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An Interaction of Economy and Environment in Dynamic Computable General Equilibrium Modelling with a Focus on Climate Change Issue in Korea : A Proto-type Model

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FOREWORD

In the beginning of the 21st century, climate change is one of hottest issues in arena of both international environment and domestic one. During the COP6 meeting held in The Hague, over 10,000 people got together from the world.

This report is a series of policy study on climate change in context of Korea. This study addresses on interactions of economy and environment in a perfect foresight dynamic computable general equilibrium with a focus on greenhouse gas mitigation strategy in Korea. The primary goal of this study is to evaluate greenhouse gas mitigation portfolios of changes in timing and magnitude with a particular focus on developing a methodology to integrate the bottom-up information on technical measures to reduce pollution into a top-down multi-sectoral computable general equilibrium framework.

As a non-Annex I country Korea has been under strong pressure to declare GHG reduction commitment. Of particular concern is economic consequences GHG mitigation would accrue to the society. Various economic assessment have been carried out to address on the issue including analyses on cost, ancillary benefit, emission trading, so far. In this vein, this study on GHG mitigation commitment is a timely answer to climate change policy field.

Empirical results available next year would be highly demanded in this situation.

I would like to thank Dr. Seunghun Joh, Prof. Rob Dellink, and Ms. Yunmi Nam for their efforts made for the project. Opinions expressed here are the authors', and do not represent the opinions of KEI.

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Korea Environment Institute
President
Sang Eun Lee

한글요약 (SUMMARY IN KOREAN)

일러두기

본보고서는 기후변화협약대응을 위한 정책설정에 필요한 기초 연구의 일환이다. 모델개발 및 구조에 대한 설명은 용어와 내용이 전문적으로 일반인을 독자로 염두에 두고 쓴 것이 아니기 때문에 구체적인 내용을 알려고 하는 독자는 영어로 된 본문을 읽는 것이 내용을 이해하는데 편리하리라고 믿는다. 또한 이 보고서는 한국에 대한 실증 분석이 아니라 개발하고 있는 모델을 검증할 목적이기 때문에, 사용된 데이터 및 가정은 이론적 검증에 편리하도록 설계되어 있다. 예를 들어 정책변수 (온실가스배출저감량), 탄력치 등은 현실적 고려를 하지 않은 것이다. 이런 맥락에서 본 연구의 기본 목적은 도출된 수치의 크기에 대한 구체적인 분석보다는 정책시행에 따른 방향과 정책에 대한 상대적 비교에 중점을 두고 있다. 또한 요약에서 언급되는 Figure, Table 은 본문을 참조하기 바란다. 한국에 대한 실증 분석 및 정책적 함의는 2001 년도 KEI 기본과제에서 제시될 예정이다.

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I. 모델 구조

1. 본 모델의 기본 개념

본 모델은 시스템 분석을 위해 개발된 것이다. 시스템분석이란 사회를 구성하는 인자들의 연관관계를 중시하는 것으로 이 모델의 중요한 인자는 경제와 환경이며, 기후변화협약대응을 중심으로 한 온실가스저감 정책이 경제와 환경에 미치는 영향을 국가차원에서 분석할 목적으로 개발되었다. 즉, 기후변화협약(UNFCCC) 이행과 관련된 의무감축설정에 따른 영향 분석이 본 연구의 주요한 목적으로 "언제, 어느 정도, 어떻게 (when, how much, and how to reduce GHG)"에 따른 경제 및 환경에 대한 파급 효과를 모의실험(simulation)을 통해 분석하는 것이다. 이것은 실증 모델이 아니고 모델을 이론적 측면에서 검증할 목적이기 때문에 proto-type model 로 지칭할 수 있다. 이를 위해 가능한 한 모델구조는 간략하게 처리되었다. 본 모델은 forward looking dynamic CGE 라고 축약할 수 있다. 여기서 CGE 는 정책변수의 영향을 simulation 을 통해 분석한다는 의미로 최적의 감축내용을 결정할 목적으로 개발한 optimization 모델과는 구분된다.

또한 기후변화정책이 장기간(dynamic) 분석을 요구한다는 속성에 근거하여 모델의 분석기간은 100 년 정도로, 핵심 분석은 UNFCCC 와 관련된 30 년 정도로 처리하였다. 본 모델은 forward looking 의 개념을 모델구조에 반영하였다. 즉, 본 모델의 기본 전제는 감축설정에 대한 경제주체들의 행위는 미래의 예측가능한 변수에 근거한다는 것이다. 이는 기존의 recursive 모델이 전년도의 정보에만 의존하여 순차적인 대응을 한다는 전제보다 합리적인 의사결정구도라고 할 수 있다.

2. 기존모델비판

기후변화와 지속가능발전과 같은 주제를 분석하기 위해서는 주제의 속성상 경제-환경의 연관관계를 장기적 관점에서 시스템적으로 분석하는 틀이 필요하다. 기후변화 분석과 관련된 기존 모델은 경제-에너지에 초점을 두고 있으며 선진국이 개발한 세계모델이 주류를 이루고 있다. 이 중 MERGE, SGM, GREEN 이 대표적이며 국내의 경우 GREEN 에 Korea 를 추가한 에너지경제연구원모델 등을 거론할 수 있다. 이들 모델은 전세계를 분석하는 global model 로서 국가별 비교 분석이 가능하지만 bottom-up 에 근거한 대안별 저감비용과 (engineering sector) top-down 형식의 micro-economic sector 와의 유기적 결합이 불가능하다는 것이 단점으로 지적된다.

3. 경제-환경 모델의 개발시 주요 관심사항

모델링의 관점에서 보면 저감대안은 크게 bottom-up 적인 개별 저감대안 (예, 에너지효율 향상을 위한 기기 교체, CNG 차량 도입 등)과 조세정책과 같은 top-down 형식으로 구분 할 수 있다. 기존의 CGE 에서 분석되는 저감대안은 탄소세와 같은 top-down 형식이 주가 된다. 그리고 bottom-up 대안은 기존의 개별 산업분류에 근거한 CGE 모델구조로 수용하기에는 상당한 어려움이 수반되지만 현실적인 측면에서 탄소세(top-down) 등과 비교할 때 실행가능성이 높고 실제 광범위하게 실행되고 있다. Bottom-up 저감 방식이 경제에 미치는 기능은 “저감 방식(경제 손실) → 기술발전 유도 → 환경산업 발전 → 저감비용 상쇄 효과 → 전체 경제효과 분석”으로 요약될 수 있다. 즉, bottom-up 저감 대안은 비용을 상쇄하는 역할에 대한 고려를 할 필요가 있으며, 이러한 점은 지금까지 빈번히 지적되어 왔다.

경제행위(예, 에너지 사용)로 인한 환경변화가 경제 시스템에 미치는 영향 즉, 경제행위로 인한 환경적 feedback 부분을 고려할 필요가 있다. 이는 누구나 인정하지만 해당부분에 대한 과학적 불확실성과 간혹 과학적 변화의 크기가 예측된다고 해도 이 변화를 화폐가치로 환산화는 과정에 대한 논란 때문에 실증분석에 반영되는 것이 제한되어왔다.

4. 본 모델의 구조

(본 모델의 구조 및 코드에 대해서는 Appendix I,II 참조)

본 모델의 구조는 논의의 편의상 간략하게 취급되었으며 해외 부분은 생략되었다. 생산부문은 제조업, 청정에너지, 화석연료, 오염저감분야 (환경산업)로 소비는 정부와 가계로 구분되었다. 청정에너지와 화석에너지 간의 완전대체를 인정하였고 오염발생원으로 제조업, 화석연료, 가계를 가정하였다. 시기별 배출량은 정책변수를 통해 외생적으로 결정되고 이를 달성하는 비용효과적인 방법은 오염발생자가 최종적으로 발생하는 오염단위에 해당하는 오염세를 지불하거나 오염저감을 하는 방안 중 최소비용의 방안을 선택하는 개념이 모델에 도입되었다. 연간 1%의 오염저감기술발전을 인정하였고, 오염할당권판매로부터 얻은 수익만큼 자본과 노동에 대한 세율을 자동적으로 감축하게 함으로써 재정지출을 가계부분과 연계하였으며 오염저감비용곡선(engineering type abatement-cost relation)을 CES 함수화하여 “오염저감분야”로 활용하였다(본문 Figure 1 참조). 분석기간은 2000-2100 이며 핵심분석기간은 2000-2030 으로 설정하였다.

5. 8 개의 배출량 시나리오

시나리오는 한국에 대한 현실적 고려없이 인위적으로 설정하였다. 다만 시기는 UNFCCC 의무감축 기간을 염두에 두고 설정하였으며 (시나리오 I), 감축방식에 따라 분석하였다(시나리오 II).

5.1 시나리오 I : 감축정책별 비교

(감축량의 변화에 대해서는 본문 Figure 2, 3 참조)

- 8_12-30: 2000-2007 BAU 유지, 2008-2012 BAU 의 70%, 2013 이후 2000 수준으로 고정
- 13-17-30: 2000-2012 BAU 유지, 2013-2017 BAU 의 70%, 2018 이후 2000 수준으로 고정
- 18_22-30: 2000-2018 BAU 유지, 2018-2022 BAU 의 70%, 2023 이후 2000 수준으로 고정
- 13-17-40: 2000-2012 BAU 유지, 2013-2017 BAU 의 60%, 2018 이후 2000 수준으로 고정
- 18_22-50: 2000-2017 BAU 유지, 2018-2022 BAU 의 50%, 2023 이후 2000 수준으로 고정

5.2 시나리오 II : 감축방식별 비교

(기간 2013-2022, 감축량 11 단위, 2023 이후 2000 수준의 80%로 고정, 본문 Figure 4, 5 참조) :

- 13_22-EQ: 2000-2012 BAU 유지, 2013-2022 사이 11 단위를 매년 동일량(11/10) 감축, 2023 이후 2000 수준의 80%로 고정
- 13_22-SM: 2000-2012 BAU 유지, 2013-2022 11 단위를 선형적으로 감축, 2023 이후 2000 수준의 80%로 고정
- 13_22-SD: 2000-2017 BAU 유지, 2013-2022 11 단위를 2018 년 이후 선형적으로 감축, 2023 이후 2000 수준의 80%로 고정

Ⅱ. 결과 및 분석

GDP 변화에 대한 본 모델의 분석결과, 감축시기와 정도에 비례하여 GDP 감소가 큰 것으로 나왔으며 이는 이론과 부합된다. 수치의 크기에 대해서는 본 모델이 실증모델이 아닌 관계로 자세한 분석은 생략하였다. GDP 변화는 본문 Figure 6,7,8,9 에 시나리오별, 시기별(100 년, 30 년)로 나타나 있다. 여기서 GDP 변화는 BAU 대비 변화율이기 때문에 감축정책으로 인하여 GDP 의 절대적 수치가 꼭 줄어드는 것은 아님을 유념하여야 한다. 한편 부분별 변화를 볼 때 화석연료 부분 생산이 전구간에 걸쳐 예상대로 가장 큰 감소를 했으며 청정연료분야는 증가 후 감소를 보여주고

있다. 본 모델의 관심사항 중의 하나인 오염세율과 저감단위비용 변화는 본문 Figure 10,11,12,13 에 나타나 있다. 이 도표에서 볼 수 있듯이 분석결과 오염세율과 저감단위비용은 서로 대체의 관계라는 전제를 확인 할 수 있다. 즉, 오염세율은 지속적으로 증가하지만 저감단위비용은 감소한다. 본문 Table 9 는 EV 를 기준으로 시나리오별 정책평가를 하고 있다. 통상 EV 는 후생함수를 매개로 한 경제정책 평가기준으로 이용되고 있으며 수치가 음(-)일 경우 정책 시행으로 인한 손실을 나타낸다. 본 연구의 경우 EV 가 모두 음수이기 때문에 수치가 적을수록 정책이 선호된다고 할 수 있다. 특히 Second Type 시나리오의 경우 갑작스런 감축(SD)의 경우 EV 손실이 균등한 감축(EQ)이나 단계적 감축(SM) 보다 크게 나타났으며 EQ 와 SM 은 동일한 비용을 수반하는 것으로 나타났다.

Ⅲ. 비판 및 향후계획

본 보고서는 모델검증이 주목적이며 현실성있는 시나리오 설정과 데이터는 2001 년 연구로 미루었다. 현실적으로 실현가능성 있는 감축시나리오를 설정하는 것은 모델의 활용이라는 측면에서 매우 중요하다. 시나리오 설정에는 경제뿐만 아니라, 정치, 계층, 국제협상 등 다양한 요소를 반영하도록 노력하여야 하겠다. 또한 본 연구에서 정책평가의 기준으로 삼은 GDP, EV 등에 대한 심층분석이 보강되어야 하겠다. 본 연구의 분석기간이 100 년이기 때문에 평가의 기준을 100 년, 30 년, 또는 50 년으로 하는 것에 따라 정책의 선호도가 바뀔 가능성이 있다. 어느 것을 택할 것인가는 비경제적 논리가 상당부분 가미되는 것이 현실이며 여기에 대비한 여러 종류의 분석과 경제적 분석을 수반해야 할 필요가 있다. 본 모델은 추후 경제-환경의 연관 관계 분석을 위해, 환경변화로 인한 단기적, 지역적 영향과 장기적, 세계적 영향 분석을 반영하는 것이 요구된다. 데이터 확보는 CGE 같이 많은 데이터가 필요한 연구에서 코딩과 더불어 모델의 성공적 수행을 담보할 주요한 요소이다. 현재 한국의 경우 1995 년 산업연관표의 활용이 가능하며 2001 년 상반기에 1998 년 산업연관표의 이용이 가능할 것으로 전망된다.

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I. INTRODUCTION

This study addresses on interactions of economy and environment in a perfect foresight dynamic computable (or applied) general equilibrium (CGE) with a focus on greenhouse gas (GHG) mitigation strategy in Korea. The primary goal of this study is to evaluate greenhouse gas mitigation portfolios of changes in timing and magnitude with a particular focus on developing a methodology to integrate the bottom-up information on technical measures to reduce pollution (the characteristics of the abatement techniques) into a top-down multi-sectoral computable general equilibrium framework. To this end, a dynamic computable general equilibrium model is constructed including pollution and abatement as a proto-type of the model. Empirical analysis based on the model developed here will be followed in a consequent project during 2001.

The dynamic setting is essential, as most of the major interactions between the economy and the environment are essentially dynamic in nature and capital formation is a typically dynamic phenomenon. Climate change issue is a good example needed to dealt with in dynamic way in that the policy perspectives are in nature to cover long-term, usually at least more couple of decades, adaptation and impact forecasting. Optimisation or simulation is two broad approaches taken for the dynamic analysis on economic interest in general and climate change issue in particular. This study takes

simulation approach : It compares consequences of GHG reduction schemes.

Standard CGE models do not pay explicit attention to the characteristics of the technologies involved, but use smooth, continuous production and utility functions. This is a common critique by mostly technically oriented scientists on these top-down economic models. On the other hand, most models that do take into account the technical aspects of changing economic structures do not model the indirect economic effects of these technologies (*i.e.* they adopt a partial framework). The large number of technological options available for pollution reduction precludes the use of discrete technology modelling in broad empirical environmental-economic analysis. Therefore, in this article a new methodology is introduced[1] in which the advantages of the top-down approach are combined with the main information of the bottom-up approach.

This study concentrates on the economic consequences of pollution and abatement, while environmental stocks and damages by poor environmental quality on the economic system or on welfare are not taken into account in this proto-type model, remains further works. The environmental sub-model is purely represented by the pollution levels and abatement activities. In policy terms to secure certain level of emission, the model cannot be used for Pigouvian analyses (see Pigou, 1920), where the optimal tax rate is determined by the trade-off between abatement costs and damage costs, but rather for Baumollian exercises where the cost-effective way to reach a predetermined policy target is analysed (see Baumol, 1977).

The organization of the paper is as follows. In Chapter II, different approaches to a dynamic specification of the CGE model are presented and compared. Chapter III describes the model structure. Then, the main results of policy scenarios are illustrated in Chapter IV followed by conclusion in Chapter V.

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[1] Essentially the same methodology is used in a static framework in Dellink *et al.* (1999).

II. DIFFERENT APPROACHES TO DYNAMIC CGE MODELS

1. Empirical CGE studies with environmental issues

In this section, a short discussion of the most relevant literature is presented; a broader and more detailed survey of the relevant literature is given in Dellink (1999b).

Computable general equilibrium models are based on neoclassical theory. There are two types of neoclassical growth models: (i) the Solow-Swan models with a fixed savings rate (Solow, 1956, 1957; Swan, 1956) and (ii) the Cass-Koopmans-Ramsey models where the optimal savings rate is determined within the (necessarily forward-looking) model (Cass, 1965; Koopmans, 1965; Ramsey, 1928). For an overview of neoclassical growth theory, see for example Chaudhuri (1989) and Barro and Sala-i-Martin (1995).

Most CGE models that include environmental issues adopt a static framework. Two (well-known) authors that have persistently analysed environmental issues using static CGE models are Bergman (see for example Bergman, 1988 and 1991) and Conrad (see Conrad, 1992 and Conrad and Schroeder, 1991 and 1993). These models focus on national economies. For the Dutch economy, static CGE models with environmental issues include HERMES (SEO, 19xx) and Dellink and Jansen (1997). Recent additions to the international literature include Naqvi, 1998, and Parry and Williams, 1999.

Looking at global CGE models with environmental issues, the three most well-known models are without doubt OECD's GREEN model (see Burniaux *et al.*, 1992 and Lee *et al.*, 1994), the MERGE model by Manne and Richels (Manne and Richels, 1992, 1995, 1999 and Manne *et al.*, 1995) and the DICE model by Nordhaus (Nordhaus, 1977 and 1994).

Though the DICE model is hugely simplified it has a large impact on research in climate economics, as the dynamic approach using both abatement costs and damages presents a better framework for climate economics than most other models. Though the Integrated Assessment models have more detail in both the economics as well as in the environmental specification, these models are so large that they are only operated at very large research institutions and are not widespread; an entry into the literature on Integrated Assessment models is given by Tol (1997) and Alcamo (1994).

