The Economics of Climate Change Policy: Critical review and future policy directions

Halkos, George

Department of Economics, University of Thessaly

June 2014

The Economics of Climate Change Policy: Critical review and future policy directions

George Halkos
Laboratory of Operations Research
Department of Economics, University of Thessaly

Abstract

This paper presents the dimensions of the climate change problem and its economic effects as well as the evolution of the international meetings to cope with it. In these lines it discusses the use of Integrated Assessment Models (IAMs), the damage cost estimates and various other issues related to global warming and concerning the significance of uncertainty and risk aversion, the importance of discounting and the impact of financial crisis on emissions predictions. The methods of constructing abatement cost curves together with adaptation policies are presented. It also refers to the basic policy approaches for reducing greenhouse gases paying attention to emissions trading schemes.

Keywords: Climate change; Integrated Assessment Models; Abatement costs.

JEL Codes: Q50; Q52; Q54; Q58.

This paper is the written version of the presentation in the International Training Seminar on Climate Change Policies (Trends, Modeling – LEAP, Evaluation – AMS) 11-15 November 2013 Energy Policy and Development Centre, National and Kapodistrian University of Athens, Kostis Palamas Room–Greece.

Work in this presentation has received funding from the "GHGsMETI" program, which takes place within the SYNERGASIA 2011 action and is supported by the European Regional Development fund and Greek National Funds, project number 11SYN_8_118. The text represents the author's views.

EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND

Ministry of Education and Religious Affairs
GSRT - Management and Implementation Agency for RTD and Innovation Activities

O.P. Competitiveness and Entrepreneurship (EPAN II), ROP Macedonia - Thrace, ROP Crete and Aegean Islands, ROP Thessaly - Mainland Greece - Epirus, ROP Attica

1. The problem of climate change and its dimensions

Greenhouse gases (hereafter **GHG**s) include emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxides (N_2O) and a number of high global warming potential (GWP)[1] gases like hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6) known as F-gases trapping heat near the surface of the earth and leading to global warming.[2] Due to these various GHGs global warming is considered as one of the most serious environmental problems caused by human activities and affecting significantly the climate.

The effects of climate change are serious and several. Coastal flooding from the rise in the sea level, intensive storms and floods and extreme weather conditions, reduced productivity of natural resources like scarce water reservoirs and lower and poorer agricultural production are some of them. Climate change is associated not only to the problem imposed to the environment but also to various physical, social and economic consequences like productivity reductions, population migration and changed climate conditions.

The socio-economic effects of global warming depend on changes in sea level, precipitation, ocean currents, spread of diseases and various other elements difficult to count and predict. As location of sources of GHG emissions is unrelated to the location of the environmental effects in terms of damages and degradation, they are considered as uniformly mixing pollutants[3] with their concentration levels to be invariant from place to place. At the same time all emitter countries are influenced by the emissions of the others implying a reciprocal spillover problem from a global public "bad" (Perman et al., 2003). Climate change may be considered as an open

[1] The importance of GWP is explained analytically in Section 3.
[2] All these GHGs are regulated by the Kyoto Protocol. Although the effect of water vapor is also significant it is not listed among the GHGs.
[3] Uniformly mixing pollutants occur when physical processes operate in such a way as to disperse them to the point in which their spatial distribution is uniform (Perman et al. 2003, p. 178).

access resource problem depending more on the world economy compared to economic activities in individual countries. This implies that actions to cope with the problem demand global cooperation (Stern et al., 2013; Arrow, 2007).[4]

In these lines, climate change is a global externality leading to market failure as the sources of pollution do not bear the full cost of their actions and the resulting external (social) costs imposed to others are not in the majority of the cases taken into consideration. With no policy interventions, polluters have no (or little) motivation to take into consideration the social costs imposed to others in their decision-making. At the same time, economists calculate that doubling of CO_2 concentrations may result to damages equal to around 1%-2% of total output (Wayne, 2008). These are accompanied by the associated GHG emissions' irreversibility, their very long residence time in the atmosphere and the inability of individual countries to internalize the negative external costs (Arrow, 2007) as well as the existence of various synergistic effects.

The main attention of scientific research has been concentrated on CO_2 emissions with a number of studies using a single pollutant case (Hourcade and Shukla, 2001; Morita *et al*., 2001). Recently, Granados et al. (2012) examined the short-run determinants of atmospheric CO_2, while Wang et al. (2013) examined the carbon emissions trends in terms of optimal balanced economic growth in the case of China and USA, discussing a number of abatement options for China. Similarly, Du et al. (2012) examined the relationship of CO_2 emissions and economic development in China, and Ibrahim and Law (2014) examined the relationship between social capital and CO_2 emissions.[5]

---

[4] Arrow (2007) refers to the USA's contribution (almost 25%) to world CO_2 emissions emphasizing that its own policy to cope with the problem may be influential making a significant difference.

[5] Many researchers have tested the validity of the Environmental Kuznets Curve (EKC) hypothesis which corresponds to an inverted U-shaped relationship between environmental damage or pollutants

The lack of extensive cross-sectional data has led to few studies examining non-CO_2 gases (Chesnaye *et al.*, 2001). At the same time, a limitation of earlier studies may be pointed out on the use of exogenous control cost functions instead of considering non-CO_2 gases in analytic models (Hyman *et al.*, 2002). The consideration of both CO_2 and non-CO_2 control options may have important benefits on the so-called multi-pollutant abatement strategies. Some of these benefits are the higher elasticity in mitigation options (Lucas *et al.*, 2005; Manne and Richels, 2001; van Vuuren *et al.*, 2003; Hyman *et al.*, 2002) and the substantial cost reductions compared to strategies coping only with CO_2 due to possible existence of cheaper control options for some non-CO_2 GHGs (Harmelink *et al.*, 2005; Blok *et al.*, 2001). Van Vuuren *et al.* (2006) and Weyant and de la Chesnaye (2006) cite that across models and on average, a multi-pollutant strategy may achieve a costs reduction of 30-60% in comparison to only CO_2 emissions abatement.

The structure of the paper is the following. Section 2 presents the evolution of the various international meetings to cope with the global warming problem. Section 3 discusses the damage cost estimates and the various uncertainties associated with the problem. Apart from presenting information on the damage costs this section refers to the various existing integrated assessment models as well as to the ways of considering the evolution of emissions. Section 4 presents the methods applied in estimating abatement cost functions. Section 5 discusses the basic policy approaches to control GHG emissions paying attention to emissions trading schemes. Section 6 refers to the policy of adaptation while the last section concludes the paper.

---

emissions (in our case CO_2) and economic growth (GDP per capita). Halkos (2012) provides a review of a number of studies exploring this issue.

