characterized as being ecologically driven (Nakićenović *et al.*, 1998). Transportation fuel demand is separated into fuel demand for personal transportation and goods transportation. The energy requirement is derived from transportation activities measured as person-km (pkm) and ton-km (tkm) and energy intensities measured as MJ pkm^{-1} and MJ tkm^{-1} (more details can be found in Azar *et al*, 2000)

The model generates an equal per capita emission trajectory towards an atmospheric stabilization target for CO_2. The model also generates per capita emission profiles for the regions: North America (NAM), Western Europe, Pacific OECD, Former Soviet Union, Central and Eastern Europe, Africa, Other Pacific Asia, Latin America, Centrally planned Asia including China, and South Asia.

The stabilization target for CO_2 can be met by CO_2 sequestration and by fuel switching, i.e., the CO_2 emissions is reduced by either expanding the production of non carbon emitting energy sources such as wind, biomass and hydro, or shifting from fuels with high carbon-to-energy ratios (such as coal) to fossil fuels with lower carbon-to-energy ratios (such as natural gas).

For each emission profile the model generates the CO_2 emission permit price, in effect the carbon tax required to bring the aggregated emissions into compliance with the CO_2 stabilization target.

Each region in the model may only emit more carbon than their allocated emission rights allow if another region is willing to sell the corresponding number of permits, thereby forcing the seller region to reduce its domestic emissions beyond the required commitment. This is modelled as if the same carbon tax were applied to all regions. It is assumed that the suppliers of permits are sufficiently numerous so that no single permit seller can affect the price received by withholding permits from the market or demand a price over the optimum where the demand and supply for permits reach each other. The revenue that a region can derive from selling emission permits is equal to the permit price multiplied with the amount of carbon permits sold.

Table 2. Main characteristics for the scenarios in this study. All scenarios are gathered from the IPCC database accessible on the web site (www.nies.go.jp/cger-e/db/ipcc.html) except the GET 1.1 scenario (see Azar *et al.*, 2000)

Source	**Scenario ID**	**Characteristics**	**Population in 2100** (billion)	**Accumulated emissions from 1990 to 2100** (GtC)
GET 1.1	Baseline	Middle Course	11.7	1218
GET 1.1	Stab 350	Stabilization of the CO_2 conc. at 350 ppm	11.7	405
GET 1.1	Stab 450	Stabilization of the CO_2 conc. at 450 ppm	11.7	800
GET 1.1	Stab 550	Stabilization of the CO_2 conc. at 550 ppm	11.7	1100
IIASA/WEC 98	A1	High growth, ample oil and gas	11.7	1318
IIASA/WEC 98	A2	High growth, return to coal	11.7	1629
IIASA/WEC 98	A3	High growth, fossil phase out	11.7	975
IIASA/WEC 98	B	Middle Course	11.7	1102
IMAGE 2.1	Baseline-A	Medium scenario, no climate related policy	11.5	1823
IMAGE 2.1	Baseline-B	Low scenario, no climate related policy	6.4	1072
IMAGE 2.1	Baseline-C	High scenario, no climate related policy	11.5	2314
IS92	IS92a	Middle scenario	11.3	1500
IS92	IS92b		11.3	1430
IS92	IS92e	High scenario	11.3	2190
IS92	IS92f		17.6	1830

3. BASELINE EMISSIONS VERSUS EMISSION ALLOWANCES UNDER A CONTRACTION AND CONVERGENCE APPROACH

The purpose of this section is to analyse when different developing regions business-as-usual emissions reaches the suggested allocation of emission allowances. These regional emission allowances are compared with regional business-as-usual emission scenarios from the literature, Table 2. There is substantial difference in the year in which the regions' business-as-usual emissions reach the allocated emission allowances, Table 3 and Figure 1.

Each region must reduce emissions below business-as-usual if atmospheric concentrations of CO_2 are to be kept below 350, 450 or 550 ppm. Centrally Planned Asia including China is the first region reaching its allowance while it takes a few decades more until the business-as-usual emissions in South Asia including India and Latin America reaches their emission allowances. Africa on the other hand could continue with business-as-usual emissions until the second half of this century without reaching their emission allowances.