Dynamic CGE models that include environmental issues are not very common. While the literature on dynamic CGE models is expanding (*e.g.* Devarajan and Go, 1998), dynamic CGE models that focus on the environment are rather limited. Jorgenson has carried out several dynamic analyses of environmental policy questions within an CGE context (see for example Jorgenson and Wilcoxen, 1990 and 1993). He uses econometric estimation of the relevant parameters, based on long-term US economic data. Other studies using dynamic CGE models with environmental issues are Böhringer, Pahlke and Rutherford (1997), Böhringer, 1998, Böhringer *et al.*, 1999 and Perroni and Rutherford, 1998. How to deal with temporal and spatial scales has drawn a wide attention from environmental studies modelling arena. Evolution of the nature over time is of in essence dynamic characteristic. Meanwhile, the corresponding consequences of the human system are some cases clearly distinguished such that it is imperative to incorporate this geographic heterogeneity in impact analysis. As scientific knowledge has kept disclosing that natural and human systems are mutually dependent not separated, the integration of economics and environment in environmental analysis has been carried out in various ways. Although localized and instantaneous environmental consequences receive attention by scientists and regulators alike, the problems defined by long-lasting pollutants, some of which disperse throughout the Earth, pose new challenges(Falk and Mendelsohn, 1993).

Environmental policymakers must address the adverse effects of a number of pollutants that accumulate in the environment(Toman and Withagen, 2000). Of particular instance is greenhouse gases such as carbon dioxide emitted by the use of fossil fuels, which bring about global warming. Due to the long lasting impacts of the global warming, the necessity of a dynamic approach to model both the impacts of accumulative carbon concentration and the related economic stakes has rapidly emerged(Baudry, 1999).

Environmental and natural resources can be distinguished as being primarily *flow* oriented or *stock* oriented. The flows that environmental stocks can generate are not irrelevant, as they govern the development of the stock over time, but the environmental damages associated with these problems are primarily related to the stock, not to the flow. For example, climate change is caused by the concentrations (stock) of greenhouse gasses as they are built up in the atmosphere, not by the emissions (flow). Other environmental resources are strictly flow oriented. For example, the moment a loud sound stops, the noise disturbance it creates vanishes.

In terms of the way that environmental media have impact on the human system, stock-oriented examples include toxic substances like PCBs and heavy metals, radioactive contamination, biological contaminants in water that require time to break down, water acidification, stratospheric ozone depletion, and accumulation of greenhouse gases. The detrimental effects of these substances on the ecological systems and human interests depend on the concentration of pollution, and thus in turn on the accumulation of non-degraded emissions. Goals for the regulation of theses damages often involve holding long-term emissions to a certain level below believed to avoid environmental danger (Toman and Withagen, 2000).

2. How to treat emission-concentration interactions in the previous models

A variety of models exist to investigate interaction between the environment and economy. In this study, we focus on models which are dynamic in time frame, general in scope, and climate change in issue. Some models do not necessarily meet the above criteria, however, most integrated assessment models (IAM) worth receiving the attention. Integrated assessments are convenient frameworks for combining knowledge from a wide range of disciplines such as economics, ecology, engineering, and so on. IPCC (1996) shows a good survey on the climate change IAM covering overview of existing IAM, preliminary results of the models, and strengths and limitations of the current models. Here we mention several models relevant to the theme of this study with a special attention to the way they treat concentrations.

2.1 ALICE

As for environmental interactions, ALICE 2.0 follows CETA (Peck and Teisberg 1992), linking emissions to concentrations, concentrations to temperatures, and temperatures to damages. The model use the "linear box" model in which one distinguishes between five separate spheres each having different properties with respect to carbon dioxide absorption (Maier-Reimer and Hasselman, 1987). It is assumed that the CO_2 emitted is distributed over the five boxes, in amounts corresponding to shares of total emissions. Within each box, the CO_2 concentration exponentially adjusts to its natural level. The accumulation of GHGs causes an increase of the equilibrium global mean temperature. For CO_2, the temperature increase is expected to be of approximate logarithmic nature.

2.2 AIM

The AIM (Asian-Pacific Integrated Model)is of a bottom-up type simulation model mainly examining global warming response measures in the Asian-Pacific region. The AIM comprises four discrete but linked models: two main models-the GHG emission model and the impact model- which are linked by two global physical models, the GHG cycle model and the climate change models (Matsuoka, Kainuma and Morita, 1994).

2.3 FUND

The FUND (Climate Framework for Uncertainty, Negotiation and Distribution) is a model that closes the loop population – economy – technology – greenhouse gas emissions – atmospheric composition – climate – climate change impacts – emission abatement. FUND was developed to compare the impacts of climate change against the impacts of greenhouse gas emission abatement with performing a cost-benefit analysis with multiple actors and under uncertainty.

A standard five-box carbon cycle model (cf. Hammitt *et al.*, 1992) is used for carbon dioxide concentrations in the atmosphere. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted with life-times according to Schimel *et al.*(1996). Other human disturbances of climate are omitted. Changes in radiative forcing follow from Shine *et al.* (1990). Radiative forcing drives the equilibrium change in the global mean temperature, to which actual temperature geometrically converges. Equilibrium sensitivities and convergence rates are calibrated to the typical outcomes of simple climate models (cf. Kattenberg *et al*., 1996).

2.4 MERGE

MERGE (A Model for Evaluating Regional and Global Effects of GHG reduction policies) is designed to explore alternatives views on a wide rage of contentious issues, e.g., costs, damages, valuation, and discounting (Manne, Mendelsohn, and Richels, 1994). It consists of a series of linked modules including 1) the costs of reducing the emissions of radiatively important gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), 2) natural system disposition and reactions to the emissions of these gases, and 3) the reaction of human and natural systems to changes in the atmospheric/climate system (Manne, Mendelsohn and Richels, 1994). According to recent version MERGE4[2], one of distinctive features of the model relevant to environmental module 1) allows for the heating effects of CO_2, CH_4 and N_2O, 2) allows for the cooling effects of sulphur emissions, 3) includes the option of carbon sinks such as afforestation, and 5) includes the option of abatement of CH_4 and of N_2O.

The emissions of each gas are divided into two categories: energy and non-energy. Emissions from energy sources are determined endogenously while emissions from non-energy sources are exogenous inputs to the model. The model assumes that prior to the industrial revolution, natural additions were offset exactly by natural removal. That is, the stock of carbon was in steady state. This implies that in MERGE anthropogenic emissions will lead to increase in stock of carbon in the atmosphere.

Regarding the future atmospheric CO_2 concentrations, the model uses a reduced form carbon cycle model. Using the carbon cycle model, it is straightforward to convert emissions into atmospheric concentrations. Carbon emissions are divided into five classes, each with different atmospheric lifetime. For CH_4 and N_2O, the atmospheric stock in year t+1 equals to the fraction of the stock in year t remaining in the atmosphere plus new emissions.

[2] http://www.stanford.edu/group/MERGE/code.htm

2.5 PAGE

PAGE (Policy Analysis for the Greenhouse Effect) is a probabilistic model that includes elements of emission policies, control costs, impact mitigation strategies and damages. Anthropogenic emissions of greenhouse gases such as carbon dioxide, methane, and nitrous oxide, and chlorofluorocarbons are dealt with in the model (Plambeck, Hope, and Anderson, 1997).

The excess concentration of anthropogenic greenhouse gases is computed as the difference between the concentration in the base year and the pre-industrial one. A portion of emissions gas gets into the atmosphere. Emissions into the atmosphere since the previous analysis year are approximated by a linear interpolation. The cumulative emissions into the atmosphere are sum of cumulative emissions in the last analysis year and the total emissions to the atmosphere since the last analysis year. Emissions remaining in the atmosphere are increased by emissions to the atmosphere since the previous model year and decreased by chemical and other interactions since the previous model year.

As for policy harmonization in targeting gases, Plambeck et. al (1997) point out that anthropogenic aerosols in the troposphere, notably sulphate, have a significant cooling effect. Aerosols, whose average lifetime are only 6 days (Charson, 1991) are produced primarily through metal smelting and the combustion of biomass and fossil fuels. Greenhouse gases, which are uniformly mixed throughout the atmosphere, can be modelled as a simple additive component in mean global forcing, whereas modelling the effect of aerosols requires regional scarcity. Consequently, policy to reduce fossil fuel burning could have a counter-intuitive warming effect in the short term by eliminating the aerosols that mask long-term greenhouse gas warming. In addition, programs that reduce acid rain by cutting sulphur emissions may also contribute to global warming.

2.6 RICE and DICE

The RICE and DICE models developed by Nordhaus are integrated economic and geophysical models of the economics of climate change(http://www.econ.yale.edu/~nordhaus/homepage/dicemodels.htm). They are the extension of the Ramsey model to include climate investments in the environment. Emissions reductions in the extended model are analogous to investment in the mainstream model. According to the models the concentrations of GHGs are regarded as “negative capital,” and emissions reductions as lowering the quantity of negative capital. Sacrifices of present consumption meaning lower emissions bring about preventing economically harmful climate change and thereby increasing consumption possibilities in the future.

The geophysical relationships that link together the different forces affecting climate change include a carbon cycle, a radiative forcing equation, climate-change equations, and a climate-damage relationship. In the new models, endogenous emissions are limited to industrial CO_2. Industrial emissions are treated as a joint product of carbon-energy. Other contributions to global warming are taken as exogenous. The new models contain a new structural approach to carbon-cycle modelling that uses a three-reservoir model calibrated to existing carbon-cycle models. Climate change is represented by global mean surface temperature, and the relationship uses the consensus of climate modellers and a lag suggested by coupled ocean-atmospheric models.

The original DICE and RICE models used an empirical approach to estimating the carbon flows, estimating the parameters of the emissions-concentrations equation from data on emissions and concentrations. This approach has been criticized that the models may understate the long-run atmospheric retention of carbon because it assumes an infinite sink of carbon in the deep oceans. DICE-99 and RICE-99 replace the earlier treatment with a structural approach that uses a three-reservoir model calibrated to existing carbon-cycle models. Thus, the RICE/DICE-99 approach matches the original DICE model and other calculations in the early periods but has better long-run properties.

3. Different types of dynamic modelling

The simplest dynamic CGE model is a steady-state model. Essentially, a steady-state model is a static model (there is only one period), where some steady-state conditions are satisfied (primarily with respect to investments; see Barro and Sala-i-Martin, 1995). The steady-state model is useful to illustrate the balanced growth path that may emerge in the long run and can be used to analyse the steady-state properties of the equilibrium. This type of model can however not be used to analyse the transition paths from the current growth path to a sustainable growth path.

The second type of model explored in this paper is the recursive-dynamic CGE model. This type of dynamic model is characterised as a series of individual one-period model simulations, and is based on the assumption that agents in the economy have no forward-looking behaviour. Hence, the model can be solved recursively, for each period separately, where the periods are linked through the capital stock. In comparison to the steady-state model, the recursive-dynamic approach has some major advantages: it enables the calculation of the transition path from the initial steady-state to a new steady-state, which is of particular importance for policy making, and which cannot be studied in a steady-state model. Naturally, the inclusion of the transition path may have significant impacts on any policy recommendations to be drawn from the analysis.

The third type of dynamic CGE model investigated here is the forward-looking model, like the standard Ramsey model with perfect foresight and certainty. This type has the advantage over recursive-dynamic models that consumers maximise their utility not only based on the current state of the economy, but also on future welfare (discounted to present values). This inter-temporal aspect lacks in a recursive-dynamic model. Empirical estimates suggest that consumers in reality do look ahead to some extent, but do not maximise their utility till infinity (see Srinivasan, 1982 and Ballard and Goulder, 1985). Intuitively, it is hard to imagine that none of the economic agents in the model takes a long-term view for his or hers decisions (see Solow, 1974). Consequently, the forward-looking and recursive-dynamic models provide extreme cases between which decision making in reality resides.

An alternative specification of the forward-looking model could be to assume that consumers maximise their discounted utility based on current prices and expectations of the future (and reconsider their actions in the next period when expectations change). This can be done in a temporary equilibrium framework or using the theory on incomplete markets. These models are closer to reality in this respect, but it may be hard to find good expectations functions for future prices and profits.

All model types discussed above are based on a finite number of periods approximation of the infinite-horizon assumption. A model is set-up for T periods, and all periods after that horizon are irrelevant to the model (apart from some transversality conditions concerning capital stock and utility after the last period). Consequently, the total number of markets (both current and future) and thus the number of decision variables is finite. Alternatively, one could specify an infinite-horizon model; these include two sub-types: Overlapping Generations (OLG) models and dynastic models. In the OLG models, consumers live for a finite time (longer than one period but shorter than the model horizon), so that in each period, two or more generations co-exist; the number of generations is infinite. The OLG framework thus deviates from the dynastic model, which assumes a finite number of consumers that live infinitively long and a social planner that ensures an optimal solution (see Ginsburgh and Keyzer, 1997). A recent example of an environmental-economic OLG-model is Gerlagh, 1999.

III. Description of a Model Structure

The main goal of this chapter is to show the main mechanisms that are at work in the model and how these mechanisms are influenced by the basic modelling assumptions. The model presented here is highly stylised[3]. It may be called a 'proto-type model', as it is used only to highlight the methodology presented above. For good empirical assessments of environmental policies, the proto-type model has to be augmented in several ways. These empirical issues will, however, not influence the main methodology presented in this article. In this chapter, social accounting matrix (SAM) is first presented. The description of model, then, is explained.

1. A General CGE Structure

A CGE is a system of simultaneous equations used to analyze interrelations of all economic sectors in a quantitative way. The CGE is composed of production equations, output disposition equations, market clearing equations, and other miscellaneous equations related to household income, government revenues and expenditures.

2. Description of the initial equilibrium using a SAM

A Social Accounting Matrix (SAM) is concise and comprehensive database of an economic structure of a society. It illustrates linkages among production, consumption, international trade, and financial flows. Table 1 shows a brief type of SAM.

Table 1. Schematic Social Accounting Matrix

	Goods	Producers	Consumers	Total
Goods		*Inputs*	*Consumption*	*Demand*
Producers	*Outputs*			*Revenues*
Consumers	*Endowments*	*Transfers*		*Income*
Total	*Supply*	*Expenditures*	*Expenditures*	

[3] Model results of steady-state, recursive, and perfect foresight are given in Dellink(2000).

The Adjusted SAM gives an alternative presentation of the economy, where Goods and Producers are aggregated[4]. The following table gives the adjusted SAM for a closed economy with 2 producers, 1 private household and a government sector:

Table 2. Adjusted SAM for a closed economy

	Producer1	Producer2	Private households	Governm-ent	Column sum	Assoc-iated prices
Producer 1	*Output*	*Intermediate deliveries*	*Consumpt-ion*	*Consumpt-ion*	*0*	*1*
Producer 2	*Intermedi-ate eliveries*	*Output*	*Consumpt-ion*	*Consumpt-ion*	*0*	*1*
Labour	*Labour demand*	*Labour demand*	*Labour supply*		*0*	*1*
Capital	*Capital demand*	*Capital demand*	*Capital stock*		*0*	*1*
Taxes	*Taxes on output and inputs*	*Taxes on output and inputs*		*Tax revenues*	*0*	*1*
Transfers			*Lumpsum transfers*	*Lumpsum transfers*	*0*	*1*
Row sum	*0*	*0*	*0*	*0*	*0*	

All rows have to add up to zero to ensure market clearance (where supply is valued positive and demand is valued negative). In the columns for the producers, the value of outputs (the quantity on the diagonal of the matrix, multiplied by the associated price of the row) have to equal the value of inputs (including tax payments), so each column has to sum to zero (this is known as the zero-profit condition). In the columns for the consumers the value of consumption has to equal the value of the endowments (including tax revenues and transfers) in order to ensure income balance.

In the base accounting matrix above, all prices are normalised to unity (without loss of generality). The reason for this is that statistics are normally only accounted in value terms. In aggregated models, the physical quantities cannot be derived in a straightforward way (as it entails adding apples and pears) so some price normalisation has to be applied and the quantities are defined to match the prices. If prices differ from unity (as will be the case in policy simulations), then one must multiply all entries in a row

[4] This is possible due to the assumption that each producer provides one unique good. The extension to multiple-output producers is straightforward, but goes beyond the scope of this text.

with the associated price (each row has it's own associated price) in order to get the zero-profit and the income-balance conditions.

The accounting matrix presented above can easily be augmented to include

- the abatement producer (include an additional row and column) and
- pollution (include additional rows for each environmental theme; the revenues are accounted in the column for the government sector; prices are effectively zero in the benchmark).

The following table gives the augmented accounting matrix:

Table 3. The Augmented SAM

	Y1	Y2	YA	Priv.	Gov.	Col. sum	Associated prices
Y1	Y_1	$-Y_{1,2}^{ID}$	$-Y_{1,A}^{ID}$	$-C_{1,Priv}$	$-C_{1,Gov}$	*0*	*1*
Y2	$-Y_{2,1}^{ID}$	Y_2	$-Y_{2,A}^{ID}$	$-C_{2,Priv}$	$-C_{2,Gov}$	*0*	*1*
YA	$-Y_{A,1}^{ID}$	$-Y_{A,2}^{ID}$	Y_A	$-C_{A,Priv}$	$-C_{A,Gov}$	*0*	*1*
L	$-L_1$	$-L_2$	$-L_A$	$\overline{L}$		*0*	*1*
K	$-K_1$	$-K_2$	$-K_A$	$\overline{K}$		*0*	*1*
τ	$-\tau_{x,1} \cdot X_1$ *(x=K,L,jj)*	$-\tau_{x,2} \cdot X_2$ *(x=K,L,jj)*	$-\tau_{x,A} \cdot X_A$ *(x=K,L,jj)*	$-\tau_{x,h} \cdot X_h$ *(x=K,L,jj)*	*Taxrev*	*0*	*1*
τ^{LS}				τ^{LS}	$-\tau^{LS}$	*0*	
E	$-E_{e,1}$ *(e=themes)*	$-E_{e,2}$ *(e=themes)*	$-E_{e,A}$ *(e=themes)*	$-E_{e,Priv}$ *(e=themes)*	$\overline{E_{e,Gov}}$ *(e=themes)*	*0*	*0*
Row sum	*0*	*0*	*0*	*0*	*0*	*0*	

In this last table, the following notation is used:

Table 4. Notations used for SAM

Symbol	Description	Symbol	Description
Y_j	Production quantity of sector *j*	$\overline{L}$	Exogenous labour supply
$Y^{ID}_{jj,j}$	Demand for input *jj* by sector *j*	$\overline{K}$	Capital supply (in 'flow' terms: capital services)
L_j	Labour demand by sector *j*	$\tau_{x,h}$	Tax rate on demand for input *x* by consumer *h* (*x*=*K*,*L*,*jj*)
K_j	Capital demand by sector *j*	τ^{LS}	Lumpsum transfer from government to the private consumer
$\tau_{x,j}$	Tax rate on demand for input *x* by sector *j* (*x*=*K*,*L*,*jj* and $x_j = Y^{ID}_{jj,j}$ for *x*=*jj*)	$E_{e,h}$	Pollution of environmental theme *e* by consumer *h*
$E_{e,j}$	Pollution of environmental theme *e* by sector *j*	$\overline{E_e}$	Endowments of pollution permits for environmental theme *e*
$C_{j,h}$	Consumption of good *j* by consumer *h*		

3. Model description

This section discusses the basic assumptions that are needed to build a multi-sectoral (dynamic) computable general equilibrium (CGE) model, including a specification of environmental pollution and abatement activities[5].