2. Evolution of various meetings in terms of global climate policy

The mitigation of harmful emissions is the aim of worldwide legislative frameworks like the European Union, the UK Climate Change Act and the Kyoto Protocol with the aim of reducing GHGs emissions by 5% below 1990 levels during the first commitment time period of 2008-2012. The established in 1988 Inter-governmental Panel on Climate Change (IPCC) by the World Meteorological Organization (WMO) considered technical and socioeconomic research in the climate change area. International efforts to cope with climate change started by the "Earth Summit" in 1992 at Rio de Janeiro leading to the United Nations Framework Convention on Climate Change (hereafter UNFCCC) that was established in 1994 for the stabilization of greenhouse gas concentrations in the atmosphere and the cooperation in tackling climate change by limiting average global temperature.

Table 1 presents the evolution and the results of the various meetings from 1979 to 2015 in terms of global climate policies.[6] A number of states commitments have taken place for additional protection in the 19 *Conferences Of the Parties* so far (**COP**s) in one of which (COP3) in 1997 the Kyoto Conference took place with the states to agree for the reduction of the six GHGs (CO_2, CH_4, N_2O, HFCs, PFCs, SF_6) and leading to the Kyoto Protocol. This Protocol committed industrial states to decrease total GHG emissions in the first commitment period (2008 to 2012) by at least 5% lower levels of their 1990 levels.

The COP serves as the Meeting of the Parties to the Kyoto Protocol (**CMP**) where all the Kyoto Protocol Parties States are represented in the CMP, while no Parties States may just participate as observers.[7] The CMP reviews the running of the

[6] The chronology and details of the major negotiations on climate change policies are presented also in McKibbun and Wilcoxen (2005) and Kolstad and Toman (2005).
[7] For more information on the Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol see http://unfccc.int/bodies/body/6397.php

Kyoto Protocol and decides on the way to implement it effectively. It meets annually during the same period as the COPs. The first CMP took place in Montreal (Canada) in December 2005 together with COP-11.

COP 19 took place in Warsaw and announced the dates and locations of COP 20/CPM 10 taking place within 1-12 December 2014 in Peru (Lima) and COP 21/CPM 11 within 30 November–11 December 2015 in France (Paris). It ended up with a number of decisions advancing Warsaw's Framework for REDD+ and International Mechanism for Loss and Damage, Durban's Platform and the Green Climate Fund and Long-Term Finance, REDD+ finance, institutional arrangements and other methodological issues.[8]

2.1 The Kyoto Ptotocol and its mechanisms

As mentioned already, in 1997 the Kyoto Protocol came in action stating that "Annex B" (industrialized "Annex I" in the convention) countries should reduce GHGs with the first period of commitment within 2008-2012 and the second period within 2013-2020. Industrial nations agreed to limit emissions of GHGs to 5.2% below 1990 levels. This would be 30% below the levels projected for 2010. The Kyoto Treaty officially took effect when Russia ratified it in November 2004. No requirements imposed on newly industrialized countries (e.g. China). In USA the Bush administration and many in Congress were opposed to the treaty. The USA would have been required to cut emissions to 7% below 1990 levels by the years 2008 through 2012. Now we have 195 participating countries in the Convention and 192 in the Kyoto Protocol.[9]

---

[8] For more information see http://unfccc.int/

[9] **List of Annex I Parties to the Convention** (Source: http://unfccc.int/parties_and_observers/parties/annex_i/items/2774.php) [With ** parties for which there is a specific COP and/or CMP decision].
Austria, Belarus**, Belgium, Bulgaria, Canada, Croatia**, Cyprus, Czech Republic**, Denmark, Estonia, European Union, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy**, Japan, Latvia, Liechtenstein**, Lithuania, Luxembourg, Malta, Monaco**, Netherlands, New Zealand, Norway, Poland,

The treaty's countries listed in Annex I are industrialized countries while non-Annex I countries are developing countries. Countries listed in Annex B are a subset of industrial countries of Annex I in the original UNFCCC. Belarus had not ratified the UNFCCC till COP3 and is excluded from Annex B, as well as Turkey. Kyoto Protocol limits emissions of Annex I of UNFCCC to the levels provided in the Annex B of the Protocol (McKibbin and Wilcoxen, 2005).

In the framework of the Kyoto Protocol, three mechanisms may be used by Annex I Parties to achieve emission targets at the lowest costs: the Clean Development Mechanism (CDM); the Joint Implementation (JI); and the International Emissions Trading (IET).

The **Clean Development Mechanism (CDM)** helps countries included in Annex I to achieve compliance with their GHG emission caps by permitting Annex I countries to satisfy part of their Kyoto Protocol emission control targets acquiring Certified Emission Reduction units from CDM emission control actions in developing countries to be traded in emission trading schemes. It also assists members not

---

Portugal, Romania, Russian Federation**, Slovakia**, Slovenia**, Spain, Sweden, Switzerland, Turkey, Ukraine**, United Kingdom of Great Britain and Northern Ireland, United States of America.
List of Non-Annex I (Source: http://unfccc.int/parties_and_observers/parties/non_annex_i/items/2833.php) [With * observer states; with ** parties for which there is a specific COP and/or CMP decision] Afghanistan, Albania**, Algeria, Andorra, Angola, Antigua and Barbuda, Argentina, Armenia**, Azerbaijan, Bahamas, Bahrain, Bangladesh, Barbados, Belize, Benin, Bhutan, Bolivia, Bosnia and Herzegovina, Botswana, Brazil, Brunei Darussalam, Burkina Faso, Burundi, Cambodia, Cabo Verde, Cameroon, Central African Republic, Chad, Chile, China, Colombia, Comoros, Congo, Cook Islands, Costa Rica, Cuba, Côte d'Ivoire, Democratic People's Republic of Korea, Democratic Republic of the Congo, Djibouti, Dominica, Dominican Republic, Ecuador, Egypt, El Salvador, Equatorial Guinea, Eritrea, Ethiopia, Fiji, Gabon, Gambia, Georgia, Ghana, Grenada, Guatemala, Guinea, Guinea-Bissau, Guyana, Haiti, Honduras, India, Indonesia, Iran (Islamic Republic of), Iraq, Israel, Jamaica, Jordan, Kazakhstan**, Kenya, Kiribati, Kuwait, Kyrgyzstan, Lao People's Democratic Republic, Lebanon, Lesotho, Liberia, Libya, Madagascar, Malawi, Malaysia, Maldives, Mali, Marshall Islands, Mauritania, Mauritius, Mexico, Micronesia (Federated States of), Mongolia, Montenegro, Morocco, Mozambique, Myanmar, Namibia, Nauru, Nepal, Nicaragua, Niger, Nigeria, Niue, Oman, Pakistan, Palau, Palestine*, Panama, Papua New Guinea, Paraguay, Peru, Philippines, Qatar, Republic of Korea, Republic of Moldova**, Rwanda, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Samoa, San Marino, Sao Tome and Principe, Saudi Arabia, Senegal, Serbia, Seychelles, Sierra Leone, Singapore, Solomon Islands, Somalia, South Africa, South Sudan*, Sri Lanka, Sudan, Suriname, Swaziland, Syrian Arab Republic, Tajikistan, Thailand, The former Yugoslav Republic of Macedonia, Timor-Leste, Togo, Tonga, Trinidad and Tobago, Tunisia, Turkmenistan**, Tuvalu, Uganda, United Arab Emirates, United Republic of Tanzania, Uruguay, Uzbekistan**, Vanuatu, Venezuela (Bolivarian Republic of), Viet Nam, Yemen, Zambia, Zimbabwe.