However, the industrialized countries have the most stringent reduction requirements. The EU, for example, has to reduce the per capita emissions from 2.6 tC capita^{-1} yr^{-1} to under 0.8 tC capita^{-1} yr^{-1} by 2050 to be domestically in compliance with their allowances for a 450 stabilization target. Thus, it is the developing countries that could be expected to sell emission permits to the industrialized countries under this contraction and convergence approach.

Table 3. Dates when Centrally Planned Asia, South Asia, Latin America and Africa reach their emission allowances or average global per capita emissions for CO_2 stabilization targets of 350, 450 and 550 ppm. Average, earliest and latest dates are presented, expect for Africa where only three scenarios were compared. Business-as-Usual Emission scenarios from Table 2, is used for the estimations.

	CPA			**SAS**			**LAM**			**Africa**		
	350	450	550	350	450	550	350	450	550	350	450	550
Average	2012	2015	2017	2020	2055	2068	2023	2033	2043	2040	2080	2090
Earliest	2010	2010	2010	2010	2020	2020	2010	2010	2010			
Latest	2020	2030	2040	2030	2070	2090	2040	2070	2090			

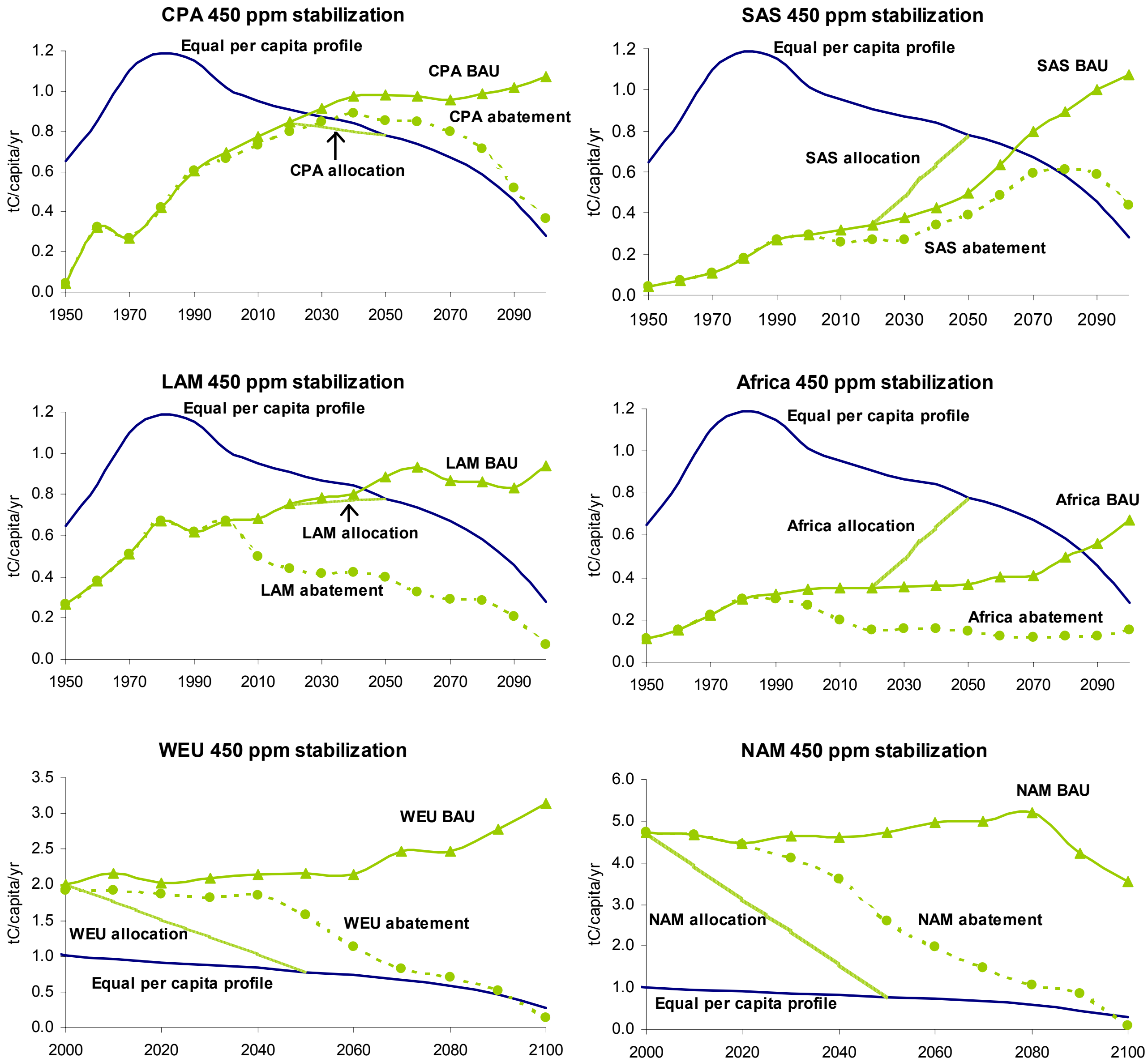

Figure 1. Carbon emissions on per capita basis from combustion of fossil fuels. Historic values until 1950 are from Marland *et al.*, 2001). The equal per capita line is an example of profile that stabilizes the atmospheric CO_2 concentration at 450 ppm. This is compared to the business-as-usual (BAU) trajectory and a CO_2 abatement trajectory for each region, which were generated with the GET 1.1 model. The emission allowances are assumed to change linearly from the present per capita emissions in industrial regions and the per capita emission by 2012 for developing regions towards the equal per capita allocation by 2050 (see dashed lines). Note that historic values are not included in the figures for Western Europe (WEU) and North America (NAM).

4. CARBON PERMIT PRICE AND CARBON REDUCTION COSTS

All numbers presented in this and next sections are generated by the GET 1.1 model and they show a scenario where a stabilization target of 450 ppm is adopted.

The energy system costs are higher in the abatement scenarios than in the business-as-usual scenario since the model is forced to use technologies that are more expensive. Further, the energy use in the business-as-usual scenario is assumed to be optimal, which means that we have excluded so called no regrets and win-win options. This suggests that costs may be overestimated.