3.1 Modelling economic issues

The model is of the *computable general equilibrium* (CGE) type. A general equilibrium model consists of a set of 'economic agents' (like consumers and producers), each of which demands and supplies commodities or services (hereafter denoted in brief as 'goods'). Agents are assumed to behave rationally. Each agent solves its own optimisation problem. The agents take prices, which give information about the decision environment (like the behaviour of other agents and government policies), as given. Equilibrium is defined as a state of the economy in which the actions of all agents are mutually consistent and can be executed simultaneously. In other words, demand must equal supply on all markets and adjusting relative prices attains equilibrium. See Shoven and Whalley, 1992 or Ginsburgh and Keyzer, 1997 for more details.

Generally, there are two categories of agents: consumers and producers. Consumers (households) maximise their utility under a budget constraint, for given prices and given initial endowments. Producers (firms) maximise profits under the restriction of their production technology, for given prices. Demand and supply, which result from the agents' optimisation problems, meet each other on the markets. The model is written in GAMS in what Ginsburgh and Keyzer (1997) call a 'CGE format', which means that the model is formulated as a system of non-linear equations that can be solved simultaneously. This format implies that no Negishi weights (see Negishi, 1972) have to be constructed for the various consumer groups.

In the current model version of the model, there is no international trade. This allows for an endogenous interest rate in the various model types.

The consumers own the production factors labour and capital (the endowments) and consume both produced goods (for which a CES-type utility function is used). There is one representative private household and a government sector. The government sector collects taxes on all traded goods (both produced goods and the primary production factors) and uses the proceeds to finance public consumption of the two produced goods and pay for a lump-sum transfer to the private household.

For government behaviour the assumption is made that government utility follows private utility (*i.e.* there is a constant ratio between the two levels of utility) throughout all model simulations by proportionately changing the existing tax rates.

In the steady state and recursive-dynamic model, the households optimise current utility subject to the (current) budget constraint. Inter-temporal borrowing of funds is not possible in these two models. In the forward-looking model, the households maximise the present value of current and future utility, using the endogenous annual savings as one of the instruments. The budget constraint is only applied to the present value of all periods and not for each individual period, so that inter-temporal borrowing of funds is assumed possible.

The labour supply is fixed, but the wage rate is fully flexible; an exogenous growth of the labour supply is assumed. This growth in the labour supply drives the growth of the economy. In the steady-state model there is no increase in labour supply (as there are no periods distinguished).

The (total) capital stock is determined endogenously within the model; the way in which capital and investments are specified differs between the model types. In the steady-state model, the capital stock is determined by the steady-state requirements, where the (new equilibrium) rental price of capital is constrained so that the price of new capital equals the price of existing capital (*i.e.* the value of Tobin's Q equals unity; see Hayashi, 1982). These conditions also determine the optimal savings and investment level in the steady-state model.

In the forward-looking model, the capital stock and investment levels are fully endogenised: there are two additional fictitious production sectors modelled. The first, which may be called the capital services producer, transforms the current capital stock into capital services (that are input for the production sectors) and next period capital stock. The second fictitious production sector transforms investments by origin into next period capital stock. The consumers are endowed with a certain capital stock in the first period of the model and a final period capital stock (the transversality condition, in this case stating that capital stock in the last period should equal capital stock in the period before times the steady-state growth rate). The forward-looking behaviour of the agents and the endogenous savings rate make this model of the Cass-Koopmans-Ramsey type.

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[5] A detailed description of the model specifications used in this article is available from the author on request. The model code is given in the appendices.

The share of both produced goods in investments are fixed exogenously in all models. Consumer savings reduce consumption so that the consumer income condition holds.

The nested-CES production function consists of the input of labour and capital and intermediate deliveries from the other producing sector. Each producer produces one unique output from the inputs. As full competition is assumed, there are no excess profits to be reaped and the maximum-profit-condition diminishes to a least-cost-condition. The production function also contains the pollution associated with production and the investments in abatement by the sector. These are discussed separately below.

3.2 Modelling environmental issues

Production processes lead to pollution. This pollution is regarded as a necessary input for the production functions (though it seems more natural to view pollution as 'unwanted output', it can equivalently be regarded as a necessary input in the production of economic outputs; the key is that there is correspondence between production and pollution for a given technology). In the policy scenarios, this pollution is controlled by the government by means of tradable environmental 'pollution permits', that the producers (and consumers) can buy from the government (the proceeds are used to reduce existing taxes). In this way, a market for pollution permits is created, where, as in all markets in the model, prices are determined endogenously by equating demand and supply. Producers have the (endogenous) choice between paying for their pollution or investing in pollution abatement, and will always choose the least-cost of the two. By consuming, the households also inevitably pollute. Just as the producers, the households can either pay for pollution permits or invest in abatement[6]. Environmental quality is not directly included in the utility function, but consumers' environmental expenditures do have an impact on the maximum consumption and utility level achievable.

A third possibility for producers (consumers) is of course to reduce their production (consumption). This becomes a sensible option when both the marginal abatement cost and the price of the permits are higher than the value added foregone in reducing production (for producers) or utility foregone in reducing consumption (for consumers). At low levels of required pollution reduction, this is not likely to be a viable option. However, if the required pollution reduction is set at a much more ambitious level, which may not be unrealistic when striving for (strong) sustainability, then both the costs of buying the pollution permits and the costs of investing in further abatement may become extremely high and reducing production (consumption) may become a least-cost strategy[7].

Normal CGE models describe the technical possibilities to change the production (or consumption) structure in the form of smooth elasticities of substitution, without paying explicit attention to the characteristics of the technologies involved. On the other hand, most models that do take into account the technical aspects of changing economic structures do not model the indirect economic effects of these technologies (*i.e.* they adopt a partial framework). In principle, both approaches can be reconciled: the available techniques can be explicitly modelled in a general equilibrium framework so that both the technical information and the indirect effect are taken into account (see Böhringer, 1998, where the same complementarity format is used as here).

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[6] Practical difficulties may lead to a different choice of policy instrument in reality. Nonetheless, the approach taken here is the cost-effective one and can therefore serve as a reference point for evaluating other policy instruments.

[7] Note that from a macro-economic point of view the labour that is 'freed' when reducing production in one sector may be used in a profitable way in other (less polluting) production sectors, if these have less pollution associated or have lower abatement cost options available.

However, practical problems stand in the way of using this integrated approach: when one looks at several environmental themes and wants to include information on all available technologies, the number of techniques that have to be specified gets very large (for climate change alone, there are around a thousand abatement techniques available; see De Boer, 1999 and Dellink and Van der Woerd, 1997). This precludes the use of discrete technology modelling in broad empirical environmental-economic analysis. Therefore, in this article a new methodology is introduced in which the advantages of the top-down approach are combined with the main information of the bottom-up approach. To this end, the bottom-up information is aggregated into so-called abatement cost curves, which give the marginal abatement costs for increasing levels of pollution reduction. These abatement cost curves also provide the information on the total (technical) potential of pollution reduction. Then, these abatement cost curves are approximated by means of an 'iso-output curve' that reflects the trade-off between pollution and abatement. These iso-output curves are then implemented in the AGE model.

The abatement process is modelled as a separate producer, where 'abatement goods' are produced using both produced goods and primary production factors as inputs. This is roughly in line with Nestor and Pasurka (1995), but there the abatement producer is an implicit part of the government sector, and hence does not have a specific structure. In our model, a CES production function is calibrated, for which the data are derived from abatement cost curves: these inputs represent the 'spending effects' of implementing technical measures. It is assumed that these spending effects are homogenous over the complete abatement cost curve and do not differ between the environmental themes. As a result, one abatement producer suffices to represent the abatement possibilities.

The output of the abatement producer is demanded by the other producers and by consumers, so each producer and consumer in principle has the same set of abatement technologies available, but each will have other substitution possibilities between investing in abatement and buying pollution permits. Consequently, both the marginal costs of abatement and the technical potential to reduce pollution through abatement will differ between the producers. The marginal abatement costs will be equalised in the model, as the resulting equilibrium is characterised by cost-effectiveness. These marginal abatement costs in the new equilibrium will also equal the price of the pollution permits. Hence, all polluters are indifferent at the margin between polluting and investing in abatement.

As the abatement cost curves are translated for each producer and environmental theme into an 'iso-output curve' of pollution and abatement, the abatement possibilities are presented as a function of pollution and not as a function of pollution reduction. Then, a CES function is calibrated to best fit the iso-output curve and the CES-elasticity thus estimated describes the sector-specific, environmental theme-specific possibilities to substitute between pollution and abatement.

Figure 1 illustrates the concept of the abatement cost curve and iso-output curves in case of the Netherlands. Note that the figure differs from a normal representation of abatement cost curves in that the x ... ate change, emissions in the N ... e above 110 kilo tonnes CO_2-e ... cal measure; the line without m ... between a technical measure a ... presents the technical options v ... ect if the number of technical n

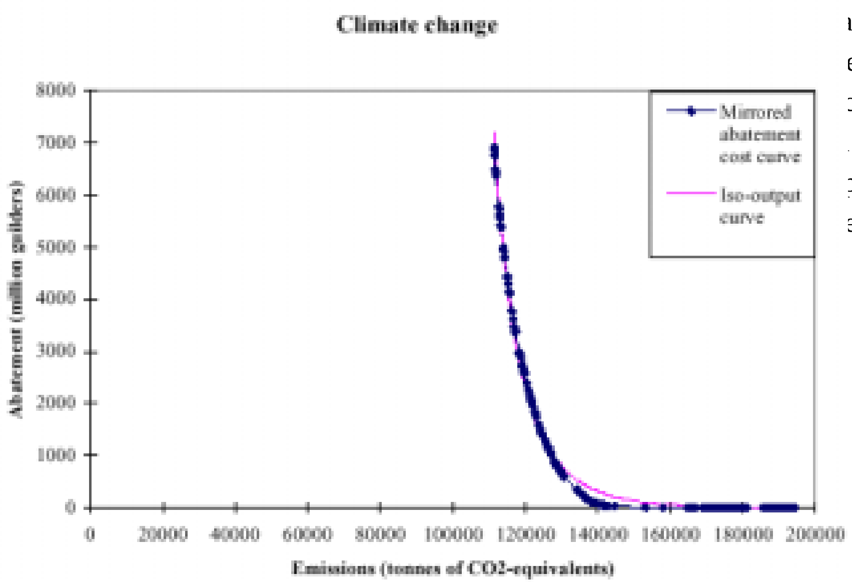


Figure 1. An iso-output curve for climate change

Though this approach may not seem very flexible at first glance, preliminary empirical analysis suggests that for all environmental themes the abatement cost curves can be fitted with a difference of less than one and a half percent margin of error (see Verbruggen, 1999). Hence, the approach taken here is relatively easy and straightforward, but a still rather accurate methodology to integrate the (bottom-up) technical measures into the (top-down) AGE model. The technical potential to reduce pollution through abatement activities provides an absolute upper bound on abatement in the model. This is a clear advantage over the traditional quadratic abatement cost curves, where no true upper bound on abatement activities exists (the abatement costs will always be finite, no matter how much pollution is abated).

Environmental policy is implemented by determining the number of pollution permits the government auctions: in the base simulations, the government distributes exactly the number of permits that allows the producers and consumers to maintain their original behaviour. The price of the permits is endogenously determined on the market by equating demand and supply, just like other prices. The revenues from the sale of the permits to producers and consumers is – by assumption – used by the government to reduce existing taxes proportionately. If the government wishes to reduce total pollution by x percent, it just takes away x percent of the permits.

A direct effect of a reduction in the number of permits is, *ceteris paribus*, a reduction in the government revenues from the permits. This puts an upward pressure on other taxes. However, as always, the CGE model is full of (mitigating) indirect effects: the producers and consumers will change their behaviour, shift towards more environmentally friendly techniques, and invest in abatement. Moreover, as the supply of permits decreases, the price of the permits will increase; this will also mitigate the loss in government revenues. On balance, the government revenues may go up or down, depending on the value of the price elasticities of demand for pollution permits by the producers and consumers.

Although the analysis of the optimal timing of policies is not a direct aim of this study, the framework is highly suited to investigate the consequences of speeding up or deferring environmental policy targets. At this stage, annual environmental targets will be satisfied and the development of these targets over time is assumed exogenous.

3.3 Parameter values for the numerical example

A social accounting matrix employed for the study is represented in table 5 below. In the accounting matrix, production outputs and consumer endowments are given as positive values, inputs and consumption are given as negative values.

All producers (Y1, Y2, Y3 and the abatement sector YA) have a Cobb-Douglas production function for intermediate deliveries and primary factors (see Table 6). The substitution possibilities between abatement and pollution is assumed to 1.4 for both CO_2 and NO_x emissions. It is assumed that as intermediate input for production and consumption, clean and dirty energy is characterised with perfect substitution. Investments are made up of goods Y1, Y2, and Y3.

Private consumers have a utility function with a CES elasticity of 1 (Cobb-Douglas utility function); the corresponding elasticity for the government is set at 0 (Leontief' utility function) as can be seen in

Table 7. The government does not save, but the private households do. The intertemporal rate of substitution of consumption is set at 0.5.

Table 5. Initial SAM

	Y1	Y2	Y3	YA	PRIV	GOVT	colsum
Y1	70	-21	-10	-22	-17	0	0
Y2	-9	160	-50	-3	-98	0	0
Y3	-18	-30	300	-2	-200	-50	0
YA	-10	-30	-40	85	-5	0	0
L	-5	-20	-57	-56	138	0	0
K	-18	-47	-97	-2	164	0	0
taxl	-5	-8	-16	0	0	29	0
taxk	-5	-4	-30	0	0	39	0
taxls	0	0	0	0	18	-18	0
Row sum	0	0	0	0	0	0	0

Note: 'Y1' indicates polluting manufacturing sector, 'Y2' dirty energy sector, 'Y3' clean energy sector; 'YA' indicates the abatement sector; 'PRIV' stands for the private households and 'GOVT' for the government consumer; 'L' and 'K' are the primary production factors labour and capital, respectively; 'taxl' are taxes on labour, 'taxk' are taxes on capital use and 'taxls' are lumpsum transfers between government and consumers; the 'price' column gives the prices associated with the rows; 'rowsum' is the sum over all rows within a single column and 'colsum' is the sum over all columns within a single row.

Table 6. Additional producer data

	Y1	Y2	Y3	YA	Explanation
InvSh	0.1	0.5	0.4	0.00	Share in origin of investments
Elas	1.0	1.0	1.0	1.0	Substitution elast. between inputs
Elas2	1.4	1.4	1.4	0.0	Subst. el. Between pollution and abatement
Elas3	+INF	+INF	+INF	+INF	Subst. el. Between inputs of Y2 and Y3
CO_2	0.1	0.6	0.0	0.0	Share in total pollution of CO_2
NO_x	0.1	0.5	0.0	0.0	Share in total pollution of NO_x

Table 7. Additional consumer data

	Priv	Gov't	Explanation
SavSh	1.0	0.0	Share in total savings

Sigma	0.5	0.5	Intertemporal subst. el.
Elas	1.0	0.0	Subst. el. between consumption goods
Elas2	1.4	0.0	Subst. el. between pollution and abatement
Elas3	+INF	+INF	Subst. el. between inputs of Y2 and Y3
CO_2	0.3	0.0	Share of polluter in total pollution of CO_2
NO_x	0.4	0.0	Share of polluter in total pollution of NO_x

Pollutions for climate change and acidification problem are generated in this model only from Y1 and Y2. Sector Y1 accounts for 10% of CO_2 emissions and 10% of NO_x emissions ; sector Y2 dirty energy accounts for 60% of CO_2 emissions and 50% of NO_x emissions; the private households account for the rest of the emissions (30% of CO_2, 40% of NO_x); the abatement sector itself and the government consumer do not pollute.

The growth rate is induced by an annual four percent autonomous increase in labour supply; the depreciation rate is set at seven percent and the interest rate at seven percent.

To allow a sufficiently long period for stabilisation to the steady state, the whole model horizon is of 100years, 2000-2100; it is expected that any short-term deviations from the long-term growth paths will have faded out by then. The policy period is much shorter: 30 years, 2000-2030.

3.4 Sectoral Structure

This section gives a more detailed delineation on the model employed here. The production structure of general CGE models consists of production functions, zero profit conditions, and input demand equations for each sector modeled. Production is normally assumed to be function of primary inputs--labor, capital, and land, which are combined according to a specified production function, and intermediate inputs, which are outputs or sectors included in the model and used in the production of other outputs or sectors in the model. These intermediate inputs are generally assumed to be used in a fixed proportion to output levels. Production functions of primary inputs can be Cobb-Douglas, CES, nested CES, or some other form. Specific functional forms are chosen according to which points are emphasized in the model. Input demand functions are derived by first order conditions for profit maximization subject to budget constraints. Primary input totals are generally assumed fixed. Zero profit conditions require that producers revenue equals the sum of the costs to produce the products.

Output disposition sectors are divided into household consumption, intermediate uses, exports, government expenditure, and inventories. In general CGE models, household consumption is modeled by a series of consumer demand equations for each output based on a specified form of utility function subject to budget constraints. Intermediate demand for outputs is based on a fixed proportion assumption that a given number of units of production from a sector are required to produce each unit of output in each sector for which it is an input. In one country models with trade, CGE models generally either assume homogeneous foreign and domestic products and model trade with single net export or net import equations, or differentiated products are assumed with an Armington demand structures for imports and constant elasticity of transformation functions for outputs sold domestically or exported.

Market clearing conditions require that the sum of all uses for each commodity is equal to its production level plus imports. Factor market clearing conditions assume that the total supply of each primary factor is fixed, and equal to the total demand for each sector.