included in Annex I to achieve sustainability and to contribute to their target of UNFCCC.

Table 1: Summary of climate change policy actions*

1979	1st World Climate Conference (WCC) in Geneva (Switzerland).
1988	The setup of the Intergovernmental Panel on Climate Change (IPCC)
1990	1st IPCC's assessment report (significant uncertainty for the first evidence that human activities might be affecting climate). 2nd WCC in Geneva (agreement for the negotiation of a global framework treaty).
1991	1st Intergovernmental Negotiating Committee (INC) meeting.
1992	The United Nations Framework Convention on Climate Change (UNFCCC) is established as an international treaty at the Earth Summit in Rio de Janeiro (Brazil); "Annex I" developed countries undertake to have their emission levels in 2000 as these of 1990; UNFCCC opens for signature together with UNCBD and UNCCD Rio's Conventions.
1994	UNFCCC comes into force.
1995	2nd IPCC's assessment report (with more confidence that human activities may be negatively affecting climate). 1st Conference of the Parties (COP-1) in Berlin (Germany) (negotiation of the legally binding targets and timetables for reduction of Annex I countries' emissions).
1996	COP-2 in Geneva (Switzerland) rejected the proposal of the imposition of uniform policies allowing Annex I countries to develop their own policies.
1997	Kyoto Protocol is officially adopted in December at COP-3 in Kyoto (Japan); Annex I/Annex B countries agree to limit emission reduction to around 5% below 1990 levels by the first commitment period 2008-2012, with various flexibility mechanisms available for compliance; no commitments for emission reductions by developing countries.
1998	COP-4 in Buenos Aires (Argentina) calls attention to make operational the Kyoto Protocol's flexibility mechanisms. 3rd IPCC's assessment report.
1999	COP-5 in Bonn (Germany) monitored the progress on the work program proposed in COP-4 and continued the call for attention to make the flexibility mechanisms of the Kyoto Protocol operational.
2000	COP-6 in Hague (the Netherlands) and deadlock on the implementation of key conditions of Kyoto Protocol.
2001	COP-6-2 in Bonn (Germany) in July continued COP-6. George Bush (U.S.A. President) stated in March opposition to Kyoto Protocol. IPCC's 3rd Assessment Report is published. COP-7 in Marrakesh (Morocco) adopted the majority of the recommendations of COP-6 and finalized in details the rules for implementing Kyoto Protocol's flexibility mechanisms (mainly the Clean Development Mechanism) and it set-up new funding mechanisms for adaption and technology transfer.
2002	COP-8 in New Delhi (India) called developed countries to transfer technology and minimize effect of climate change on developing countries.
2003	At COP-9 in Milan (Italy) parties agreed to the Adaptation Fund as proposed at COP-7 to support developing countries to adapt more to climate change.
2004	COP-10 in Buenos Aires (Argentina) discussed the progress since COP-1.
2005	Kyoto Protocol comes into force. In COP-11 in Montreal (Canada) we have the 1st Meeting of the Parties to Kyoto Protocol (CMP 1); discussions on next stage of Kyoto Protocol under the Ad-Hoc Working Group on additional commitments for Annex I parties (AWG-KP).
2006	At COP-12 (CMP 2) in Nairobi (Kenya) parties adopted a 5-year plan to support adaptation by developing countries and agreed on procedures for the Adaptation Fund.
2007	4th IPCC's assessment report. On the Bali (Indonesia) Road Map Parties at COP-13 (CMP 3) agreed on a post-2012 outcome in two work streams: AWG-KP and Ad-Hoc outcome in two work issues: the AWG-KP and the Ad-Hoc Working Group on Long Term Cooperative Action Under the Convention.
2008	COP-14 (CMP 4) in Poznan (Poland) in December advanced the Bali Action Plan and discussed the development and transfer of technologies and reviewed financial mechanisms of the Convention.
2009	Copenhagen (Denmark) Accord was discussed at COP-15 (CPM 5) with countries submitting later their emission control or mitigation plans.
2010	Cancun (Mexico) Agreements discussed and mainly accepted by COP-16 (CMP 6).
2011	Durban (South Africa) Platform for Enhanced Action was discussed and accepted by COP-17 (CMP 7).
2012	Doha (Qatar) Amendment to Kyoto Protocol adopted by COP-18 (CMP 8).
2013	COP-19 (CMP 9) in Warsaw (Poland) concluded with a set of decisions advancing more among others Warsaw's Framework for REDD+ and International Mechanism for Loss and Damage, Durban's Platform and the Green Climate Fund and Long-Term Finance.
2014	COP-20 (CPM 10) will take place in December 2014 at Lima (Peru)
2015	COP 21 (CPM 11) will take place at the end of 2015 at Paris (France).

* For details see UNFCCC Secretariat (https://unfccc.int/essential_background/items/6031.php).

Certified Emission Reductions (CERs) are a kind of carbon credits or emissions units issued by CDM Executive Board for emissions control performed and verified by an operational entity according to the Kyoto Protocol rules. These CERs may be used by Annex I countries to meet their emission targets or by unit operators under the European Union Emissions Trading Scheme to meet the terms of their obligations to give up EU allowances and certified emission reductions for carbon dioxide emissions of their units.

Joint implementation (**JI**) allows Annex I countries to satisfy part of their targeted emissions by investing in efforts resulting to emissions control credits in other Annex I countries. The traded units are the emission reduction units. In this way, countries with binding GHG emissions targets (Annex I countries) are helped to meet their requirements. Any Annex I country is able to invest in a *joint implementation effort* in any other Annex I country as an alternative emission control plan to reduce emissions at home. Thus countries may reduce the costs of meeting their targets under the Kyoto Protocol by investing in efforts that lower GHG emissions in an Annex I country where abating pollutants may be cheaper and in this way to use the resulting emission reduction units for the achievement of their committed target.