The abatement cost varies between 0 and 2.5% yr^{-1} of the regions expected GDP, and it takes some 50 years before the abatement cost climbs above 1 % of GDP. In net present value, the costs of the abatement scenarios for the developing regions are almost 900 billion US$ (at 1990 prices and exchange rate). This is of course a high cost but comparisons with expected future GDP levels suggest that the costs might be manageable. The developing regions aggregated GDP are expected to be roughly 34 higher by the end of this century than in 1990 in the business-as-usual scenario. However, with a cost that varies between 0-2.5%, GDP becomes 33 times higher in 2100 in the abatement scenario. And with a growth rate of 3% yr^{-1} GDP would become 34 times higher by 2101. Thus, the cost amounts to a delay of roughly a year. Similar observations regard the cost of meeting stringent stabilization targets at the global and national level has previously been presented (Persson and Azar, 2001; Azar and Schneider, 2001).

As mentioned in the Methodology section, the model generates the CO_2 emission permit price that are required to bring the aggregated emissions into compliance with the 450 ppm stabilization target. The computed price of carbon emission permits is 16 US$ tC^{-1} by year 2010, 69 US$ tC^{-1} by year 2050, and almost 800 US$ tC^{-1} by the end of this century, Figure 2. The scenario was generated under the assumption that the 450 ppm target should be met at the least cost, calculated as net present value costs discounted with a discount rate of 5 percent yr^{-1}. This means that the permit price grows by 5 percent yr^{-1}. This explains the low value in the beginning of the century and the rapid growth and eventually high permit price towards the end of the century. These values are uncertain, dependent on discount rate (varied from 2 to 10% yr^{-1}) and technological options (carbon sequestration allowed or not) the carbon permit price ranges from 60 to 200 US$ tC^{-1} by 2050 and from 400 to 1200 US$ tC^{-1} by 2100.

The potential sales of the permits might, with the suggested contraction and convergence approach, be large enough to cover the estimated extra energy costs for the developing regions. To this aspect, the analysis turns below.