Household income is assumed to be a function of factor income, transfers, savings, and taxes. Other sectors--government expenditure, inventory, taxes, and savings--are assumed to be proportional to output or income levels, or are assumed fixed.

The production sector is where most of the changes in structure were made to allow simulation of the energy input tax and emission control through timing and magnitude differentiated. The basic structure of general CGE is discussed first, and this is followed by a discussion of the changes to the production structure needed for this analysis.

The production structure of general CGE models consist of production functions, zero profit conditions, and input demand equations for each sector modeled. Production is normally assumed to be function of primary inputs--labor and capital, or which are combined according to a specified production function, and intermediate inputs, which are outputs or sectors included in the model and used in the production of other outputs or sectors in the model. These intermediate inputs are generally assumed to be used in a fixed proportion to output levels.

Production functions of primary inputs can be Cobb-Douglas, CES, nested CES, or some other forms. Specific functional forms are chosen according to which points are emphasized in the model.

Input demand functions are derived by first order conditions for profit maximization subject to budget constraints. Primary input totals are generally assumed fixed. Zero profit conditions require that producers revenue equals the sum of the cost to produce the products.

Nested CES functions were used in this model to permit different substitution elasticities between pairs of inputs. Major modifications to the general CGE model structure were made for this analysis.

First, in this model, energy sectors, which are intermediate inputs, are separated from other intermediate inputs. Energy sectors are distinguished clean- or dirty energy based on where they emit GHG or not. They, then, are made flexible inputs rather than a fixed proportion input so that substitution of clean- with dirty-energies vis-à-vis with other inputs is possible when the energy price increases due to an output tax on the energy.

Second, it is assumed that producers make a cost-effective choice between purchasing pollution permits or paying pollution taxes and spending on abatement activity.

Emission sector and abatement sectors are substituted each other in the model so that fictitious environmental services sector in this model is composed of residual of emission after abatement of the emission generated by production activity. As previously noted, in this proto-type model no environmental impact of emission residual specified and remains further works. Equation 1 represents production function and environmental service sectors in general functional form (for a definition of indices see Table 8).

$$Y_{j,t} = CES(Y^{ID}_{1,j,t},...,Y^{ID}_{J,j,t}, K_{j,t}, L_{j,t}, ES_{1,j,t},...,ES_{E,j,t}; \sigma^1_j,...,\sigma^V_j) \quad \text{for each } (j,t) \tag{1}$$ [8]

[8] As usual, '…' is used to indicate all items within the range as given by the items listed before and after.

A general nested CES production function with for example 4 inputs and 2 levels can be written as:

$Y = (a_1X_1^{\rho}+ a_2X_2^{\rho}+ a_{34}X_{34}^{\rho})^{1/\rho}$, and $X_{34} = (a_3X_3^{\psi}+ a_4X_4^{\psi})^{1/\psi}$ for some parameters a_1, a_2, a_{34}, a_3, a_4, where $\rho=(\sigma-1)/\sigma$ and $\psi=(\varphi-1)/\varphi$. A convenient notation is: $Y = \text{CES}(X_1, X_2, X_{34}; \sigma)$; $X_{34} = \text{CES}(X_3, X_4; \varphi)$.

Table 8. Definition of indices

Indices		
Label	Entries	Description
j and *jj*	1,…,J,A	Production sectors, including Abatement producer (A) j={High-polluting sector, Low-polluting sector, Abatement producer}
H	1,…,H	Consumer groups h={Private households, Government}
E	1,…,E	Environmental themes e={Climate change, Acidification}
V_J	1,…,V_J	‘CES-knots’ in production functions v_J={Economic inputs, Environmental inputs, Production}
V_H	1,…,V_H	‘CES-knots’ in utility functions v_H={Goods, Environmental inputs, Consumption}
T	1,…,T	Time periods t={1998,1999,…,2030}

Parameters	
Symbol	Description
g_L	Exogenous growth rate of labour supply
$apei_{e,t}$	Autonomous pollution efficiency improvement; assumed equal across all agents
δ_K	Depreciation rate
r	Steady-state interest rate
I^S	Base level investments (calibrated to steady-state)
K^S	Base level capital stock (calibrated to steady-state)
$\overline{L_{h,t}}$	Exogenous labour supply by consumer *h* in period *t*
$\overline{E_{e,h,t}}$	Endowments of pollution permits for environmental theme *e* by consumer *h* in period *t*
ι_j	Input share of good *j* for investments (by origin)
$\tau_{K,j}$	Tax rate on capital demand by sector *j*
$\tau_{L,j}$	Tax rate on labour demand by sector *j*
$\tau_{jj,j}$	Tax rate on input of good *jj* by sector *j*
$\tau_{j,h}$	Tax rate on consumption of good *j* by consumer *h*
$\tau_{K,h}$	Tax rate on the supply of capital by consumer *h*
$\tau_{L,h}$	Tax rate on the supply of labour by consumer *h*

τ_h^{LS}	Lumpsum transfer from government to consumer *h*, with $\sum_{h=1}^{H} \tau_h^{LS} = 0$ and $\sum_{h=1}^{H} \tau_h^{LS} \cdot \alpha_t^{LS} = 0$
τ^{SUB}	Lumpsum transfer from (excess) private households to the subsistence consumer
σ_j^v	Substitution elasticities between inputs combined in knot v_J in production function for sector *j*
$\sigma_{e,j}^A$	Substitution elasticities between pollution and abatement for environmental theme *e* in production function for sector *j*
σ_h^v	Substitution elasticities between consumption goods combined in knot v_H in utility function for consumer *h* (within same time period)
$\sigma_{e,h}^A$	Substitution elasticities between pollution and abatement for environmental theme *e* in utility function for consumer *h*
σ_h^{Util}	Intertemporal substitution elasticities in utility function for consumer *h* (between time periods)

Variables

Symbol	Description
$Y_{j,t}$	Production quantity of sector *j* in period *t*
$Y_{jj,j,t}^{ID}$	Demand for input *jj* by sector *j* in period *t*
$L_{j,t}$	Labour demand by sector *j* in period *t*
$K_{j,t}$	Capital demand by sector *j* in period *t*
$I_{j,t}$	Investment originating in sector *j* in period *t*
$I_{h,t}$	Investment by consumer *h* in period *t*
$\Pi_{j,t}$	(Net) profits in sector *j* in period *t* (equal to zero)
$E_{e,j,t}^U$	‘Unabatable’ emissions of environmental theme *e* by sector *j* in period *t*
$E_{e,j,t}^A$	‘Abatable’ emissions of environmental theme *e* by sector *j* in period *t*
$A_{e,j,t}$	Investment in abatement of environmental theme *e* by sector *j* in period *t* {note that $\sum_{e=1}^{E} A_{e,j,t} \equiv Y_{A,j,t}^{ID}$ }
$ES_{e,j,t}$	Emission services of environmental theme *e* by sector *j* in period *t*
$E_{e,h,t}^U$	‘Unabatable’ emissions of environmental theme *e* by consumer *h* in period *t*
$E_{e,h,t}^A$	‘Abatable’ emissions of environmental theme *e* by consumer *h* in period *t*

$A_{e,h,t}$	Investment in abatement of environmental theme *e* by consumer *h* in period *t* {note that $\sum_{e=1}^{E} A_{e,h,t} \equiv C_{A,h,t}$ }
$ES_{e,h,t}$	Emission services of environmental theme *e* by consumer *h* in period *t*
$W_{h,t}$	Welfare level of consumer *h* in period *t*
U_h	Total welfare of consumer *h* over all periods
$C_{j,h,t}$	Consumption of good *j* by consumer *h* in period *t*
$S_{h,t}$	Savings by consumer *h* in period *t*
$\overline{K_{h,t}}$	Capital supply by consumer *h* in period *t* (in 'flow' terms: capital services)
$p_{j,t}$	Equilibrium market price of good *j* (including A) in period *t*
$r_{K,t}$	Equilibrium market rental price of capital in period *t*
$p_{L,t}$	Equilibrium market wage rate in period *t*
$p_{e,t}$	Equilibrium market price of pollution permits for environmental theme *e* in period *t*
$p_{h,t}^{W}$	Equilibrium price of the 'utility good' (consumption bundle)
α_t	Endogenous change in existing tax rates to offset government income from sale of pollution permits in period *t*
α_t^{LS}	Endogenous change in lumpsum transfers to offset government income from sale of pollution permits in period *t*
$Taxrev_{h,}$	Endogenous tax revenues for consumer *h* in period *t* (only nonzero for Government)

The zero profit constraint for all modeled outputs requires that the after tax revenue for the output is equal to the total costs of all primary inputs, fixed intermediate inputs, energy sectors, abatement expenditure(Equation 2).

$$\begin{aligned}0 = \Pi_{j,t} = \quad & p_{j,t} \cdot Y_{j,t} - \sum_{jj=1}^{J} (1+\tau_{jj,j}) \cdot p_{jj,t} \cdot Y_{jj,j,t}^{ID} - (1+\tau_{A,j}) \cdot p_{A,t} \cdot Y_{A,j,t}^{ID} \\ & -(1+\tau_{L,j}) \cdot p_{L,t} \cdot L_{j,t} - (1+\tau_{K,j}) \cdot r_{K,t} \cdot K_{j,t} - \sum_{e=1}^{E} p_{e,t} \cdot E_{e,j,t} \end{aligned} \quad \text{for each } (j,t) \qquad (2)$$

Emission is treated here as a joint product along with other ordinary goods. Emission output is produced emission input less abatement. Thus, emission out is an unabated residual and magnitude of emission abated is dependent upon abatement activity. Pollution is generated through production activities as well as consumption activities such that emission services

Production functions are defined for goods and consumption agents, household and government(Equations 3 and 4).

$$ES_{e,j,t} = CES(E^{U}_{e,j,t}, CES(E^{A}_{e,j,t}, A_{e,j,t}; \sigma^{A}_{e,j}); \sigma^{ES}_{e,j}) \quad \text{for each } (e,j,t), \text{ with } \sigma^{ES}_{e,j} = 0 \tag{3}$$

$$ES_{e,h,t} = CES(E^{U}_{e,h,t}, CES(E^{A}_{e,h,t}, A_{e,h,t}; \sigma^{A}_{e,h}); \sigma^{ES}_{e,h}) \quad \text{for each } (e,h,t), \text{ with } \sigma^{ES}_{e,h} = 0 \tag{4}$$

In energy sector, autonomous technology in abatement is generally expected defined as a ratio of emission generated to goods produced, which can be called emission intensity. The model employs a parameter called autonomous pollution efficiency improvement (apei) assumed equal across all agents(Equations 5-8).

$$\left(E^{A}_{e,j,t+1} \middle/ Y_{j,t+1}\right) = (1 - apei_{e,t+1}) \cdot \left(E^{A}_{e,j,t} \middle/ Y_{j,t}\right) \quad \text{for each } (e,j,t) \tag{5}$$

$$\left(E^{U}_{e,j,t+1} \middle/ Y_{j,t+1}\right) = (1 - apei_{e,t+1}) \cdot \left(E^{U}_{e,j,t} \middle/ Y_{j,t}\right) \quad \text{for each } (e,j,t) \tag{6}$$

$$\left(E^{A}_{e,h,t+1} \middle/ W_{h,t+1}\right) = (1 - apei_{e,t+1}) \cdot \left(E^{A}_{e,h,t} \middle/ W_{h,t}\right) \quad \text{for each } (e,h,t) \tag{7}$$

$$\left(E^{U}_{e,h,t+1} \middle/ W_{h,t+1}\right) = (1 - apei_{e,t+1}) \cdot \left(E^{U}_{e,h,t} \middle/ W_{h,t}\right) \quad \text{for each } (e,h,t) \tag{8}$$

Emission service function takes a CES function with nesting CES to choose cost-effective way to decide how much to abate and how much to pay for emission. Again, in order to fulfill this intention, an environmental service function needs to be specified.

Consumers maximize their utility subject to budget constraints. Consumption utility is composed of market goods and environmental services here emission residual for individual period(Equation 9). The aggregate utility over whole period in concern is for also CES type with inter-temporal substitution elasticities(Equation 10). Budget constraints are concerned at income-expenditure balance for each period(Equation 11) and the expenditure-income for the total period is given in Equation 12.

$$W_{h,t} = CES(C_{1,h,t}, \dots, C_{J,h,t}, ES_{1,h,t}, \dots, ES_{E,h,t}; \sigma^{1}_{h}, \dots, \sigma^{V}_{h}) \quad \text{for each } (h,t) \tag{9}$$

$$U_{h} = CES(W_{h,1}, \dots, W_{h,T}; \sigma^{Util}_{h}) \quad \text{for each } h \tag{10}$$

$$p^{W}_{h,t} \cdot W_{h,t} = \sum_{j=1}^{J} (1+\tau_{j,h} \cdot \alpha_t) \cdot p_{j,t} \cdot C_{j,h,t} + p_{A,t} \cdot A_{e,h,t} + \sum_{e=1}^{E} p_{e,t} \cdot E_{e,h,t} \quad \text{for each } (h,t) \tag{11}$$

$$\sum_{t=1}^{T} p^{W}_{h,t} \cdot W_{h,t} + p_{K,T} \cdot K_{h,T} = (1-\tau_{L,h} \cdot \alpha_t) \cdot p_{K,1} \cdot \frac{\overline{K_{h,1}}}{(r+\delta)} + \sum_{t=1}^{T} (1-\tau_{L,h} \cdot \alpha_t) \cdot p_{L,t} \cdot \overline{L_{h,t}} + \sum_{t=1}^{T} \sum_{e=1}^{E} p_{e,t} \cdot \overline{E_{e,h,t}} - \sum_{t=1}^{T} \tau^{LS}_{h} \cdot \alpha^{LS}_{t} + \sum_{t=1}^{T} TaxRev_{h,t} \quad \text{for each } h \tag{12}$$

In this model, government budget is fixed regardless of revenue change due to sale of pollution permits. It is carried out by introduction of two instruments: α_t, Endogenous change in existing tax rates to offset government income from sale of pollution permits in period t and

α_t^{LS} , Endogenous change in lumpsum transfers to offset government income from sale of pollution permits in period t.

The capital stock in period t equals to the capital stock at the start of the previous period less deprecation plus investment in the previous period(Equation 13). The terminal condition on capital follows a transversality condition(Equation 14). Changes in population are treated exogenous(Equation 15).

$$p_{K,t} = (1-\delta_K) p_{K,t+1} + r_{K,t} \quad \text{for each } t \tag{13}$$

$$\sum_{h=1}^{H} K_{h,T} = (1+g_L) \cdot \sum_{h=1}^{H} K_{h,T-1} \tag{14}$$

$$\overline{L_{h,t+1}} = \overline{L_{h,t}} \cdot (1+g_L) \quad \text{for each } (h,t) \tag{15}$$

Government expenditure is defined that changes in government expenditure for each period is identical to that of private household(Equation 16).

$$\frac{W_{'government',t}}{W_{'government',0}} = \frac{\sum_{\substack{h=1 \\ h \neq 'gov.'}}^{H} W_{'privatehouseholds',t}}{\sum_{\substack{h=1 \\ h \neq 'gov.'}}^{H} W_{'privatehouseholds',0}} \quad \text{determines } \alpha_t \text{ and } \alpha_t^{LS} \tag{16}$$

Conventional approach is applied to the market clearance rules for goods, capital, labor, pollution permits, and savings-investment (Equations 17-21).

$$Y_{j,t} = \sum_{jj=1}^{J} Y_{j,jj,t}^{ID} + Y_{j,A,t}^{ID} + I_{j,t} + \sum_{h=1}^{H} C_{j,h,t} \quad \text{for each } (j,t)\text{; determines } p_{j,t} \tag{17}$$

$$\sum_{j=1}^{J} K_{j,t} + K_{A,t} = \sum_{h=1}^{H} \overline{K_{h,t}} \quad \text{for each } t\text{; determines } r_{K,t} \tag{18}$$

$$\sum_{j=1}^{J} L_{j,t} + L_{A,t} = \sum_{h=1}^{H} \overline{L_{h,t}} \quad \text{for each } t\text{; determines } p_{L,t} \tag{19}$$

$$\sum_{j=1}^{J} E_{e,j,t}^{U} + \sum_{j=1}^{J} E_{e,j,t}^{A} + E_{e,A,t}^{U} + E_{e,A,t}^{A} + \sum_{h=1}^{H} E_{e,h,t}^{U} + \sum_{h=1}^{H} E_{e,h,t}^{A} = \sum_{h=1}^{H} \overline{E_{e,h,t}} \quad \text{for each } (e,t) \tag{20}$$

determines $p_{e,t}$.

$$\sum_{h=1}^{H} S_{h,t} = \sum_{j=1}^{J} p_{j,t} \cdot I_{j,t} \quad \text{for each } t \tag{21}$$

3.5 The policy alternatives

The models as specified above are employed to analyse greenhouse gas mitigation portfolios in terms of timing and magnitude: It compares economic consequences of GHG reduction schemes with changes in "when and how much". These scenarios are not based on actual climate change policy in Korea. They are just numerical example, chosen to give insight into the dynamic workings of the model specifications. Note that under simulation approach like current study, more attention is paid into results of individual scenario, rather than making comparison and giving priority among policies. Each scenario is viewed separate in policy analysis.

Two types of scenarios are selected for the simulations. The first type is to follow United Nations Framework of Climate Change Convention (UNFCCC) commitment period schemes, whose is five year term starting from years 2008 through 2022. We have set arbitrary five mitigation portfolios. The common structure of the schemes are to keep business-as-usual (BAU) emission until starting the commitment period then reduce certain percentage of BAU level, keep the fixed level of 2000 after the end of commitment.

Scenario *8-12_30* : Keep BAU level for 2000-2007, then 30% reduction of BAU for 2008-2012 and fixed level of 2000 after 2012.

Scenario *13-17_30* : Keep BAU level for 2000-2012, then 30% reduction of BAU for 2013-2017 and fixed level of 2000 after 2017.

Scenario *18-22_30* : Keep BAU level for 2000-2017, then 30% reduction of BAU for 2018-2022 and fixed level of 2000 after 2022.

Scenario *13-17_40* : Keep BAU level for 2000-2012, then 40% reduction of BAU for 2013-2017 and fixed level of 2000 after 2017.

Scenario *18-22_50* : Keep BAU level for 2000-2017, then 30% reduction of BAU for 2018-2022 and fixed level of 2000 after 2022.