The Kyoto Protocol includes “assigned annual amounts” which may be acquired or transferred. Commitment of the Kyoto Protocol is that every country has to limit GHG emissions to some percentage of 1990 emissions on an average annual basis over a five-year. As mentioned the first commitment period was within 2008-2012. Two or more Annex I countries are allowed to form a “bubble” offering them the opportunity to reallocate permits among themselves. Additionally, the Protocol promotes the joint implementation between countries where a country or a company of a country finances emissions control efforts in another country. The Protocol allows for CDM by which emissions trading can be conducted with non-Annex I countries.

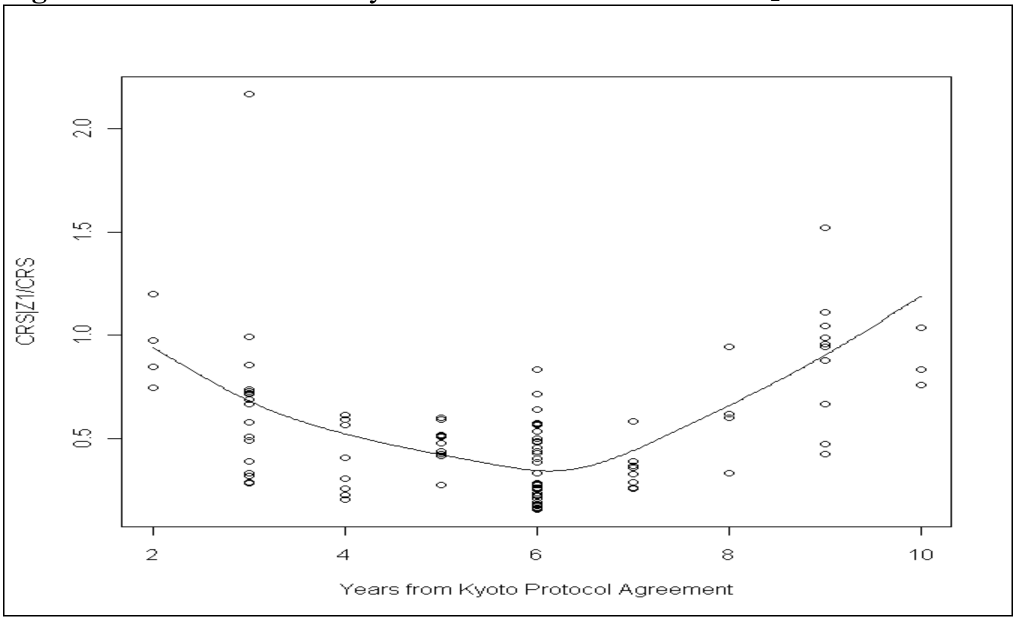
International Emissions Trading (IET) allows Annex I countries to meet part of their targeted emissions by using emissions trading. The total cap of emissions for Annex I countries is determined by the counties with each one agreeing to an individual target. Assigned Amount Units are the traded units each one equal to one ton of CO_2e.

An issue with the Kyoto Protocol agreement is to make developing countries tackle the problem under the constraint of lower income levels and maybe their less polluting activities compared to the developed countries. A possible solution to this issue may be the imposition of a global emissions tax that will internalize the external cost imposed to the global society. What is important is to assess the social cost of the GHG emissions and each country to pay the corresponding tax. This tax may be low or even negative for some countries with Stiglitz (2006) mentioning that this cost is the difference in the deadweight loss of the tax on emissions and the tax it substitutes.

Barrett (2007) mentions three deficiencies of the Kyoto Protocol. Namely, it deals only with the control of GHG emissions and fails to modify the incentives causing the social costs; it provides only a short-run way of tackling a very long-run problem; and it does not paying attention or even ignoring developing countries.

Halkos and Tzeremes (2014) in order to capture the influence of countries compliance with Kyoto Protocol Agreement (KPA), conditioned the years a country has signed the agreement until 2007. Their results show that for the first six years after countries signed the Kyoto protocol agreement there is a positive effect on their environmental efficiencies while after that time period it seems that countries avoid to comply with the actions imposed by the agreement. This is shown in Figure 1 where it can be seen that countries adopt the agreement for a certain time period (six years) trying to improve environmental performances by reducing CO_2 emissions. But after that, countries are not complying with the Kyoto Protocol and their higher economic growth rates are not associated with the relative reductions on CO_2 emissions implying a negative effect on their environmental efficiencies.

Figure 1: Global effect of Kyoto Protocol on countries' CO_2 environmental efficiency



Source: Halkos and Tzeremes (2011)

3. GHG emissions, damage costs estimates and uncertainties

Carbon dioxide emissions are one of the most significant anthropogenic effects released into the atmosphere from, among others, the change in human land use and the fossil fuels combustion. But non-CO_2 gases are also significant. Methane (CH_4) and nitrous oxide (N_2O) are present in the atmosphere naturally. The emissions of CH_4 stem from production and transport of coal, natural gas and oil together with the decomposition of organic wastes while N_2O emissions come from agricultural and industrial activities and from combustion of fossil fuels and solid wastes.

By clearing and cultivating forests, portion of the carbon stored in the woody matter of trees is released directly due to burning while other carbon is emitted more slowly due to decay. In the last two centuries almost 20-25% of the rise in CO_2 concentrations is due to changes in land use like forests' clearing and soil cultivation for agriculture. CO_2 sinks are the oceans (e.g. phytoplankton, coral reefs, various sea plants and animals) and land – sequestration in soil, trees etc. Use of fossil fuels are the source of more than 80% of GHG emissions while more than 10%, and about 12% are due to deforestation and various other changes in the use of land (Hackett, 2011).

Each GHG has different ability to absorb heat in the atmosphere. HFCs and PFCs are the most heat-absorbent while N_2O absorbs 270 times more heat per molecule compared to CO_2 and CH_4 traps 21 times more heat per molecule than CO_2 (Hackett, 2011). Carbon dioxide concentrations have risen more than 25% since the Industrial Revolution and they are steadily increasing (almost 0.5% yearly) (Hackett, 2011). Simultaneously, concentrations of nitrous oxides and methane are rising too. F-gases are expected to increase rapidly due to quick expansion of various emitting industries (semiconductor manufacture and magnesium production) and the substitution of ozone depletion substances (ODSs) like CFCs and HCFCs with HFCs in some applications (aerosols, air-conditioning, foams etc) under the Montreal Protocol.