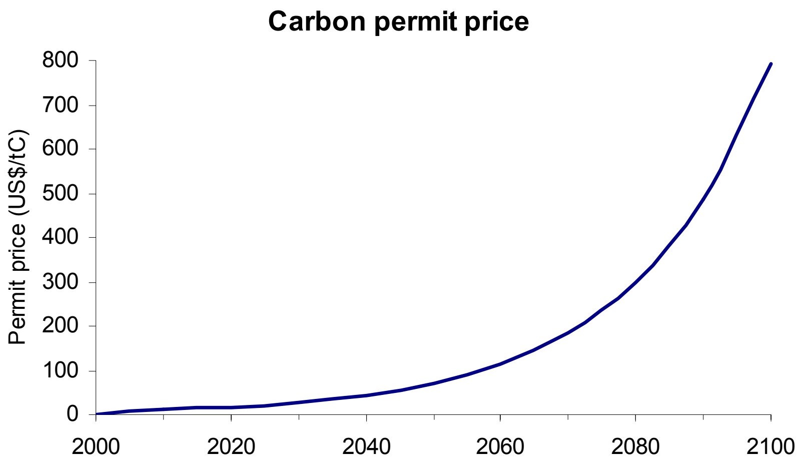

Figure 2. Price of emission permits (US$ tC^{-1}) development for a 450 ppm CO_2 stabilization target.

5. POTENTIAL REVENUES FROM CARBON TRADING

Whether the developing regions will gain or not on carbon trading, depends on how the permits are allocated. With a contraction and convergence allocation as suggested in this paper, each developing region except Centrally Planned Asia may sell emission permits to mainly industrialized countries during almost the whole century if they abate their CO_2 emissions according to the abatement scenarios in Figure 1. SAS could buy emission permits after 2080 while LAM and Africa could sell emission permits throughout the century.

The revenues to Africa, Latin America and South Asia from selling of emission permits, to the price shown in Figure 2, increase up to a few percent of the assumed GDP, Figure 3. Centrally Planned Asia on the other hand is purchasing emission permits from other regions during the whole commitment period.

However, changing the energy system from the business-as-usual scenario to the carbon abatement scenario increases as mentioned the energy system cost. By 2050 the revenues to SAS, LAM and Africa from selling of emission permits could correspond to about 0.5-2% of the regional GDP while the extra energy system cost corresponds to about 1% of the GDP. For SAS and Africa, there are net benefits with the trading until 2060-2080, i.e., the revenues are higher than the extra energy system costs. On the other hand, the extra energy system cost in CPA and LAM is higher than the revenues from trading during the whole century.

In absolute numbers, the aggregate net present value of revenues for all analysed developing regions from selling of emission permits could be about 400 billion (10^9) US$ during the period 2020-2100, which could be compared to the net extra energy system cost, approximately 900 billion US$, Figure 4.