Figure 2 illustrates reduction path required for the first type during whole period 2000-2100 and figure 3 for 2000-2030. Since from 2023 through 2100 the emission level is fixed at 2000 level, the percentage reduction compared to BAU is increasing up to almost 100 percent in 100 years from 2000.

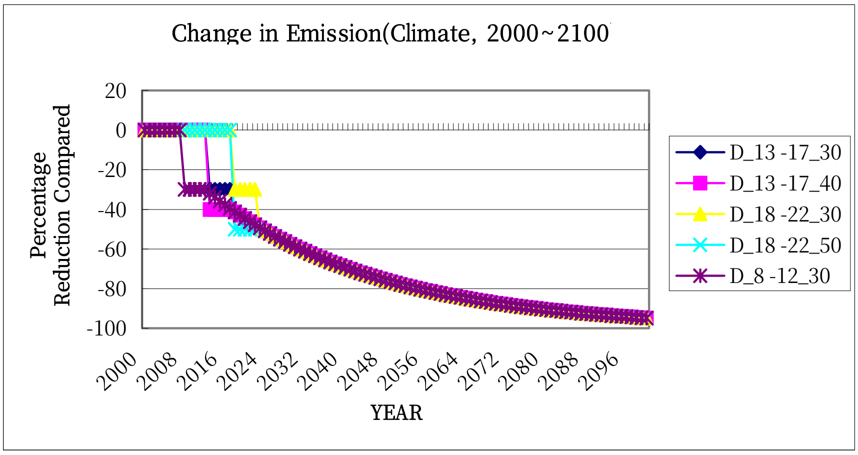


Figure 2. Required emission reductions in the simulations- The first type(2000-2100)

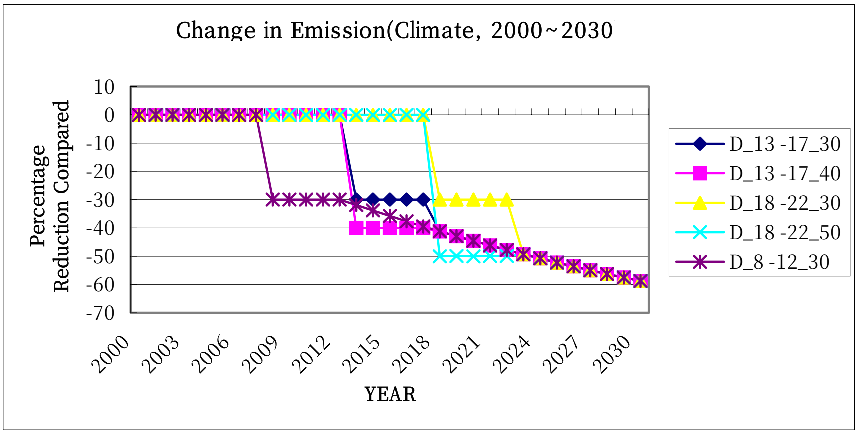


Figure 3. Required emission reductions in the simulations- The first type(2000-2030)

While the above five scenarios are simulated just on differentiating timing and amounts of emission reduction for each commitment period, the second type of reduction plans assume same period and same amount in GHG reduction options then compare results of changes according to the way that the society takes action in order to fulfil the commitment. The period in concern is for 10 years 2013-2022, which covers the 2^{nd} and 3^{rd} commitment period. The amount to be allowed to emit the pollutions is 11 units during 10 years. Unlike the first mitigation type, a society is free to allocate mitigation timing and amounts as long as 11 units emitted during 10 years. It assumed that all three schemes are ruled by keeping BAU level for 2000-2012 and after the given commitment period 80 percentage of emission compared to 2000 is enforced for the remaining periods.

The first scenario adopted here is to keep BAU for 2000-2012 then shares the emission permits even during the 2013-2022, and fixed at 80 percentage of 2000 level from 2023. It is called ‘equal strategy’.

The second one is to emit pollution in linearly decreasing manner so as to secure given 11 unit of emission. It is called ‘smooth strategy.’

The third one is to apply to keep 2012 level until 2017 then emission is linearly decreasing. It is called 'sudden strategy.'

Figures 4 and 5 illustrate reduction paths for 2000-2100 and 2000-2030, respectively.

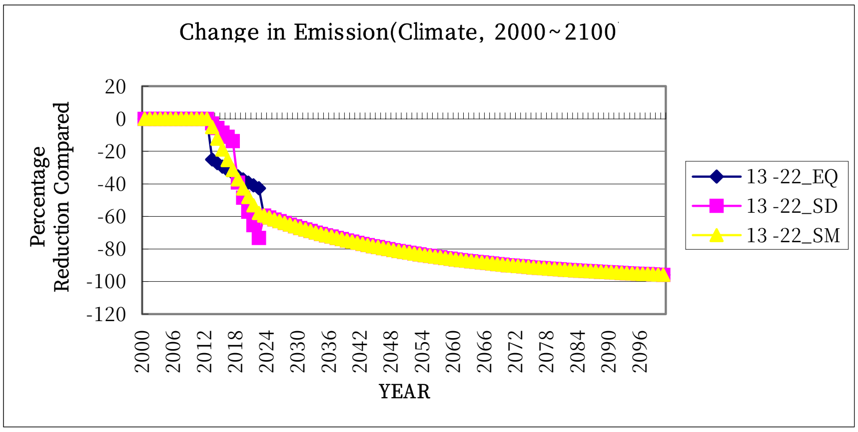
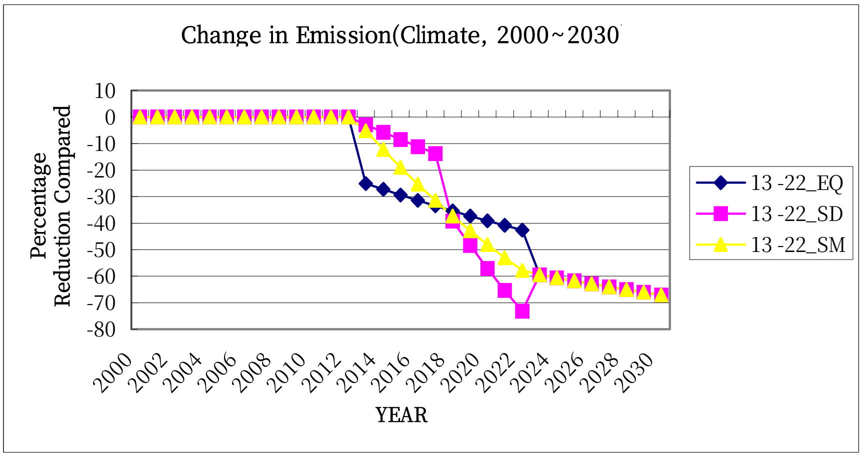


Figure 4. Required emission reductions in the simulations-The second type(2000-2100)

Figure 5. Required emission reductions in the simulations- The second type(2000-2030)



IV. RESULTS

The proto-type model here assumes forward-looking behaviour of the consumers: households maximise the total present value of all current and future consumption. Consequently, the model is solved for all periods together and the growth path in the periods between the initial steady-state equilibrium and the new equilibrium is endogenously determined.

The GDP changes in the first types of simulation give a good example that a society's economic decision is based on the future foresight (figures 6 and 7). Since the society knows the information that in the future there will be enforced reduction of pollution emission implying increase in the prices, they consume more now before the prices go up. Then it results in GDP increases until the mandatory reduction takes place. It applies to all five cases. What the society consumes more compared to BAU means the future consumption of society is borrowed. Note that in the forward-looking model economic resources are free to move between the whole periods. The primary reason for the increase in the present GDP is of course relevant to a discounting rate. From sustainability perspective, it can be interpreted that the consumption of current generation is closely related to sacrifice of the future generation. It is about middle of the period around after 2050 that the GDP keeps falling down and turn upward (figure 6). With focusing on 2000-2030, figure 7 zooms in the trends of the GDPs.

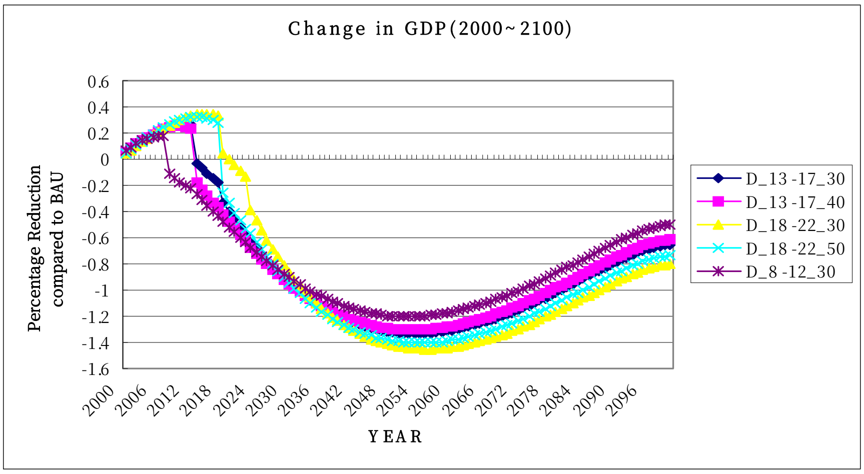


Figure 6. Results for GDP changes in mitigation schemes- The first type(2000-2100)

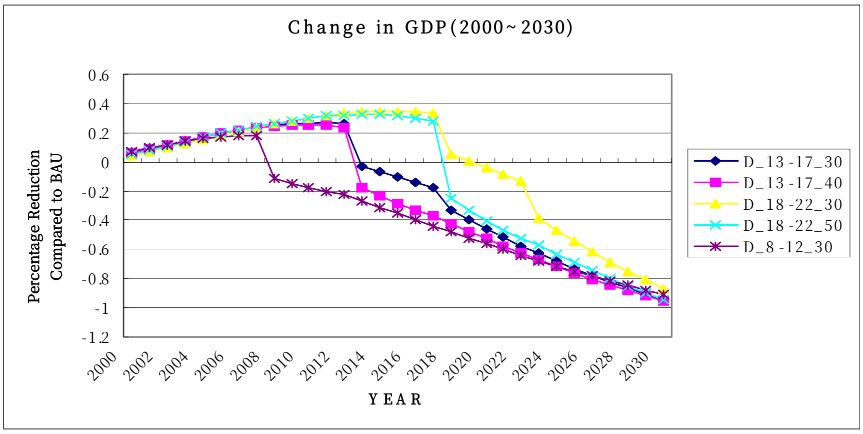


Figure 7. Results for GDP changes in mitigation schemes-The first type(2000-2030)

Compared to a recursive-dynamic model, it is expected that the forward-looking behaviour will lead to a more ‘smooth’ development of economic growth and utility, as consumers anticipate on reductions in the number of pollution permits allowed in later periods (for empirical results see Dellink, 2000).

As previously described, the second type of policy scenarios assumes that the amounts of emission for all three cases are identical. With this framework, main purpose of the scenarios adopted here is to compare consequences of mitigation strategies relevant to the way of reduction; equal reduction, smooth reduction, and sudden reduction. Figures 8 and 9 show the GDP changes for 2000-2100 and 2000-2030, respectively. The figures indicate that a society’s GDP in all cases increases until the reduction starts to be effective then falls when reduction takes place. Of particular interest is to compare GDP change paths. Until the middle period year 2019, the magnitude of GDP decrease is larger in order of “equal strategy”, “smooth strategy”, and “sudden strategy.” After then, the orders are reversed by “sudden strategy”, “smooth strategy”, and “equal strategy.” The paths of three cases are similar at those of reductions (see Figure 8, 9), since GDP is closely related with reduction policy implemented.

The economic interpretation is that consumers know in advance that environmental policy will be stricter in a certain time, and they react by increasing current consumption in the early periods. Due to the time preference, this has a relatively large positive influence on total economic utility (which is optimised in this model).

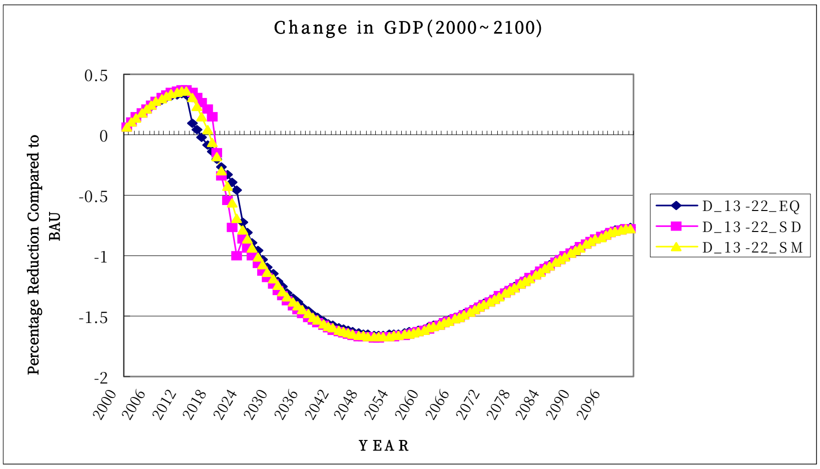
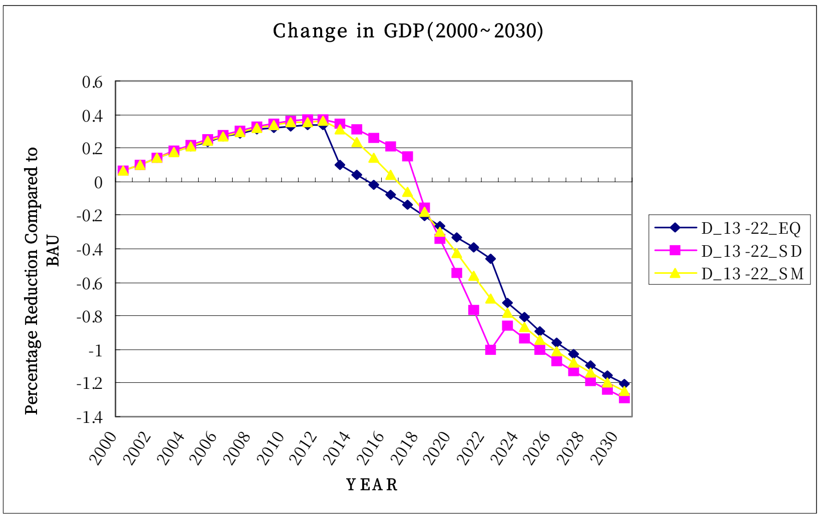


Figure 8. Results for GDP changes in mitigation schemes-The second type(2000-2100)

Figure 9. Results for GDP changes in mitigation schemes-The second type(2000-2030)



Naturally, this can only be achieved by decreasing their savings and hence decreasing investments. This is reflected by a lower interest rate in the early periods. Then, immediately following the high consumption levels in the early periods, the savings/investment level increases rapidly, accompanied by lower consumption levels. These high investment levels are needed to assure long-term growth of the economy and are induced by the low price of capital (the low interest rate). The combined effects of the changes in consumption and investment levels govern the changes in GDP.

Following general analysis of the model results, we focus on what has driven such changes with a focus on linkages of GDP, prices, outputs, and others. First, of special interest is the relation between output changes. The simulation results reveal that due to delimit to emission, dirty energy sector Y2 shares the largest burden as expected. The outputs decrease for a whole period. While due to infinite substitution with dirty energy, clean energy Y3 increases for a while then decreases also but in less degree than dirty energy sector. The reason for the output contract is responsible of decrease in GDP. Among others, decrease of Y1 and consumption sectors have caused both energy sectors to reduce outputs. Abatement sector YA may include direct and indirect activities as long as they are related at emission reduction. They, for instance, are to cover pollution mitigation equipment and energy efficiency devices. In this model, no taxes on labour and capital utilized for the sector, this is a strong assumption. The underlying interpretation for this is the environmental industry sector is free of government fiscal policy: No taxes are imposed on the sector. In dynamic sense, this assumption is beneficial or not to the sector. When government reaps more revenue from selling the pollution permits, the tax rates on the primary inputs labour and capital are automatically reduced. Note that in this model, we assume endogenous tax rate. That is, when tax rate goes down implying decrease in production cost, it means relative costs with the abatement sector are reduced, *in vice versa*.

The particular point of the model is the introduction of pollution permits and abatement sector. With this structure, polluting agents here Y1, Y2 and private household (see Tables 6 and 7) choose whether to pay pollution tax or spend resources on abatement in a way the society is to meet a target designated. Keep in mind that the allocation of reduction is decided through least cost effective way from a society perspective. As we are interest in individual sector dimension, we might put constraints on the sector in concern, then it, however, does not guarantee efficient mitigation points.

In this model, abatement prices and pollution rates indicate relative prices in each period divided by private welfare index (see Appendix II: GAMS code for details). The results show that abatement cost is decreasing while endogenous pollution tax is increasing (figures 10-13). No changes in pollution taxes take place during BAU and the rates go up suddenly when reduction options take place and keeps increasing.