F-Gases are generated (not naturally) in various industrial processes after the substitution of the Ozone Depleting Substances (ODS, chlorofluorocarbons CFCs and hydrochlorofluorocarbons HCFCs) that were faced out under the Montreal Protocol. They are also emitted from a number of industrial sources such as use of PFCs in aluminium smelting or in semiconductor manufacture or use of SF_6 as insulating gas in various electrical systems (Halkos, 2010).[10]

3.1 *Global Warming Potential*

Global Warming Potential (**GWP**) is an index that measures different GHGs emissions with different atmospheric lifetimes and different radiative properties. Maintaining the climate impact constant, GWP measures allow for comparison and substitution among different gases to accomplish the desirable target (Fuglestvelt *et al*., 2003). CO_2 has a GWP equal to 1 for reasons of comparison. CH_4 and N_2O have GWPs equal to 25 and 298 respectively. Atmospheric lifetimes of PFCs and SF_6 are very long ranging, as can be seen from Table 2, from 3,200 years for SF_6 to 50,000 years for perfluoromethane (CF_4). Usually GHGs emissions estimates are expressed in millions of metric tons of CO_2 equivalents (mmt of CO_2e), weighting each pollutant by the value of its GWP.

Specifically, N_2O lasts longer in the atmosphere (approximately 114 years) and is stronger in trapping heat (about 298 times more compared to CO_2). As nitrous oxide has a GWP equal to 298 this implies that it has 298 times more radiative forcing compared to CO_2 in terms of kgs. **CO_2e** describes different GHGs in a common unit showing the amount of CO_2 that will result to equivalent global warming effect. GHGs quantities are expressed as CO_2e by multiplying the GHG amount by its GWP. For instance 1 kg of N_2O emissions may be expressed as 298 (GWP for 100-years) kg of CO_2e.

At the same time, GHGs have to be treated carefully as they have a long run (LR) character in terms of their effects and at the same time they are accumulating in

[10] Fluorinated gases (CFC, PCFC, HFC, PFC, SF_6) comprised around 25% of anthropogenic radiative forcing of climate in 1980 and 1990 (IPCC, 1990). This percentage may be attributed to anthropogenic gases CFCs and PCFCs, which were regulated due to their depleting influence on stratospheric ozone by the Montreal Protocol, but were not included in the Kyoto Protocol (Halkos, 2010).

the atmosphere over the entire world. Scientific predictions indicate that if the current trends continue then the mean temperatures may increase by 2-6^o Fahrenheit in the century.

Table 2: Lifetimes and Global Warming Potentials (GWPs) relative to CO_2

		GWP for different time horizon		
	Lifetime (years)	**20-years**	**100-years**	**500-years**
Carbon dioxide (CO_2)		1	1	1
Methane (CH_4)	12	72	25	7.6
Nitrous oxide (N_2O)	114	289	298	153
Trichlorofluoromethane (CFC-11)	45	6,730	4,750	1,620
Chlorotrifluoromethane (CFC-13)	640	10,800	14,400	16,400
Dichlorotetrafluoroethane (CFC-114)	300	8,040	10,000	8,730
Hydrofluorocarbon (HFC-23)	270	12,000	14,800	12,200
Hydrofluorocarbon (HFC-32)	4.9	2,330	675	205
Hydrofluorocarbon (HFC-125)	29	6,350	3,500	1,100
Fluorocarbon 134a (HFC-134a)	14	3,830	1,430	435
Sulphur hexafluoride (SF_6)	3,200	16,300	22,800	32,600
Nitrogen trifluoride (NF_3)	740	12,300	17,200	20,700
Tetrafluoromethane (CF_4)	50,000	5,210	7,390	11,200

Source: http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html

3.2 Integrated Assessment Models

Integrated Assessment Models (hereafter **IAMs**) can help policy and decision makers. IAMs aim at evaluating climate change control policies, assessing and quantifying how crucial is the climate change and trying to report various dimensions of the climate change problem in a common framework (Kolstad, 1998). Furthermore, as defined by Kolstad (1998) an IAM includes not only human activities but also aspects of physical relationships forcing climate change. IAMs combine world economic activity and the environment providing useful information on policy choices.

According to Parson (1995) an integrated assessment model seeks to provide information for use by relevant decision-makers rather than advanced understanding. Additionally, a substantial characteristic is that an IAM is capable to combine different areas, methods, styles of study or degrees of confidence than would typically characterize a study of the same issue. Similarly and according to Weyant et al.

(1996) an IAM is a mathematical tool where the knowledge from different fields is combined for the purpose of dealing with the issue of climate change.

An integrated model includes many definitions and interpretations but these interpretations have elements in common such as the cooperation of different disciplines and fields and the participation of stakeholders (Rotmans, 1998). The first generation of these models focusing on environmental issues emerged in the late 1970s (Nordhaus, 1979; Edmonds and Reilly, 1985). In the next decade the Regional Acidification INformation and Simulation computer model of acidification in Europe was developed (**RAINS**; Alcamo et al., 1990). Models like the Dynamic and Regional Integrated models of Climate and Economy (**DICE** and **RICE**; Nordhaus 1994a, 2007; Nordhaus and Boyer, 2000; Nordhaus, 2008; de Bruin et al., 2009); Global Change Assessment Model (**GCAM**; Edmonds et al., 1994); the Massachusetts Institute of Technology Joint Program on the Science and Policy of Global Change model (**MIT**; Prinn et al., 1996); Model for Energy Supply Strategy Alternatives and their General Environmental Impact **(MESSAGE**; Messner and Strubegger, 1995); Tool to Assess Regional and Global Environmental and Health Targets for Sustainability (**TARGETS**; Rotmans and de Vries, 1997); Integrated Model for the Assessment of the Greenhouse Effect **(IMAGE**; Alcamo et al., 1998); Climate Framework for Uncertainty, Negotiation, and Distribution (**FUND**; Tol, 2002a; Tol, 2005); Asia-Pacific Integrated Model (**AIM**; Kainuma et al., 2002); Policy Analysis of the Greenhouse Effect (**PAGE**; Hope et al., 1993; Hope, 2006; Hope, 2009); model for evaluating regional and global effects of GHG reduction policies (**MERGE**; Manne et al., 1995; Manne and Richels, 2005); TIMES Integrated Assessment Model (**TIAM**; Loulou and Labriet, 2008; Loulou, 2008); Community Integrated Assessment System (**CIAS**; Warren et al., 2008; Mastrandrea, 2010); and World

Induced Technical Change Hybrid model (**WITCH**; Bosello et al., 2010) consider at the same time the costs of mitigation and the social costs of carbon.