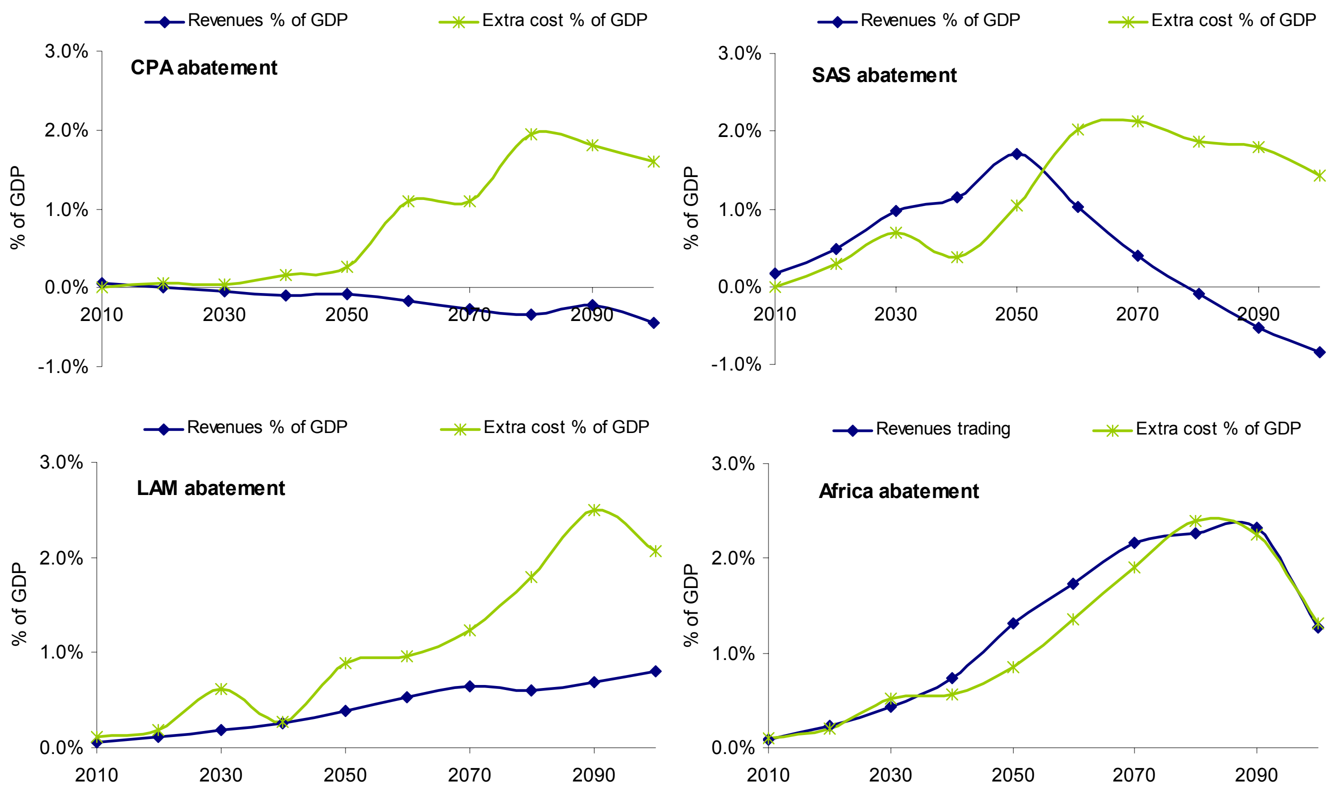

Figure 3. Revenues from the sales/purchases of emission permits, and extra energy system cost as percent of GDP for the carbon abatement scenarios leading to stabilization of the CO_2 concentration at 450 ppm. CPA purchases emission permits from other regions for a cost corresponding up to 0.5 percent of the GDP. The other developing regions sell emission permits to CPA and industrialized countries. However, the change of the energy system from the reference scenario to a carbon abatement scenario could increase the energy system cost corresponding up to a few percent of the regions GDP.

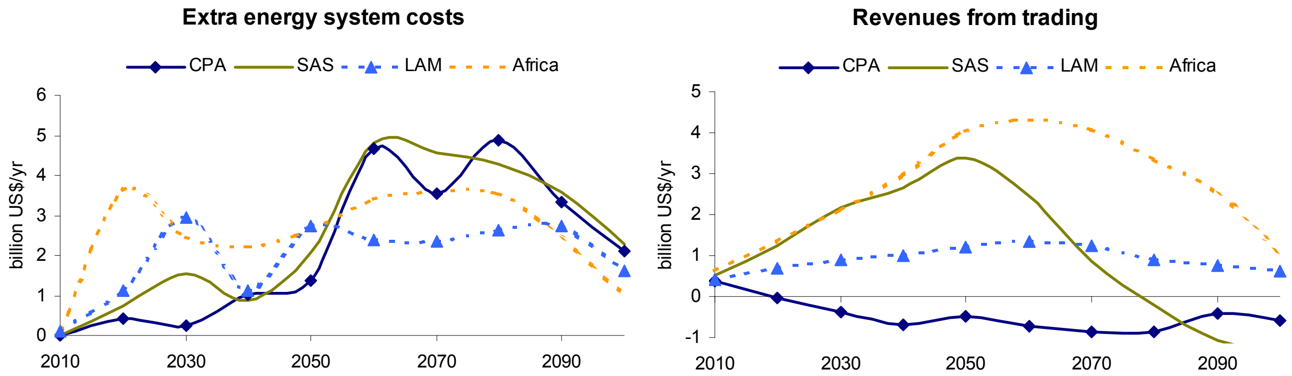

Figure 4. Extra energy system cost for changing the energy system from the business-as-usual scenario to the abatement scenario, and revenues from trading (billion 1990 US$).

6. DISCUSSION AND CONCLUSIONS

In this paper, a contraction and convergence approach for emission allowances have been analysed. The regional per capita emission allowances are assumed to develop linearly from the present levels in industrialised countries and from the 2020 per capita emission levels in developing countries to 2050 when they converge with an equal per capita emission profile towards the CO_2 stabilization target of 350, 450 or 550 ppm, respectively. The analysis has had two main objectives. First, to estimate when business-as-usual emission scenarios for CO_2 in four developing regions reach the suggested emission allowances. Second, to estimate the economic implications on the developing regions following the allocation of emission quotas.