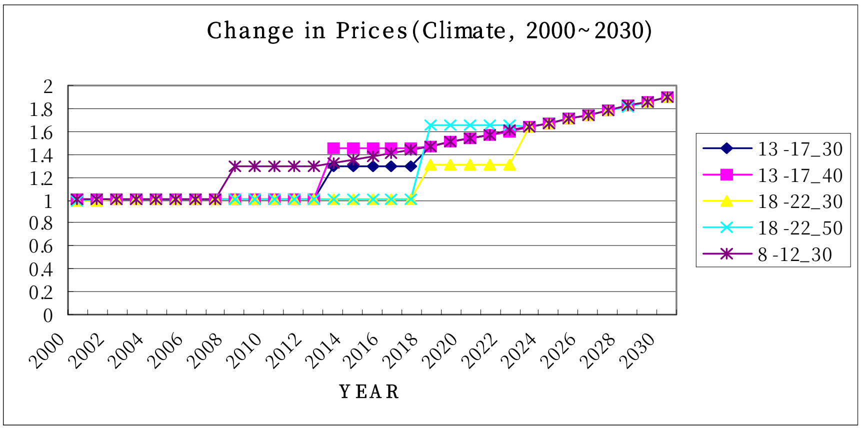


Figure 10. Pollution tax rate changes-The first type(2000-2030)

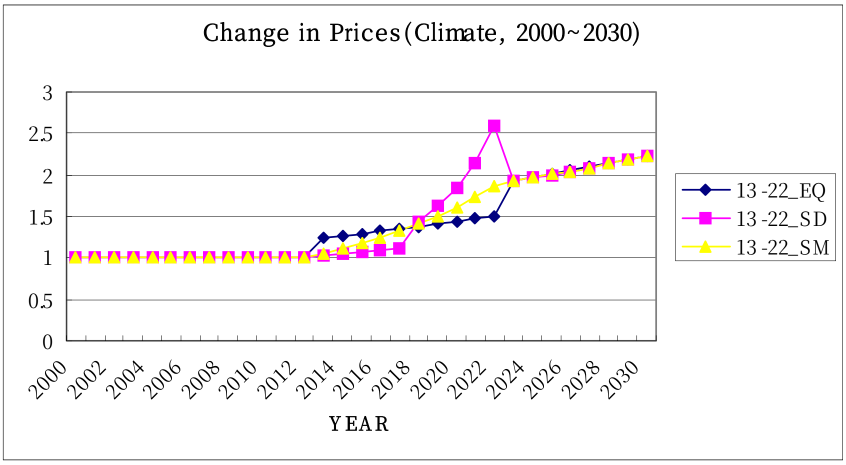


Figure 11. Pollution tax rate changes-The second type(2000-2030)

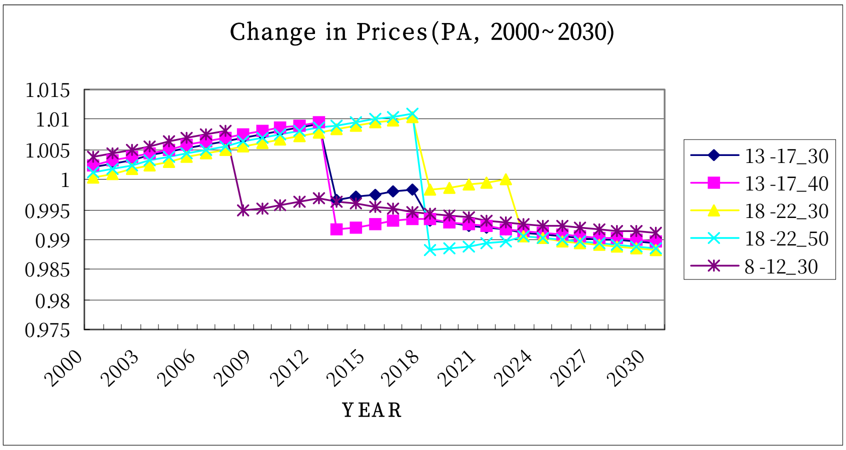


Figure 12. Changes in unit abatement cost- The first type (2000-2030)

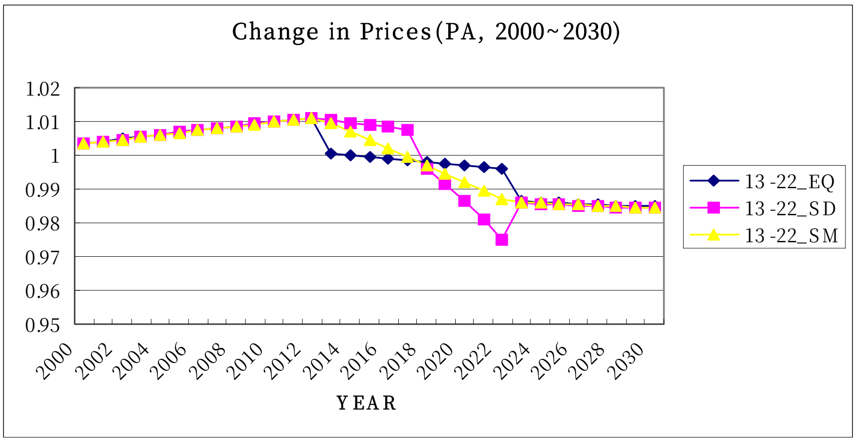


Figure 13. Changes in unit abatement cost- The second type (2000-2030)

The abatement cost increases until the beginning of the reduction then goes down in a large degree and recovers the price increase very slowly and starts to decrease. In this model total output of pollution permit “goods” is set exogenously according to a policy goal such that relative prices of permit which is equivalent to pollution tax rates, goes up when supply of permits decrease. Keep in mind that BAU implies that the economy is in equilibrium. The prices suddenly go up with implementation of reduction policy and measures and shows proportional paths to reduction schemes. The sudden change is related to the following reasons. First, no banking system is assumed in this model. If we introduce the banking system here, the degree of price changes might be different under the current forward-looking framework. Second, as emission levels are capped to 2000 level after the policy period, the amounts of pollution that a society has to reduce keeps increasing over time. The BAU assumes emission increases following economic growth less autonomous pollution efficiency improvement.

Welfare measurement

To analyse the economic impacts of various policies, better performance indicators than GDP levels are wanted. Welfare changes are an obvious candidate for performance analysis: if total welfare in the economy improves, the policy is socially beneficial. The changes in welfare can in practice not be measured directly, as utility cannot be measured (or at least not in a cardinal sense). Therefore, approximations of welfare changes like Marshallian consumer surplus are often used to evaluate policies (see Varian, 1992); these approximating indicators contain both an income and substitution effect of the policy, while the exact welfare change is given only by the substitution effect.

In a computable general equilibrium framework, using the specification of the utility function, some exact measures of welfare changes can be calculated (because the characteristics of both the old and new equilibria can exactly be calculated). The mostly used indicator for welfare changes is the sum (over consumers) of the present values of equivalent variations (see for example Shoven and Whalley, 1992). The Equivalent Variation (EV) of a policy is defined as the change in income, with prices remaining at their old levels, that would be equivalent to the proposed price change, in terms of its welfare impact on the consumer. In formula, for one consumer and one good, the EV can be written as $EV = (Q^{new} - Q^{old}) \cdot P^{old}$, where Q^{new} and Q^{old} are the new and old quantities (or real income), respectively, and P^{old} is the old equilibrium price.

An alternative to the EV is provided by the Compensation Variation (CV) measure. The CV of a change in a price measures the change in income at the new level of prices that would keep the consumer at the old level of welfare (in other words: the income change that would compensate for the price change). In formula, again for one consumer and one good, and using similar notation: $CV = (Q^{new} - Q^{old}) \cdot P^{new}$. Both concepts originated in Hicks (1939) and they both give an exact measure of the welfare change. Still, they will almost always differ, as the prices used in the calculations differ (this is even more prominent in a multi-goods case). There is no objective preference for either of both measures.

In the multi-sectoral dynamic CGE model, these concepts of Equivalent Variation and Compensating Variation can both be calculated. The model specification uses a fictitious production sector (the Welfare producer) that produces ‘utility goods’ using the consumption goods as inputs. The consumers then demand not the consumption goods themselves, but rather the utility good. Note that the utility function in effect becomes a production function; the utility function actually used in the model is confined to the consumption of the utility good. This set-up has no impacts on the model results, as it is perfectly similar to a set-up where consumer directly demand consumption goods. The main advantage of the set-up is that real welfare changes of the consumer can directly be read from the model as the real changes in the welfare producer. In technical terms: the left-hand side of the income balance equation is part of the welfare production sector, whose income is made up of selling the ‘utility goods’, while the right-hand side of the income balance equation belongs to the consumer, who spends it on buying utility goods. The EV and CV of the policies can be derived directly from the change in activity of the welfare producer, using the old-equilibrium and new-equilibrium price of the ‘utility goods’ as the price index.

In the analyses above, damages by poor environmental quality on the economic system and on welfare are not taken into account. The environmental sub-model is purely represented by the pollution levels and abatement activities. The absence of environmental quality in the utility function has a major consequence: the utility function is no longer a good measure of welfare. The welfare measurement is confined to the economic sources of welfare: consumption. However, in reality, welfare also depends on other issues, like environmental quality. Environmental policy will in general lead to a lower level of consumption and hence a downward pressure on welfare. This represents the economic costs of environmental policy. On the other hand, the impacts of environmental policy on environmental quality will be positive. This higher environmental quality is not captured in the proto-type models, and the ‘environmental sources’ of welfare cannot be taken into account as this would entail a valuation of environmental quality in money terms. Such valuations are not broadly available.

Instead of confining the analysis to the economic sources of welfare, one could attempt to augment the models to include environmental welfare effects. These environmental welfare effects should at least include a damage function (negative impacts of low environmental quality on the availability of economic goods) and the amenity value of environmental quality (high environmental quality induces welfare *per se*, even without the use of the environment in the economic process).

In an empirical study, it would seem too ambitious to include environmental damages and the amenity value of environmental quality. However, in the proto-type models it is possible to add the most relevant theoretical augmentations needed. This is however beyond the scope of the current paper.

Consequently, the models described above are incapable of studying true welfare effects, and must be confined to the economic indicators of utility change, the Equivalent Variation and Compensating Variation, based on the development household income. The results are presented in Table 9.

Table 9. Policy evaluation criteria

	EV_TOTAL	D_EMIS-30	D_EMIS
First Type			
8-12_30	-0.476	18.403	524.906
13-17_30	-0.439	15.927	522.431
18-22_30	-0.394	12.261	518.765
13-17_40	-0.451	16.707	523.211
18-22_50	-0.417	14.069	520.573
Second Type			
13-22_EQ	-0.498	16.985	537.489
13-22_SM	-0.498	16.985	537.489
13-22_SD	-0.502	16.985	537.489

The EV_TOTAL indicates Equivalent Variation summed over whole period 2000-2100(see for detailed definition, GAMS code in appendix). Comparing scenarios 8-12_30 (reduction takes place 2008-2012 with 30% BAU) with 13-17_40 (2013-2017 with 40% BAU) or 18-22_50 (2018-2022 with 50% BAU) are typical subject of simulation. The second (D_EMIS-30: reduction total 2000-2030) and third terms (D_EMIS: reduction total 2000-2100) indicate amounts of emission reduced by implementing policy alternatives.

The second type reveals interesting points in that reduction strategy with “equal” and “smooth” fashion reveals the same results but both cases bring about less cost “sudden” way. Here, the reduction amounts for the three cases are same by definition: we assumed 11 units of emission is allowed during 2013-2022. More in-depth analysis will be required to give explanations on the results.

V. Conclusion

This study addresses on interactions of economy and environment in a perfect foresight dynamic computable (or applied) general equilibrium (CGE) with a focus on greenhouse gas (GHG) mitigation strategy in Korea. The primary goal of this study is to evaluate greenhouse gas mitigation portfolios of changes in timing and magnitude with a particular focus on developing a methodology to integrate the bottom-up information on technical measures to reduce pollution (the characteristics of the abatement techniques) into a top-down multi-sectoral computable general equilibrium framework. To this end, a dynamic computable general equilibrium model is constructed including pollution and abatement as a proto-type of the model.

The CGE model is kept relatively simple, to allow maximum focus on the dynamic interactions between economy and environment. The model describes a national economy with three ordinary production sectors, one abatement sector and two consumer groups (in the current model version, there is no international trade). The two primary production factors are capital and labour.

Pollution is controlled by the government through a system of tradable ‘pollution rights’, which the producers and consumers can buy from the government. Producers and consumers have the endogenous choice between paying for their pollution by buying pollution rights or spending resources on pollution abatement activity, and will always choose the least-cost of the two.

The abatement cost curves, which describe the marginal abatement costs, are translated for each producer / consumer and environmental theme into an ‘iso-output curve’ of pollution and abatement, *i.e.* the abatement possibilities are presented as a function of pollution (a downward sloping curve). Then, a constant elasticity substitution (CES) function is calibrated to best fit the iso-output curve, and the CES-elasticity thus estimated describes the sector- and environmental theme-specific possibilities to substitute between pollution and abatement.

It should be noted that the model provides insight into the least costs of achieving a predetermined environmental policy objective, but cannot calculate the optimal rate of pollution control, as the damages caused by pollution are not taken into account.

A conclusion that can be drawn from the analysis is that the dynamic specification of the model is highly relevant. Not only are the numerical results influenced significantly by the model specification, the main interactions between economy and ecology can also be better specified in a dynamic context. Even with a simple specification of the abatement sector, there are dynamic interactions that influence the costs of abatement for the polluters, the price of the pollution permits and the economic impacts of the environmental policy.

The primary findings from the numerical examples are as follows:

The gross domestic product (GDP) changes in the first types of simulation is consistent with a foreword looking framework adopted for the model, implying that a society’s economic decision is based on the future foresight. Since the society knows the information that in the future there will be enforced reduction of pollution emission, they consume more now before the prices go up, resulting in GDP increases until the mandatory reduction takes place.

For the second type of policy scenarios assuming the amounts of emission for all three cases are identical, the results indicate that a society’s GDPs in all cases increase until the reduction starts to be effective then it falls when reduction takes place. Of particular interest is to compare GDP change paths. Until the middle period year 2019, the magnitude of GDP falls are larger in order of “equal strategy”, “smooth strategy”, and “sudden strategy.” After then, the orders are reversed by “sudden strategy”, “smooth strategy”, and “equal strategy.” The paths of three cases are similar at those of reductions, since GDP is closely related with reduction policy implemented. The economic interpretation is that consumers know that environmental policy will be stricter in a particular time, and they react by increasing current consumption in the early periods. Due to the time preference, this has a relatively large positive influence on total economic utility which is optimised in this model.

The simulation results reveal that due to delimit to emission, dirty energy sector Y2 shares the largest burden as expected. The outputs decrease for a whole period. While due to infinite substitution with dirty energy, output of clean energy sector Y3 increases for a while then decreases also but in less degree than dirty energy sector. The reason for the output contract is responsible for decrease in GDP. Among others, the decreases of Y1 and consumption sectors have caused both energy sectors to reduce the outputs. Abatement sector YA may include direct and indirect activities as long as they are related at emission reduction. They, for instance, are to cover pollution mitigation equipment and energy efficiency devices. In this model, no taxes on labour and capital utilized for the sector, this is a strong assumption. The underlying interpretation for this is the environmental industry sector is free of government fiscal policy: No taxes are imposed on the sector. In dynamic sense, this assumption is beneficial or not to the sector. When government reaps more revenue from selling the pollution permits, the tax rates on the primary inputs labour and capital are automatically reduced. Note that in this model, we assume endogenous tax rate. That is, when tax rate goes down implying decrease in production cost, it means relative costs with the abatement sector are reduced, *in vice versa*.

The particular point of the model is the introduction of pollution permits and abatement sector. With this structure, polluting agents here Y1, Y2 and private household choose whether to pay pollution tax or spend resources on abatement in a way the society is to meet a target predetermined. In this model, the abatement cost is decreasing while endogenous pollution tax is increasing. No changes in pollution taxes during business-as-usual (BAU) and the rates go up suddenly when reduction options take place and keeps increasing. The abatement cost increases until the beginning of the reduction then goes down in a large degree and recovers the prices increase very slowly and starts decreases. In this model total output of pollution permit “goods” is set exogenously according to a policy goal such that relative prices of permit which is equivalent to pollution tax rates, goes up when supply of permits decrease. The prices suddenly go up with implementation of reduction and shows proportional paths to reduction schemes. The sudden change is related to first, no banking system is assumed in this model and second, as emission levels are capped to 2000 level after the policy period, the amounts of pollution that a society has to reduce keeps increasing over time.

The magnitude of equivalent variations (EVs) for the second type indicates that reduction strategy with equal and smooth fashion reveals the same results but both cases bring about less cost “sudden” way. Here, the reduction amounts for the three cases are same by definition: we assumed 11 units of emission is allowed during 2013-2022. More in-depth analysis will be required to give explanations on the results.

For a policy design associated with GHG reduction plan, the problem are narrow downed “when,” “how much”, and “how”. All three factors are interrelated in policy decision process. However, it can be said that “when and how much “ to reduce is a main concern in international perspective, while “how” to comply the given amounts of reduction in a certain timing way is more pertinent to domestic interest.

This study is to give answers to three policy design criteria in a simulation basis. The eight scenarios employed here shed an informative light on policy design. As CGE is for in nature quantitative analysis, the results give specific numbers associated with policies implemented with keeping economic theory. The comparison of policy alternatives is possible through numerical iteration in a way to give best results for policy evaluation criteria such as EV. Based on the study results, we assert that sudden mitigation of GHGs brings in more cost to the society: it is of "how" issue. In climate change issue, it is very difficult to find out best solution to "how much and when," let alone considering three factors simultaneously. There exist strong assumptions and uncertainties required in order to set the model framework: Main components to be considered include, among others, technology change, multi-country behaviour, and emission trading and the prices. Therefore, it is in more reality to set-up policy scenarios based on certain criteria such as political feasibility, technical feasibility, international negotiation, and so forth. Then the model simulates with the given sets of policy scenarios so as to enable to compare the results and find the best policy among the scenarios.

The model presented here is a proto-type such that for the empirical analysis, some works are required. Introduction of environmental components is one of them. In the present model, only amounts of emission linked with economic activities are represented. Biophysical relationship of emission changes and the corresponding impact on the economic sector is not specified in this model. From a perspective of sustainability issue, the explicit representation of physical environment is of special importance. As long as the current model is to keep CGE framework, it seems expected to make a choice of trade-off: Whether to keep perfect foresight structure in disaggregated micro-sectors or to simplify economic sectors with introduction of environmental module. As a background knowledge and process to model an interaction of economy and environment, of particular points are how to integrate flow-based emission into stock-based framework vis-à-vis environmental impact of short term and local consequences versus long term and global ones. In economic sectors, it seems not much free from having strong assumptions adopted in the proto-type model more realistic. Some critical points in concern are economic and population growth rate. Currently the model assumes economic growth rates are identical among all economic sectors for the whole period. Sector-specific and period specific growth assumption would bring out the model results more acceptable. Population growth rate which is implicitly liked with productivity growth need to be based on their own figures. Specific structure of the model will be dependent data availability and possibility of obtaining model solutions.

In parallel to constructing a model, colleting data for the model is big constraint to be overcome. For Korea study, official input-output data base of 1995 which was published by The Bank of Korea will be utilized and other data such as elasticity values and capital stock will come from the previous studies. Forecasting data on economic growth will be mainly dependent on studies by Korea Development Institute. Sensitivity analysis will be carried out with some significant input values.

Making policy scenarios in context of climate change issue is of another importance for the study. Because this study takes simulation approach, designing realistic and feasible scenarios are critical and starting line for the study. Taking among others, economic, political, social, international circumstances into consideration would come to secure the policy chosen more socially acceptable.