IAMs can be classified into two different categories. There are ***policy optimization models*** with which, given a certain policy scenario or goal, key policy variables such as carbon emissions control rates are optimized. A further classification of policy optimization models is *cost-benefit (CBA)* and *cost-effectiveness analyses*. In a CBA application the costs of achieving the optimal policy intervention for an environmental target are compared with the resulting benefits given a predetermined constraint (say a specific level of global temperature increase) while in cost-effectiveness the least cost methods of achieving an environmental target are preferred over the more expensive ones. Models such as DICE/RICE, FUND and MERGE are examples of the optimization policy.

The second category of integrated assessment models is referred to policy evaluation models known as ***simulation models***. Applying these types of models environmental, economic and social consequences of specific policies can be calculated. These models include greater complexity in terms of regional detail and natural and social processes. Some representative models of this category are the AIM, MESSAGE, IMAGE and CIAS.

According to Rotmans and Dowlatabadi (1998) integrated assessment models are classified in *macroeconomic-oriented* and *biosphere-oriented models*. Specifically, macroeconomic models are neoclassical models based on a equilibrium framework. The ICLIPS model uses a Ramsey economic growth model formulation (Tóth et al., 1997) while MIT for the development of Emissions Prediction and Policy Analysis (EPPA) model uses a computable economic equilibrium model in a full macroeconomic framework (Babiker et al., 2001). A Computable General

Equilibrium framework in studying the interactions of energy and environment with economy is presented in GEM-E3 (Capros et al., 1995, 1997). Models establishing a connection between energy production (consumption) and aggregated macroeconomic growth models are ETA-MACRO (Manne, 1981), GLOBAL-2100 (Manne and Rishels, 1993), MARKAL-MACRO (Hamilton et al., 1992) and MERGE (Manne and Richels, 2005). At the same time biosphere-oriented models are system based models entailing geophysical and biogeochemical processes. Finally there is a category which combines the characteristics of both orientations known as *hybrid models*. Examples of the tradeoffs of a general equilibrium framework and the dynamic environment are the GCAM and the MIT models.

Recently, models have been developed that incorporate co-benefits for different countries and regions analyses of policies that maximize the benefits between air pollution control and greenhouse gas abatement. An example of these models is the GAINS model (Amann et al., 2008).

3.3 Damage costs

Stern review (Stern, 2007) concludes that serious and early action to control GHGs makes sense with the avoided damage costs to outset the associated costs of achieving the targeted abatement. In summary it can be said that doing nothing to cope with GHGs (Business as Usual, **BAU**) would imply a climate change damage equal to approximately 10.9% reduction in global consumption per capita. Stabilization at 550 parts per million CO_2e will reduce costs to 1.1% and these costs to stabilize at 550 ppm would be approximately 1% of gross world product. The Stern review estimated climate change costs by using IAMs and various scenarios for

GHGs emissions and concentrations and the associated damage costs corresponding to reduced consumption.[11]

Damage costs estimations can be found also in the various integrated assessment models (IAMs) like DICE, PAGE and FUND. Nordhaus (1994a) presents estimates of percentage losses in world's gross product; Roughgarden and Schneider (1999) moving on in the lines of Nordhaus and various other surveys, present a damage function and its confidence intervals; Heal and Kriström (2002) and Pizer (2006) approach uncertainty by subjective analysis and using experts' opinions. Particularly, Pizer (2003) modified the DICE model (Nordhaus, 1994b) by substituting in a more complex way the quadratic relationship between temperature change and damage. Nordhaus (2008) presents a range of marginal damages of pollutants between $6 and $65/t carbon with a central estimate of $27. In line with the Nordhaus' (2008) estimates, Interagency Working Group on Social Cost of Carbon (2010) cites a mean cost of $21/t and a $65/t in the 95th% estimate.

In the case of GHGs air pollution the first cost-benefit analysis is fount in Nordhaus (1991) while Tol (2013) cites 16 studies and 17 estimates of climate's change global welfare impacts (Nordhaus 1994a,b, 2006, 2008, 2011; Fankhauser 1994, 1995; Tol 1995, 2002a,b; Bosello et al. 2012; Maddison 2003; Mendelsohn et al. 2000a,b; Maddison and Rehdanz 2011; Rehdanz and Maddison 2005). Specifically, Tol (2013) applying kernel density estimators to 588 estimates expressed in US$ 2010 and referring to emissions in the year 2010 offers a list of 75 studies with 588 estimates of carbon emissions' social cost. From these studies, Tol finds a mean marginal cost of carbon equal to $196 per metric tone of carbon and a mode estimate

[11] Future consumption losses have to be discounted to the present by appropriate consumption discount rates (d) like $d = \rho + g\,\varepsilon$
where ρ is the social discount rate of time preference. g is the growth rate of average consumption and ε the elasticity of the social weight for a consumption change (For more information see Arrow, 2007).

of \$49/tC; while with 3% and 0% rate of time preference a mean social cost of carbon equal to \$25/tC and \$296/tC respectively is calculated. Obviously using different rates of time preference lead to high asymmetry in estimates with higher rates of time preference indicating that future climate change costs present a lower present value. [12]

3.4 Uncertainties

The associated potential effects of climate change are related among others to energy demand, human health, agriculture, extinction of species and loss of ecosystems etc. The effect of past GHGs on global temperatures is not easy to be estimated. The IPCC (2001) claims that in the 20th century, global temperatures increased in the range of $0{,}6\pm0{,}2^{\circ}$ C and provide a number of possible effects of global warming on climate like extreme weather events (with very possible summer droughts in continental areas, higher heat waves, etc), tropical storm intensity (hurricanes, etc), decomposition of methane hydrates, etc.

Climate change uncertainties may be distinguished as parametric and stochastic (Kelly and Kolstad, 1999; Kann and Weyant 2000; Peterson, 2006). The existing IAMs examine mainly the prametric uncertainty attributed to the assumed main parameters like climate sensitivity, damage functions etc. According to Golub et al. (2011) climate sensitivity and damage functions justify the parametric while

[12] **Discounting** is important. Future costs and damages associated with GHG emissions are expressed in present value (PV) terms. PV of €1 received 25 years from now is the amount we have to invest today to have €1 in 25 years. At 5%, this is almost 30 cents; at 2.5% this is 54 cents. But mitigation cost takes place today, while climate damages appear in the future and thus lower discount rates result to higher mitigation costs. The calculation of PV of net benefits requires estimation of benefits and costs flows from different competitive projects for each year into (a finite time horizon) future. A proper discount rate is chosen and the PV of net benefits is estimated for each year into the future. The PV of the total net benefit (TNB) flows are given as:

$$PV_{TNB}= (B_0-C_0)/(1+r)^0 + (B_1-C_1)/(1+r)^1 +...+ (B_n-C_n)/(1+r)^n$$

Where C and B are respectively total costs and benefits in a given time period; r is the discount rate; and n is the project's end period (in years) from the current time. $(B_1 - C_1)$ represents the total net benefits one year from the current time; and $(1+r)^n$ implies that the sum (1+r) is taken to the end period of the project (n^{th} power).

temperature and economy's performance "unresolved" processes justify the stochastic component of uncertainty. Golub et al. (2011) discuss analytically the discrete uncertainty modeling and the special form of real options analysis to model climate policy in case of parametric uncertainty while stochasticity is tackled with the use of stochastic dynamic programming.