The analysis indicates that the business-as-usual emission scenarios for Centrally Planned Asia including China reach the suggested allowances by 2010-2040. Latin America's and South Asia's (including India) business-as-usual emission scenarios reaches their allowances a few decades later than CPA, while Africa's business-as-usual emissions reach the allocated emissions rights during the second half of this century. In the same time, the suggested allocation approach requires toughest challenges for the industrialized countries. The U.S., for example, has emission allowances that require that their per capita emissions have to be abated from more than 5 tC capita^{-1} yr^{-1} by 2010 to less than 0.8 tC capita^{-1} yr^{-1} by 2050. The developing countries could therefore be expected to be sellers of emission permits to the Western world.

A stabilization of the atmospheric CO_2 concentration at 350, 450 or 550 ppm could thus not be achievable without carbon dioxide abatement in both developed and developing countries.

Economic analyzes, including this, clearly show that the economic cost of stabilizing the atmospheric concentration of CO_2 will be lower if developing countries adopted abatement targets under the United Nations Framework Convention on Climate Change already from the beginning. However, since it is the developed countries that have caused most of the emissions so far, they should bear the main costs, at least in the initial phase. This could be done by offering a generous allocation of emissions allowances to developing countries for the coming decades, maybe along the lines sketched in this paper.

Almost all developing regions, except CPA, can sell emission permits during almost the whole century by accepting the suggested contraction and convergence allocation approach. The net economic benefits for the developing regions could be high before 2060, while the benefits are smaller after 2060. The developing countries might, hence, have economic incentives for an early involvement in a protocol that could foster their energy systems to be less CO_2 emitting.

The results presented in this paper are part of an ongoing research project. In the near future, it would be extended with more extensive sensitivity analysis.

Acknowledgements

Christian Azar, Maria Grahn and Kristian Lindgren are gratefully acknowledged for their development and regionalisation of the GET model. Financial support from the Swedish Energy Agency is gratefully acknowledged. Dean Abrahamson is acknowledged for comments on early manuscripts. CGER-NIES, IIASA &WEC, RIVM and J. Leggett, W.J. Pepper and R.J. Swart are gratefully acknowledged for their supply of data.

References

Azar C. (2000) Economics and distribution in the greenhouse, Climatic Change, 47, 233-238.

Azar C., K. Lindgren and B.A. Andersson (2000) Hydrogen or methanol in the transportation sector?, Department of Pysical Resource Theory, Chalmers University of Technology and Göteborg University, Göteborg.

Azar C. and S.H. Schneider (2001) Are the economic costs of stabilizing the atmosphere prohibitive? Submitted for publication.

Baer P., J. Harte, B. Haya, A.V. Herzog, J. Holdren, N.E. Hultman, D.M. Kammen, R.B. Norgaard and L. Raymond (2000) Equality and greenhouse gas responsibility, Science, 289, 2287.