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http://www.stanford.edu/group/MERGE/code.htm

http://www.econ.yale.edu/~nordhaus/homepage/dicemodels.htm

APPENDIX I. MATHEMATICAL REPRESENTATION OF THE FORWARD-LOOKING PROTO-TYPE MODEL
-- GENERAL FORMULATION

Producers

Goods production functions:

$$Y_{j,t} = CES(Y^{ID}_{j,1,t},...,Y^{ID}_{j,J,t}, K_{j,t}, L_{j,t}, ES_{1,j,t},..., ES_{E,j,t}; \sigma^1_j,...,\sigma^V_j) \quad \text{for each } (j,t)^9 \quad (22)$$

Zero profit conditions:

$$0 = \Pi_{j,t} = \quad p_{j,t}\cdot Y_{j,t} - \sum_{jj=1}^{J}(1+\tau_{jj,j})\cdot p_{jj,t}\cdot Y^{ID}_{jj,j,t} - (1+\tau_{A,j})\cdot p_{A,t}\cdot Y^{ID}_{A,j,t} - (1+\tau_{L,j})\cdot p_{L,t}\cdot L_{j,t} - (1+\tau_{K,j})\cdot r_{K,t}\cdot K_{j,t} - \sum_{e=1}^{E} p_{e,t}\cdot E_{e,j,t} \quad \text{for each } (j,t) \quad (23)$$

Environmental services 'production' functions:

$$ES_{e,j,t} = CES(E^U_{e,j,t}, CES(E^A_{e,j,t}, A_{e,j,t}; \sigma^A_{e,j}); \sigma^{ES}_{e,j}) \quad \text{for each } (e,j,t), \text{ with } \sigma^{ES}_{e,j} = 0 \quad (24)$$

$$ES_{e,h,t} = CES(E^U_{e,h,t}, CES(E^A_{e,h,t}, A_{e,h,t}; \sigma^A_{e,h}); \sigma^{ES}_{e,h}) \quad \text{for each } (e,h,t), \text{ with } \sigma^{ES}_{e,h} = 0 \quad (25)$$

$$\left(E^A_{e,j,t+1}\big/Y_{j,t+1}\right) = (1-apei_{e,t+1})\cdot\left(E^A_{e,j,t}\big/Y_{j,t}\right) \quad \text{for each } (e,j,t) \quad (26)$$

$$\left(E^U_{e,j,t+1}\big/Y_{j,t+1}\right) = (1-apei_{e,t+1})\cdot\left(E^U_{e,j,t}\big/Y_{j,t}\right) \quad \text{for each } (e,j,t) \quad (27)$$

$$\left(E^A_{e,h,t+1}\big/W_{h,t+1}\right) = (1-apei_{e,t+1})\cdot\left(E^A_{e,h,t}\big/W_{h,t}\right) \quad \text{for each } (e,h,t) \quad (28)$$

$$\left(E^U_{e,h,t+1}\big/W_{h,t+1}\right) = (1-apei_{e,t+1})\cdot\left(E^U_{e,h,t}\big/W_{h,t}\right) \quad \text{for each } (e,h,t) \quad (29)$$

---

[9] As usual, '…' is used to indicate all items within the range as given by the items listed before and after.

A general nested CES production function with for example 4 inputs and 2 levels can be written as:

$Y = (a_1X_1^{\rho} + a_2X_2^{\rho} + a_{34}X_{34}^{\rho})^{1/\rho}$, and $X_{34} = (a_3X_3^{\psi} + a_4X_4^{\psi})^{1/\psi}$ for some parameters a_1, a_2, a_{34}, a_3, a_4, where $\rho=(\sigma-1)/\sigma$ and $\psi=(\varphi-1)/\varphi$. A convenient notation is: Y = CES(X_1, X_2, X_{34}; σ); X_{34} = CES(X_3, X_4; φ).

Consumers

Utility functions:

$$W_{h,t} = CES(C_{1,h,t},...,C_{J,h,t}, ES_{1,h,t},..., ES_{E,h,t}; \sigma_h^1,...,\sigma_h^V) \quad \text{for each } (h,t) \quad (30)$$

$$U_h = CES(W_{h,1},...,W_{h,T}; \sigma_h^{Util}) \quad \text{for each } h \quad (31)$$

Income balances – expenditures side:

$$p^W_{h,t} \cdot W_{h,t} = \sum_{j=1}^{J} (1+\tau_{j,h} \cdot \alpha_t) \cdot p_{j,t} \cdot C_{j,h,t} + p_{A,t} \cdot A_{e,h,t} + \sum_{e=1}^{E} p_{e,t} \cdot E_{e,h,t} \quad \text{for each } (h,t) \quad (32)$$

Income balances – income side:

$$\sum_{t=1}^{T} p^W_{h,t} \cdot W_{h,t} + p_{K,T} \cdot K_{h,T} = (1-\tau_{L,h} \cdot \alpha_t) \cdot p_{K,1} \cdot \frac{\overline{K_{h,1}}}{(r+\delta)} + \sum_{t=1}^{T} (1-\tau_{L,h} \cdot \alpha_t) \cdot p_{L,t} \cdot \overline{L_{h,t}} + \sum_{t=1}^{T}\sum_{e=1}^{E} p_{e,t} \cdot \overline{E_{e,h,t}} - \sum_{t=1}^{T} \tau_h^{LS} \cdot \alpha_t^{LS} + \sum_{t=1}^{T} TaxRev_{h,t} \quad \text{for each } h \quad (33)$$

Capital accumulation (as the volume of capital is free, the equation is written for the associated prices):

$$p_{K,t} = (1-\delta_K) p_{K,t+1} + r_{K,t} \quad \text{for each } t \quad (34)$$

Terminal condition on capital (transversality condition):

$$\sum_{h=1}^{H} K_{h,T} = (1+g_L) \cdot \sum_{h=1}^{H} K_{h,T-1} \quad (35)$$

Demographic developments:

$$\overline{L_{h,t+1}} = \overline{L_{h,t}} \cdot (1+g_L) \quad \text{for each } (h,t) \quad (36)$$

Rule for development in government expenditures:

$$\frac{W_{'government',t}}{W_{'government',0}} = \frac{\sum_{\substack{h=1 \\ h \neq 'gov.'}}^{H} W_{'privatehouseholds',t}}{\sum_{\substack{h=1 \\ h \neq 'gov.'}}^{H} W_{'privatehouseholds',0}} \quad \text{determines } \alpha_t \text{ and } \alpha_t^{LS} \quad (37)$$

Market clearance

Goods markets balance:

$$Y_{j,t} = \sum_{jj=1}^{J} Y^{ID}_{j,jj,t} + Y^{ID}_{j,A,t} + I_{j,t} + \sum_{h=1}^{H} C_{j,h,t} \quad \text{for each } (j,t)\text{; determines } p_{j,t} \quad (38)$$

Capital markets balance:

$$\sum_{j=1}^{J} K_{j,t} + K_{A,t} = \sum_{h=1}^{H} \overline{K_{h,t}} \text{ for each } t\text{; determines } r_{K,t} \tag{39}$$

Labour markets balance:

$$\sum_{j=1}^{J} L_{j,t} + L_{A,t} = \sum_{h=1}^{H} \overline{L_{h,t}} \text{ for each } t\text{; determines } p_{L,t} \tag{40}$$

Pollution permits markets balance:

$$\sum_{j=1}^{J} E^{U}_{e,j,t} + \sum_{j=1}^{J} E^{A}_{e,j,t} + E^{U}_{e,A,t} + E^{A}_{e,A,t} + \sum_{h=1}^{H} E^{U}_{e,h,t} + \sum_{h=1}^{H} E^{A}_{e,h,t} = \sum_{h=1}^{H} \overline{E_{e,h,t}} \text{ for each } (e,t)$$

(41)

determines $p_{e,t}$.

Savings/investments balance:

$$\sum_{h=1}^{H} S_{h,t} = \sum_{j=1}^{J} p_{j,t} \cdot I_{j,t} \text{ for each } t \tag{42}$$

- **List of symbols**

Indices

Label	Entries	Description
j and *jj*	1,…,J,A	Production sectors, including Abatement producer (A) j={High-polluting sector, Low-polluting sector, Abatement producer}
h	1,…,H	Consumer groups h={Private households, Government}
e	1,…,E	Environmental themes e={Climate change, Acidification}
v_J	1,…,V_J	'CES-knots' in production functions v_J={Economic inputs, Environmental inputs, Production}
v_H	1,…,V_H	'CES-knots' in utility functions v_H={Goods, Environmental inputs, Consumption}
t	1,…,T	Time periods t={1998,1999,…,2030}

Parameters

Symbol	Description
g_L	Exogenous growth rate of labour supply
$apei_{e,t}$	Autonomous pollution efficiency improvement; assumed equal across all agents
δ_K	Depreciation rate
r	Steady-state interest rate
I^S	Base level investments (calibrated to steady-state)
K^S	Base level capital stock (calibrated to steady-state)
$\overline{L_{h,t}}$	Exogenous labour supply by consumer *h* in period *t*
$\overline{E_{e,h,t}}$	Endowments of pollution permits for environmental theme *e* by consumer *h* in period *t*
ι_j	Input share of good *j* for investments (by origin)
$\tau_{K,j}$	Tax rate on capital demand by sector *j*
$\tau_{L,j}$	Tax rate on labour demand by sector *j*
$\tau_{jj,j}$	Tax rate on input of good *jj* by sector *j*
$\tau_{j,h}$	Tax rate on consumption of good *j* by consumer *h*
$\tau_{K,h}$	Tax rate on the supply of capital by consumer *h*

Symbol	Description
$\tau_{L,h}$	Tax rate on the supply of labour by consumer *h*
τ_h^{LS}	Lumpsum transfer from government to consumer *h*, with $\sum_{h=1}^{H}\tau_h^{LS} = 0$ and $\sum_{h=1}^{H}\tau_h^{LS}\cdot\alpha_t^{LS} = 0$
τ^{SUB}	Lumpsum transfer from (excess) private households to the subsistence consumer
σ_j^v	Substitution elasticities between inputs combined in knot v_J in production function for sector *j*
$\sigma_{e,j}^A$	Substitution elasticities between pollution and abatement for environmental theme *e* in production function for sector *j*
σ_h^v	Substitution elasticities between consumption goods combined in knot v_H in utility function for consumer *h* (within same time period)
$\sigma_{e,h}^A$	Substitution elasticities between pollution and abatement for environmental theme *e* in utility function for consumer *h*
σ_h^{Util}	Intertemporal substitution elasticities in utility function for consumer *h* (between time periods)

Variables

Symbol	Description
$Y_{j,t}$	Production quantity of sector *j* in period *t*
$Y_{jj,j,t}^{ID}$	Demand for input *jj* by sector *j* in period *t*
$L_{j,t}$	Labour demand by sector *j* in period *t*
$K_{j,t}$	Capital demand by sector *j* in period *t*
$I_{j,t}$	Investment originating in sector *j* in period *t*
$I_{h,t}$	Investment by consumer *h* in period *t*
$\Pi_{j,t}$	(Net) profits in sector *j* in period *t* (equal to zero)
$E_{e,j,t}^U$	‘Unabatable’ emissions of environmental theme *e* by sector *j* in period *t*
$E_{e,j,t}^A$	‘Abatable’ emissions of environmental theme *e* by sector *j* in period *t*
$A_{e,j,t}$	Investment in abatement of environmental theme *e* by sector *j* in period *t* {note that $\sum_{e=1}^{E} A_{e,j,t} \equiv Y_{A,j,t}^{ID}$ }
$ES_{e,j,t}$	Emission services of environmental theme *e* by sector *j* in period *t*

Symbol	Description
$E^U_{e,h,t}$	'Unabatable' emissions of environmental theme *e* by consumer *h* in period *t*
$E^A_{e,h,t}$	'Abatable' emissions of environmental theme *e* by consumer *h* in period *t*
$A_{e,h,t}$	Investment in abatement of environmental theme *e* by consumer *h* in period *t* {note that $\sum_{e=1}^{E} A_{e,h,t} \equiv C_{A,h,t}$ }
$ES_{e,h,t}$	Emission services of environmental theme *e* by consumer *h* in period *t*
$W_{h,t}$	Welfare level of consumer *h* in period *t*
U_h	Total welfare of consumer *h* over all periods
$C_{j,h,t}$	Consumption of good *j* by consumer *h* in period *t*
$S_{h,t}$	Savings by consumer *h* in period *t*
$\overline{K_{h,t}}$	Capital supply by consumer *h* in period *t* (in 'flow' terms: capital services)
$p_{j,t}$	Equilibrium market price of good *j* (including A) in period *t*
$r_{K,t}$	Equilibrium market rental price of capital in period *t*
$p_{L,t}$	Equilibrium market wage rate in period *t*
$p_{e,t}$	Equilibrium market price of pollution permits for environmental theme *e* in period *t*
$p^W_{h,t}$	Equilibrium price of the 'utility good' (consumption bundle)
α_t	Endogenous change in existing tax rates to offset government income from sale of pollution permits in period *t*
α^{LS}_t	Endogenous change in lumpsum transfers to offset government income from sale of pollution permits in period *t*
$Taxrev_{h,t}$	Endogenous tax revenues for consumer *h* in period *t* (only nonzero for Government)

APPENDIX II. GAMS CODE

```
$title  Proto-type perfect-forsight dynamic CGE model


$ontext
For 2000 KEI project
"AN INTERACTION OF ECONOMY AND ENVIRONMENT IN DYNAMIC COMPUTABLE
GENERAL EQUILIBRIUM MODELLING WITH A FOCUS ON CLIMATE CHANGE ISSUE IN
KOREA : A PROTO-TYPE MODEL"
led by Seunghun JOH with assistant from  Ms.Yunmi Nam. This is a modified version of Rob
Dellink(2000) whose is a co-author of the KEI project.


corresponding address: Seunghun Joh at shjoh@kei.re.kr;
Rob Dellink at Rob.Dellink@alg.shhk.wau.nl


$offtext
$offlisting
$offsymxref
*option solprint=off;


file scherm /'con'/;


Sets
        t         time periods
                  /2000*2100/
      tpol(t)   policy periods
                /2000*2030/
        tf(t)    first period
        tl(t)    last period
        FJ        production inputs
                  /L, K, Y1, Y2,Y3, YA/
    J(FJ)       production sectors
                  /Y1,Y2,Y3,YA/
    Jz(J)       polluting industry
```

```
                /Y1/
     Jd(J)     dirty energy sector
                /Y2/
     Jc(J)     clean energy sector
                /Y3/
     JA(J)      only abatement sector
                /YA/
       F(FJ)    primary production factors
                /L labor,K capital/
       E        emission
                /CLIMATE ,ACID/
       H        consumers
                /PRIV Private households, GOVT Government/
       runs     set of all model simulations
              /BAU, 8-12_30, 13-17_30, 18-22_30,13-17_40,
              18-22_50, 13-22_eq, 13-22_sm,13-22_sd/
     baserun(runs)  /BAU/
     ;

Alias (J,JG);
tf(t)      = YES$(ORD(t) EQ 1);
tl(t)      = YES$(ORD(t) EQ CARD(t));

Scalars
       g        Assumed growth rate                    /0.04/
       delta    Assumed depreciation rate              /0.07/
       r        Assumed interest rate           /0.07/
      apei    Assumed autonomous pollution efficiency
              improvement                /0.01/
       thetat   Budget share of model horizon in infinite-horizon
       I0       Base year investment (calibrated to steady-state)
       K0       Base year capital stock (calibrated to steady-state)

Parameters
```