Another type of uncertainty stems from the role of clouds, which decrease the solar radiation "reaching" earth's ground by reflecting ultraviolet radiation. This implies that increasing clouds may reduce the effect of greenhouse (McKibbin and Wilcoxen, 2002). At the same time the existence of aerosols in the atmosphere coming from fossil fuels combustion, volcanoes or forests' burning reflect part of the solar radiation and thus reduce climate change. Clouds and aerosols together absorb infrared and this increases warming (McKibbin and Wilcoxen, 2002).

If uncertainty is absent, the efficient control level of emissions may be achieved either by using taxes or tradable permits. But in the case of uncertainty the two instruments are different. If marginal costs are flat (steep) and marginal benefits steep (flat) then permits (taxes) are preferred. Empirical evidence shows that marginal cost curves for controlling GHGs are quite steep with the marginal benefits from controlling emissions being flat. Obviously, uncertainty in cost estimates has to be tackled carefully. Van Vuuren et al. (2007) taking into consideration a number of abatement options, like reductions of non-CO_2 emissions, carbon plantations and various measures in the energy system find that mitigation scenarios end up to lower levels of regional emissions but with increased land use. Cost estimates uncertainty is almost 50%.

3.5 Evolution of emissions

We can approximate the evolution of emissions using the concept of the Environmental Kuznets Curve (EKC) hypothesis and the Kaya identity. A number of EKC studies consider the factors causing this inverted U-shape pattern relationship between environmental damage and per-capita income (for a brief review see Halkos, 2012).[13]

On the other hand, the Kaya identity connects the main factors that determine the level of human effect with climate in the form of CO_2 emissions. That is

$$CO_2 \text{ emissions} \equiv \text{Population} \times (\text{GDP/c}) \times (\text{Energy intensity}) \times (\text{Carbon intensity})$$

where CO_2 emissions come from fossil fuels combustion; GDP/c stands for Gross Domestic Product per capita representing the standards of living; Energy intensity is defined as Energy over GDP; Carbon intensity is defined as CO_2 emissions over energy.[14] Thus policies to reduce emissions must concentrate on more efficient energy use (reducing energy per unit of GDP) and fuel switching (reducing carbon intensity of energy).[15]

Table 3 presents the indices of CO_2 emissions and Kaya identity's main factors (reference year 1990=100; OECD/IEA, 2013). The average annual change (in %) between the reference year and 2011 is presented in the parentheses. As can be

[13] Various efforts have been done in presenting historical or projected data of CO_2 emissions. Schmalensee et al. (1998) using reduced-form models and country panel data for the time period 1950–1990 projected CO_2 emissions from fossil fuels combustion through to the year 2050 and find evidence of an inverted U-shape relationship between CO_2 emissions and per-capita income with a turning point within the sample. Boden et al. (2012) discuss global, regional and national fossil-fuel CO_2 emissions.

[14] Kaya identity differs from the IPAT. The latter reflects the impact of human activity on the environment. That is

$$I = P \times A \times T$$

where I the Human Influence on the environment; P the population; A stands for the mean consumption level (Affluence) for the population with increasing consumption levels to negatively affect the environment; and T represents Technology.

[15] If we totally differentiate Kaya's Identity then this is expressed as growth rates. That is

$$\%\Delta(CO_2 \text{ emissions})=\%\Delta(\text{Population})+\%\Delta(\text{GDP/c})+\%\ \Delta(\text{Energy intensity})+\ \%\ \Delta(\text{Carbon intensity})$$

where Δ represents changes in percentage (%). That is the percentage change in emissions equals the sum of percentage changes in population, GDP/c, energy and carbon intensities.

seen the driving forces in the increase of CO_2 emissions globally are population and GDP/c offsetting energy intensity with carbon intensity to remain stable mainly due to continuous use of fossil fuels and slow adaptation of low-carbon alternatives.

Table 3: Indices of CO_2 emissions and Kaya identity's main factors (reference year 1990=100). In parentheses the average annual change between reference year and 2011

	CO_2 emissions	**Population**	**GDP/c**	**Energy intensity**	**Carbon intensity**
World	149 (1.9%)	132 (1.3%)	148 (1.9%)	77 (-1.2%)	100 (0.0%)
Annex I Parties	96 (-0.2%)	110 (0.5%)	135 (1.4%)	70 (-1.7%)	93 (-0.3%)
Non-Annex I Parties	261 (4.7%)	138 (1.5%)	220 (3.8%)	77 (-1.2%)	112 (0.5%)
Annex I Kyoto Parties	88 (-0.8%)	104 (0.2%)	132 (1.3%)	70 (-1.7%)	91 (-0.4%)
Annex II Parties	106 (0.3%)	114 (0.6%)	132 (1.3%)	74 (-1.4%)	95 (-0.3%)
Annex II North America	110 (0.4%)	125 (1.1%)	133 (1.4%)	69 (-1.7%)	95 (-0.20%)
Annex II Europe	93 (-0.3%)	110 (0.4%)	132 (1.3%)	74 (-1.4%)	87 (-0.7%)
Annex II Asia Ocania	120 (0.9%)	108 (0.3%)	121 (0.9%)	86 (-0.7%)	107 (0.3%)
Non-OECD Total	194 (3.2%)	135 (1.5%)	198 (3.3%)	68 (-1.8%)	106 (0.3%)
OECD Total	111 (0.5%)	117 (0.7%)	135 (1.4%)	75 (-1.4%)	94 (-0.3%)

Source: Highlights © OECD/IEA (2013).

In more details, Table 4 presents the total and per capita CO_2 emissions in million tons and in kg respectively by sector in the year 2011 with the last column to display the percentage change in CO_2 emissions in the time period 1990-2010 (OECD/IEA, 2013). Similarly, Table 5 presents CO_2 emissions in the year 2011 per Total Primary Energy Supply (TPES), per GDP in Purchasing Power Parity and per capita with percentage changes in parentheses for the time period 1990-2010 (OECD/IEA, 2013).