Berk M.M. and G.J. den Elzen (2001) Options for differentiation of future commitments in climate policy: how to realise timely participation to meet stringent climate goals? Climate Policy, 1, 465-480.
Beckerman W. and J. Pasek (1995) The equitable international allocation of tradable carbon emission permits, Global Environmental Change, 5, 405-413.
Bolin B. and H.S. Kheshgi (2001) On strategies for reducing greenhouse gas emissions, Proceedings of the National Academy of Sciences, 98, 4850-4854.
Grahn M. (2002) Regionalisation of the Global Energy System Model. Work in progress.
Grübler A. and N. Nakićenović (1994) International burden sharing in greenhouse gas reduction, IIASA, Austria.
Gupta S. and P.M. Bhandari (1999) An effective allocation criterion for CO_2 emissions, Energy Policy, 27, 727-736.
Gustavsson, L., Börjesson, P., Johansson, B. and Svenningsson, P., 1997. Reducing CO_2 emissions by substituting biomass for fossil fuels. Energy, 20, 1097-1113.
Harvey L.D.D. (1995) Creating a global warming implementation regime, Global Environmental Change, 5, 415-432.
IPCC, Intergovernmental Panel on Climate Change, 1996. Impacts, Adaptation and Mitigation Options. IPCC Working Group II Cambridge University Press, Cambridge, UK.
Kinzig A.P. and D.M. Kammen (1998) National trajectories of carbon emissions: analysis of proposals to foster the transition to low-carbon economies, Global Environmental Change, 8, 183-208.
Larson, E. D. (1993). Technology for electricity and fuels from biomass. Annual Review of Energy and the Environment, 18,567-630.
Larson, E. D. and C.I. Marrison (1997). Economic scales for first generation biomass-gasifier/gas turbine combined cycles fueled from energy plantations. Journal of engineering for gas turbines and power, 119, 285-290.
Marland, G., T.A. Boden and R. J. Andres (2001). Global, Regional, and National Fossil Fuel CO2 Emissions. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.
Meyer A., 2000. Contraction and convergence: The global solution to climate change. Schumacher Briefing No. 5, Greenbooks for the Schumacher Society, Bristol, USA.
Nakićenović N., A. Grübler and A. McDonald (1998) Global Energy Perspectives, IIASA & WEC, Cambridge University Press, Cambridge UK.
Neij L. (1999). Cost dynamics of wind power. Energy, 24, 375-389.
Neumayer E. (2000). In defence of historical accountability for greenhouse gas emissions, Ecological Economics, 33, 185-192.
Ogden J.M., M.M. Steinbugler and T.G. Kreutz (1999). A comparison of hydrogen, methanol and gasoline as fuels for fuel cell vehicles: implications for vehicle design and infrastructure development. Journal of Power Sources, 79, 143-168.
Persson T.A. and C. Azar (2001) Energy and CO_2 mitigation strategies for India - allocation of emission permits and revenues from emission trading. Submitted for publication.
Philibert C. (2000) How could emissions trading benefit developing countries. Energy Policy, 28, 947-956.
Thomas C.E.S., B.D. James, F.D. Lomax and I.F. Kuhn Jr. (1998). Integrated analysis of hydrogen passenger vehicle transportation pathways. In Proceedings of the 1998 US

DOE Hydrogen Programme Review. Directed Technologies, Inc. Arlington, Virginia.
Torvanger A. and L. Ringius (2000) Burden differentiation: criteria for evaluation and development of burden sharing rules. The joint CICERO-ECN Project on Sharing of Burden of Greenhouse Gas Reduction Among Countries. CICERO working paper 2000:1, Oslo, Norway.
UN/FCCC (1995) Conclusion of Outstanding Issues and Adoption of Decisions, Appendix 1, Berlin, Germany.
Williams R.H., E.D. Larson, R.E. Katofsky and J. Chen (1995). Methanol and hydrogen from biomass for transportation. Energy for Sustainable Development, 1(5), 18-34.

Appendix 1. Capital costs and conversion efficiencies

These estimates are intended to reflect the efficiency and the cost of the technologies once they are mature.

Table A.1. Energy conversion into electricity

Fuel	Conversion efficiency %	Capital costs USD/kW_e
Coal	50	1300
Oil	50	1000
Natural gas	60	700
Biomass	50	1300
Hydrogen	70	1300
PV	n.a	1200
Wind	n.a	600
Hydropower	n.a	1000

Sources: The estimates are based on various sources, including Gustavsson (1997), ABB (1998), Neij (1999), IPCC (1996), Larson and Marrison (1997).

Table A.2. Energy conversion into heat

Fuel	Conversion efficiency %	Capital costs USD/kW_{Th}
Coal	90	300
Oil	90	100
Natural gas	90	100
Biomass	90	300
Hydrogen	90	100

Source: Rounded from Gustavsson (1997) for all fuels but hydrogen, which we set equal to natural gas.

Table A.3. Energy conversion into hydrogen and methanol

Primary energy source	H_2 Conversion efficiency (a) %	H2 Capital costs USD/kW_{H2}	MeOH Conversion efficiency (a) %	MeOH Capital costs USD/kW_{MeOh}
Coal	65	1300	60	1300
Natural gas	85	400	70	500
Biomass	65	1300	60	1300
Solar hydrogen	n.a	2000	n.a	n.a

(a) The conversion efficiency is defined as higher heating value of the energy contained in the product divided by the higher heating value of all energy inputs to the process assuming that all external energy requirements are provided using the same type of fuel as the feedstock

(b) We have not included any running costs in our estimates of the total cost of hydrogen. However, these are generally small (some 10-20%) compared with the overall cost.

Source: Conversion efficiencies are from Larson (1993) and Williams et al (1995), capital costs are based on Thomas et al (1997), Ogden *et al* (1999).