modstat Indicator for solution found

ev Equivalent variation in income

ev1 uncorrected ev in income

ev2 Time specific income development

ev3 Sum of ev2 over time

ev4 total ev based on ev3

check

gdp Annual Gross Domestic Product

emis Total pollution

Demis Change in Emission compared to BAU

ab Sectoral abatement

prd Sectoral production

inputs Sectoral inputs and consumption

invest Current investments

prices Equilibrium prices

RANKING POLICY EVALUTION CRITERIA

index(t) Index from zero to one

goal(t,E,runs) Policy objective per simulation

SUSTAIN(E) Sustainable levels of pollution

tax(*,*) Tax on inputs by producers

taxls(H) Lumpsum transfer between households

YBAR(J) Base level production

YEBAR(E,*) Base level fictituous output of pollution permits

IDBAR(JG,J) Base level intermediate deliveries

FBAR(F,J) Base level factor use

EBAR Base level emissions

PBAR(*,*) Base level price of capital use

CBAR(J,H) Base level consumption

WBAR(H) Base level welfare

ENDOW(*,H) Base level factor endowments

PERMITS(t,E,H) Level of pollution permits per

```
                    household
        SBAR(H)       Base level savings (calibrated to steady-state)
        INVSH(J)      Base level input shares for investments
        elas(*)       Substitution elasticities
        elas2(*) Substitution between pollution and abatement
        elas3(*) Substitution between clean and dirty energy
        sigma(H)      Intertemporal substitution
        cterm(H)      Terminal consumption
        qgrow(t)      Exogenous reference growth rate for
                  quantities
        pgrow(t)      Exogenous reference growth rate for prices
       egrow(t)     Exogenous reference growth rate for pollution;

         Table sam(*,*)
        Y1     Y2     Y3     YA     PRIV   GOVT   colsum
Y1      70     -21    -10    -22    -17    0      0
Y2      -9     160    -50    -3     -98    0      0
Y3      -18    -30    300    -2     -200   -50    0
YA      -10    -30    -40    85     -5     0      0
L       -5     -20    -57    -56    138    0      0
K       -18    -47    -97    -2     164    0      0
taxl    -5     -8     -16    0      0      29     0
taxk    -5     -4     -30    0      0      39     0
taxls   0      0      0      0      18     -18    0
rowsum  0      0      0      0      0      0      0
;
      Table Y_DATA(*,J) Producer data
        Y1     Y2     Y3     YA
INVSH   0.1    0.5    0.4    0
ELAS           1      1      1      1
ELAS2         1.4     1.4    1.4    0
ELAS3        +inf  +inf  +inf  +inf
CLIMATE        0.10   0.60   0.00   0
ACID    0.10   0.50   0.00   0
```

```
;
Table HH_DATA(*,H) Household data
            PRIV  GOVT
SAVSH       1     0
ELAS        1     0
ELAS2             1.4    1.4
ELAS3             +inf   +inf
SIGMA       0.5   0.5
CLIMATE           0.30   0
ACID              0.40   0
;
ENDOW(F,H)      = SAM(F,H);
K0              = sum(H, ENDOW("K",H)) / (r + delta);
I0              = (g + delta) * K0;
tax("K",J)$SAM("K",J)   = SAM("taxk",J)/SAM("K",J);
tax("L",J)$SAM("L",J)   = SAM("taxl",J)/SAM("L",J);
tax(JG,J)               = 0;
YBAR(J)                 = SAM(J,J);
YEBAR(E,J)              = Y_DATA(E,J);
YEBAR(E,H)              = HH_DATA(E,H);
IDBAR(JG,J)             = -SAM(JG,J);
IDBAR(J,J)              = 0;
FBAR(F,J)               = -SAM(F,J);
EBAR(E,J)               = YEBAR(E,J);
EBAR(E,H)               = YEBAR(E,H);
ENDOW(E,"govt")         = sum(J, EBAR(E,J))+sum(H, EBAR(E,H));
PERMITS(t,E,H)          = ENDOW(E,H);
PBAR(FJ,J)      = 1 + tax(FJ,J);
PBAR(FJ,h)      = 1 + tax(FJ,h);
INVSH(J)        = Y_DATA("INVSH",J);
SBAR(H)         = HH_DATA("SAVSH",H)*I0;
CBAR(J,H)       = -SAM(J,H) - INVSH(J)*SBAR(H);
WBAR(H)         = sum(J, CBAR(J,H));
TAXLS(H)        = SAM("TAXLS",H);
```

```
elas(J)         = Y_DATA("ELAS",J);
elas2(J) = Y_DATA("ELAS2",J);
elas(H)         = HH_DATA("ELAS",H);
elas2(H)        = HH_DATA("ELAS2",H);
elas3(H)        = HH_DATA("ELAS3",H);
sigma(H)        = HH_DATA("SIGMA",H);
qgrow(t)        = (1+g)**(ORD(t)-1);
pgrow(t)        = (1+r)**(1-ORD(t));
egrow(t)      = (1+g-apei)**(ORD(t)-1);
thetat          = 1-((1+g)/(1+r))**CARD(t);
SUSTAIN("CLIMATE")= 0.75*ENDOW("CLIMATE","govt");
SUSTAIN("ACID")           = 0.75*ENDOW("ACID","govt");

display  endow,k0,i0,invsh,yebar,ebar,permits,ybar,idbar,fbar,pbar,cbar,sbar,
     wbar,tax,elas,elas2;
*        Interrupt calculations if the steady-state is inconsistent:
Abort$(g gt r) "Error: growth rate exceeds interest rate?", g, r;

*---------- MPSGE - Begin of the Model ------------------------------
$ontext

$model:FORSIGHT

$sectors:
        Z(t,J)    ! Activity levels of production sectors
        W(t,H)  ! Activity levels of welfare
        K(t)      ! Capital stock
        I(t)      ! Investments

$commodities:
        p(t,J)    ! Price of commodities
        rk(t)     ! Rental price of capital
        pl(t)     ! Wage rate
        pe(t,E)  ! Price of emissions
```

```
        pw(t,H)! Price of welfare prod
        pk(t)     ! Price of capital assets
        pkt       ! Terminal price of capital

$consumers:
        CON(H)          ! Consumers

$auxiliary:
        kt        ! Terminal capital stock
    endotax(t) ! Endogenous tax adjustment
    endols(t) ! Endogenous lumpsum adjustment

$prod:Z(t,J)  e0:0          e1(e0):ELAS(J)  e2(e0):ELAS2(J)          e3(e1):elas3(j)    t:0
        o:p(t,J)  q:YBAR(J)
        o:pe(t,E)           q:(YEBAR(E,J)*egrow(t)/qgrow(t))

    i:p(t,JG)$(Jz(JG))     q:IDBAR(JG,J)    p:pbar(JG,J) e1:
    i:p(t,JG)$(Jd(JG))     q:IDBAR(JG,J)    p:pbar(JG,J) e3:
    i:p(t,JG)$(Jc(JG))     q:IDBAR(JG,J)    p:pbar(JG,J) e3:
    i:rk(t)          q:FBAR("k",J)   a:CON("GOVT")
   n:endotax(t)  m:tax("K",J)
   +                 p:pbar("K",J)     e1:
   i:pl(t)           q:FBAR("l",J)    a:CON("GOVT") n:endotax(t)     m:tax("L",J)
   +                 p:pbar("L",J)     e1:
    i:pe(t,E)              q:(EBAR(E,J)*egrow(t)/qgrow(t))  e2:
    i:p(t,JA)                q:IDBAR(JA,J)     p:pbar(JA,J)       e2:

$prod:K(t)
        o:pk(t+1)          q:(1-delta)
        o:pkt$tl(t)        q:(1-delta)
        o:rk(t)            q:(r+delta)
        i:pk(t)            q:1

$prod:I(t)
```

```
        o:pk(t+1)       q:1
        o:pkt$tl(t)     q:1
        i:p(t,J)        q:INVSH(J)

$prod:W(t,H)  e0:0  e1(e0):ELAS(H)     e2(e0):ELAS2(H)     t:0
        o:pw(t,H)       q:WBAR(H)
        o:pe(t,E)       q:(YEBAR(E,H)*egrow(t)/qgrow(t))
        i:p(t,JG)$not(JA(JG))    q:CBAR(JG,H)    p:pgrow(t)     e1:
        i:pe(t,E) q:(EBAR(E,H)*egrow(t)/qgrow(t))      p:pgrow(t)      e2:
        i:P(t,JA)q:CBAR(JA,H)  p:pgrow(t)     e2:

$demand:CON(H)         s:sigma(H)
        d:pw(t,H)       q:(qgrow(t)*WBAR(H))  p:pgrow(t)
        e:pl(t)    q:(qgrow(t)*ENDOW("L",H))
        e:pk(tf)   q:(ENDOW("K",H)/(r+delta))
        e:pkt      q:(-SBAR(H)/I0)       r:kt
        e:pe(t,E)       q:PERMITS(t,E,H)
        e:pw(t,"GOVT") q:(qgrow(t)*TAXLS(H))  r:endols(t)

$report:
        v:U(H)          w:CON(H)
        v:Win(JG,t,H)   i:p(t,JG)       prod:W(t,H)
        v:Zin(JG,t,J)     i:p(t,JG)           prod:Z(t,J)
        v:inv(t)          o:pk(t)             prod:I(t)
        v:U2(t,H)         o:pw(t,H)           prod:W(t,H)
       v:EMJ(t,E,J)       i:pe(t,E)           prod:Z(t,J)
        v:EMH(t,E,H)      i:pe(t,E)           prod:W(t,H)
        v:ABATJ(t,JA,J)i:p(t,JA)       prod:Z(t,J)
        v:ABATH(t,JA,H)       i:p(t,JA)       prod:W(t,H)
        v:Y(t,J)          o:p(t,J)        prod:Z(t,J)

$constraint:endotax(t)
W(t,"GOVT") =g= W(t,"PRIV");
```

```
$constraint:endols(t)
W(t,"PRIV") =g= 0.99999*W(t,"GOVT");

$constraint:kt
sum(tl(t), k(t) - (1+g)*k(t-1)) =e= 0;

$offtext
*---------- MPSGE - End of the Model ------------------------------

$sysinclude mpsgeset forsight
endols.lo(t) = 1;
putclose scherm 'We are now starting the model simulations'/;
forsight.workspace=15;
putclose scherm 'We are now starting the model simulations'/;

*POLICY SCENARIOS; based on UNFCCC committment schedule,
*determine the number of permits per simulation:

goal(t,E,"BAU") = 0;

*8-12_30 :bau for 2000-2007, 30% reduction of bAU for 2008-2012, fixed at 2000 level from 2013
goal(t,E,"8-12_30")$(ord(t) le 8)  = ENDOW(E,"GOVT")*egrow(t);
goal(t,E,"8-12_30")$(ord(t) ge 9 and ord(t) le 13)  = 0.7*ENDOW(E,"GOVT")*egrow(t);
goal(t,E,"8-12_30")$(ord(t) ge 14)  = ENDOW(E,"GOVT");

*13-17_30 :bau for 2000-2012, 30% reduction of bAU for 2013-2017, fixed at 2000 level from 2018
goal(t,E,"13-17_30")$(ord(t) le 13)  = ENDOW(E,"GOVT")*egrow(t);
goal(t,E,"13-17_30")$(ord(t) ge 14 and ord(t) le 18)  = 0.7*ENDOW(E,"GOVT")*egrow(t);
goal(t,E,"13-17_30")$(ord(t) ge 19)  = ENDOW(E,"GOVT");

*18-22_30 :bau for 2000-2017, 30% reduction of bAU for 2018-2022, fixed at 2000 level from 2023
goal(t,E,"18-22_30")$(ord(t) le 18)  = ENDOW(E,"GOVT")*egrow(t);
goal(t,E,"18-22_30")$(ord(t) ge 19 and ord(t) le 23)  = 0.7*ENDOW(E,"GOVT")*egrow(t);
goal(t,E,"18-22_30")$(ord(t) ge 24)  = ENDOW(E,"GOVT");
```

```
*13-17_40 :bau for 2000-2012, 40% reduction of bAU for 2013-2017, fixed at 2000 level from 2018
goal(t,E,"13-17_40")$(ord(t) le 13)  = ENDOW(E,"GOVT")*egrow(t);
goal(t,E,"13-17_40")$(ord(t) ge 14 and ord(t) le 18)  = 0.6*ENDOW(E,"GOVT")*egrow(t);
goal(t,E,"13-17_40")$(ord(t) ge 19)  = ENDOW(E,"GOVT");

*18-22_50 :bau for 2000-2017, 50% reduction of bAU for 2018-2022, fixed at 2000 level from 2023
goal(t,E,"18-22_50")$(ord(t) le 18)  = ENDOW(E,"GOVT")*egrow(t);
goal(t,E,"18-22_50")$(ord(t) ge 19 and ord(t) le 23)  = 0.5*ENDOW(E,"GOVT")*egrow(t);
goal(t,E,"18-22_50")$(ord(t) ge 24)  = ENDOW(E,"GOVT");

***within period strategy

*13-22 :BAU for 2000-2012,constant at 2000*10*1.1 for 2013-2022,fixed at 2000*0.9 level from 2023

goal(t,E,"13-22_eq")$(ord(t) le 13)  = ENDOW(E,"GOVT")*egrow(t);
goal(t,E,"13-22_eq")$(ord(t) ge 14 and ord(t) le 23)  = 1.1*ENDOW(E,"GOVT");
goal(t,E,"13-22_eq")$(ord(t) ge 24)  = ENDOW(E,"GOVT")*0.8;
*goal(t,E,"13-22_eq")$(ord(t) ge 24)  = 0.9;
*13-22 :BAU for 2000-2012,linear decreasing (2013,1.426), to meet with area 11(=2000*10*1.1 )
*for 2013-2022, (2022,0.774) st emission(2013-2022) =-0.0652*year + 1.426
*fixed at 2000*0.8 level from 2023

goal(t,E,"13-22_sm")$(ord(t) le 13)  = ENDOW(E,"GOVT")*egrow(t);
goal(t,E,"13-22_sm")$(ord(t) ge 14 and ord(t) le 23)
            = (-0.065*(ord(t)-13)+ 1.426)+0.315/10;
*here +(11-9.584)/10 is adjustment term
goal(t,E,"13-22_sm")$(ord(t) ge 24)  = ENDOW(E,"GOVT")*0.8;

*13-22 :BAU for 2000-2012,at 2012 level till 2017 mid. of the committement period
*then linear decreasing (2017,1.426), to meet with area 11(=2000*10*1.1 )
*for 2013-2022, area 2013-2017 is 7.130 then 11-7.130=3.870
* st (2022,0.122) st emission(2013-2022) =-2.592*year + 1.426
*fixed at 2000*0.8 level from 2023
```

```
goal(t,E,"13-22_sd")$(ord(t) le 13)  = ENDOW(E,"GOVT")*egrow(t);
goal(t,E,"13-22_sd")$(ord(t) gt 13 and ord(t) le 18 )  =ENDOW(E,"GOVT")*egrow('2012');
goal(t,E,"13-22_sd")$(ord(t) gt 18 and ord(t) le 23)  =
(-0.1304*(ord(t)-18) + 1.426) - (12.304-11.001)/5;
goal(t,E,"13-22_sd")$(ord(t) gt 23)  = ENDOW(E,"GOVT")*0.8;

LOOP(runs,
        w.l(t,H) = qgrow(t);
        z.l(t,J)   = qgrow(t);
        k.l(t)     = K0*qgrow(t);
        i.l(t)     = I0*qgrow(t);
        pw.l(t,H)          = pgrow(t);
        p.l(t,J)   = pgrow(t);
        rk.l(t)    = pgrow(t);
        pk.l(t)    = pgrow(t)*(1+r);
        pl.l(t)    = pgrow(t);
        pkt.l      = sum(tl, pgrow(tl));
        kt.l       = K0*sum(tl, qgrow(tl))*(1+g);
        pe.l(t,E)      = pgrow(t);

    endotax.l(t) = 1;
    endols.l(t) = 1;

    YEBAR(E,J)$(not(baserun(runs)))     = 0;
        YEBAR(E,H)$(not(baserun(runs)))          = 0;
    PERMITS(t,E,"GOVT")       = goal(t,E,runs);

        forsight.iterlim = 20000;

$include forsight.gen
        solve forsight using mcp;

        IF (((forsight.modelstat <> 1) OR (forsight.solvestat <> 1)),
```

```
                    modstat(runs) = 0;
putclose scherm 'We have NOT solved this ', runs.tl, ' simulation !?'/;
abort$(modstat(runs)=0) "Model NOT solved";
                    ELSE modstat(runs) = 1;
putclose scherm 'We have succesfully solved this ', runs.tl, ' simulation'/;
);
          cterm(H)       = sum(tl, w.l(tl,H)/qgrow(tl));
      gdp(runs,t)        = sum(H, U2.l(t,H))+i.l(t);

*CHECK GDP CHANGES COMPARED TO BAU
gdp('d_8-12_30',t)= 100*(gdp('8-12_30',t)/gdp('BAU',t)-1);
gdp('d_13-17_30',t)= 100*(gdp('13-17_30',t)/gdp('BAU',t)-1);
gdp('d_18-22_30',t)= 100*(gdp('18-22_30',t)/gdp('BAU',t)-1);
gdp('d_13-17_40',t)= 100*(gdp('13-17_40',t)/gdp('BAU',t)-1);
gdp('d_18-22_50',t)= 100*(gdp('18-22_50',t)/gdp('BAU',t)-1);
gdp('d_13-22_eq',t)= 100*(gdp('13-22_eq',t)/gdp('BAU',t)-1);
gdp('d_13-22_sm',t)= 100*(gdp('13-22_sm',t)/gdp('BAU',t)-1);
gdp('d_13-22_sd',t)= 100*(gdp('13-22_sd',t)/gdp('BAU',t)-1);

       ev(runs,H) = 100*(( thetat*U.l(H)**(1-1/sigma(H))
          + (1-thetat)*cterm(H)**(1-1/sigma(H)) )**
         (1/(1- 1/sigma(H))) -1);
       ev1(runs,H)  =  U.l(H);
       ev2(runs,t,H)$(ord(t) lt (card(tpol)+1))= U2.l(t,H)/WBAR(H);
       ev2(runs,"tt",H) = sum(t, ev2(runs,t,h));
       emis(runs,t,E)= sum(J, EMJ.l(t,E,J))+sum(H, EMH.l(t,E,H));
       Demis(runs,t,'climate') =
      100*(emis(runs,t,'climate')/emis('BAU',t,'climate')-1);

* CHECK TOTAL AMOUNTS OF EMISSION REDUCED BY POLICIES IMPLEMENTED
emis(runs,'total_30',e) = sum(t, emis('bau',t,e)$(ord(t) lt (card(tpol)+1))) - sum(t, emis(runs, t,e)$(ord(t) lt
(card(tpol)+1)));


emis(runs,'total',e) = sum(t, emis('bau',t,e)) - sum(t, emis(runs, t,e));
```

```
emis(runs,'equal',e) = sum(t, emis('bau',t,e)$(ord(t) ge 14 and ord(t) le 23)) - sum(t, emis(runs, t,e)$(ord(t)
ge 14 and ord(t) le 23));

emis(runs,'emicheck',e)= sum(t, emis(runs, t,e)$(ord(t) ge 14 and ord(t) le 23));

        ab(runs,t,J)        = sum(JA, ABATJ.l(t,JA,J));
        ab(runs,t,H)        = sum(JA, ABATH.l(t,JA,H));
        prd(runs,t,J)       = Y.l(t,J);
        inputs(runs,t,JG,J)         = Zin.l(JG,t,J);
        inputs(runs,t,JG,H)         = Win.l(JG,t,H);
        invest(runs,t)      = i.l(t);

gdp('d_13-22_sd',t) = 100*(gdp('13-22_sd',t)/gdp('BAU',t)-1);

*prd("com",t,J) = 100*(prd(runs,t)/invest('bau')-1);

*invest(runs,t)    = 100*(invest(runs,t)/invest('bau',t)-1);
      prices(runs,t,"PW_PRIV") = pw.l(t,"PRIV");
      prices(runs,t,"PK") = pk.l(t)/pw.l(t,"PRIV");
      prices(runs,t,"RK") = rk.l(t)/pw.l(t,"PRIV");
      prices(runs,t,"PA") = p.l(t,"YA")/pw.l(t,"PRIV");
      prices(runs,t,"P_CLIMATE") =
      pe.l(t,"CLIMATE")/pw.l(t,"PRIV");
      prices(runs,t,"P_ACID") = pe.l(t,"ACID")/pw.l(t,"PRIV");

RANKING(RUNS,'EV_TOTAL') = EV(RUNS,'PRIV');
RANKING(RUNS,'EV2_00-30') = EV2(RUNS,"TT",'PRIV');
RANKING(RUNS,'D_EMIS-30') = MIS(RUNS,"TOTAL_30","CLIMATE");
RANKING(RUNS,'D_EMIS') = EMIS(RUNS,"TOTAL","CLIMATE");
*RANKING(RUNS,'ev/D_EMIS')$(not baserun(runs)) =
RANKING(RUNS,'EV_TOTAL')/EMIS(RUNS,"TOTAL","CLIMATE");
abort$((forsight.objval gt 1.e-4)*(baserun(runs))) "Benchmark replication error! Largest error: ",
forsight.objval;
);
```

```
$libinclude xldump GDP GDPchange.xls
$libinclude xldump prices PE&PA.xls
$libinclude xldump emis emission.xls

* Finally, reproduce the solutions
display modstat, goal, gdp, ev, ev2, ab, prd, inputs, invest, prices,RANKING, endow
emis, Demis;

************End of the Model************
```