Table 4: Total (in million tons) and per capita (in kg) CO_2 emissions by sector in 2011 (CO_2/c in parentheses)

	Electricity and heat production	Other Energy industry own Use	Manufacturing Industry and Construction	Transport	Other sectors	% Change 1990-2010
Annex I Parties	5589.5 (4324)	663.6 (513)	1956.9 (1514)	3386.6 (2620)	1758.3 (1360)	-3.9
Non-Annex I Parties	7477.2 (1320)	879.3 (155)	4551.7 (803)	2500.9 (441)	1464.6 (259)	160.8
Annex I Kyoto Parties	3234.2 (3606)	384.8 (429)	1290.5 (1439)	1691.2 (1886)	1112.8 (1241)	-12.1
Non-OECD	8154.6 (1426)	857.6 (150)	4740.9 (829)	2557.2 (447)	1577.5 (276)	94
OECD	4912.1 (3960)	685.2 (552)	1767.8 (1426)	3330.2 (2685)	1645.5 (1326)	10.7
USA	2212 (7089)	266 (852)	597.9 (1916)	1638.1 (5250)	573.2 (1837)	8.6
OECD Europe	1353.6 (2439)	182.5 (329)	590.8 (1065)	936.5 (1688)	683.6 (1232)	-5.2
EU-27	1320 (2622)	168 (334)	547.3 (1087)	891.5 (1771)	615.9 (1224)	-12.6
Non-OECD Europe/Eurasia	1399.4 (4121)	138.1 (407)	478.1 (1408)	384.8 (1133)	342.6 (1009)	-31.2
Africa	412.2 (394)	39.9 (38)	163 (156)	245.9 (235)	106.7 (102)	77.7
World	13066.8 (1878)	1542.9 (222)	6508.7 (935)	7001.1 (1006)	3222.9 (463)	49.3

Source: Highlights © OECD/IEA (2013).

Table 5: CO_2 emissions in 2011 per Total Primary Energy Supply (TPES), per GDP in Purchasing Power Parity and per capita (% changes in parentheses for 1990-2011)

	CO_2 / TPES (in tons CO_2/terajoule)	CO_2 / GDP PPP (in kg CO_2/US 2005 $)	CO_2/ Population (in CO_2/c)
Annex I Parties	55.3 (-7.0)	0.36 (-35.2)	10.33 (-12.6)
Non-Annex I Parties	57.7 (11.9)	0.52 (-13.8)	2.98 (89.4)
Annex I Kyoto Parties	53.7 (-8.6)	0.33 (-36.1)	8.60 (-15.7)
Non-OECD	57.4 (5.7)	0.55 (-27.7)	3.13 (43.4)
OECD	55.6 (-5.6)	0.33 (-29.6)	9.95 (-5.1)
USA	57.6 (-5.1)	0.40 (-34.6)	16.94 (-12.9)
OECD Europe	51 (-12.5)	0.25 (-36.9)	6.75 (-14.5)
EU-27	51.2 (-13.5)	0.25 (-40.2)	7.04 (-17.9)
Non-OECD Europe / Eurasia	55.7 (-10.1)	0.75 (-40.0)	8.08 (-30.5)
Africa	33 (-0.4)	0.34 (-15.7)	0.93 (7.7)
World	57.1 (0.0)	0.45 (-23.2)	4.50 (13.5)

Source: Highlights © OECD/IEA (2013).

Production using energy creates entropy, which increases when the initial useful energy is turned to redundant energy that cannot be converted into work. The existing mass of living organisms in an area is the biomass. Fossil fuels originate from biomass existing long time before human beings. The existence of biomass and its availability depends on the existence of lands and waters. The necessary areas to supply the required ecological services to maintain life can be assessed by the notion of the ***EC**ological **F**ootprint* (ECF). The notion approximates the area needed to supply what a society or an economy needs to consume as well as to absorb the resulting wastes[16].

If we distinguish between renewable and non-renewable energy then the latter are finite and may be exhausted if we have an irrational use.[17] In terms of the ecological footprint and by using the IPAT equation, the total environmental effect can be approximated as:

$$\text{Effect} = \text{Population x (GDP/c) x (ECF/GDP)}$$

In this way it is obvious that ecological footprint must be less than the available area.

[16] We assume that the total waste emissions are lower that the assimilative capacity of the environment to absorb them. In the case of carbon, economic growth with reduced carbon footprint requires low carbon growth.

[17] For sustainability it is necessary to assume that harvesting rates are lower than the rates of regeneration.

3.5.1 Impact of financial crisis on emissions projections

Global financial crisis is an interesting issue in terms of affecting emissions projections. Peters et al. (2012) showed that the level of global CO_2 emissions from burning fossil-fuels and cement production increased almost 6% in 2010 surpassing 9 billion metric tones of carbon and offsetting more than the 1.4% decrease in 2009. They show that the impact of the financial crisis of the years 2008–2009 on emissions has a short-run character due to the significant increase of emissions in emerging countries and the return to high emissions in developed countries accompanied with higher fossil-fuel intensity globally.

Recently all major organizations (like among others IEA, OECD, McKinsey and Company and IIASA) have updated their projections including the effect of financial crisis on emissions. The results are similar and reveal a modest impact of financial crisis on emissions. Specifically, for 2020 and 2030 emissions projections only about 6% appear to have dropped relative to estimates before the global financial crisis (McKinsey and Company, 2010). This small impact appears to be more significant in developed countries than in developing countries. In a by-sector analysis, sectors which are linked to GDP appear to be more affected than sectors which are not linked to GDP. On the one hand, examples of sectors linked to GDP are the power, industry and services sectors. On the other hand, sectors such as agriculture, forestry and waste generation are linked with population and not with GDP, therefore they suffer less or no impact from crisis.

There are three reasons for this modest change relative to the pre-crisis results. Firstly, projections are made using long historical time series and consider a large time period towards 2030. Therefore, financial crisis is a relatively small time period. Second, a number of large developing countries such as China, which produce a large amount of emissions, are less exposed to the crisis or their economic systems have been adapted well to the new economic reality. Last, some sectors like agriculture, forestry and waste generation are not linked with GDP and are not affected by the crisis.

The modest reduction in emissions projection has not altered the total abatement potential relative to the pre-crisis period. However, there might be slightly lower abatement costs and lower fossil fuels prices. It is very important for the countries to continue their efforts for emissions reductions as any delay may result in a less abatement potentials in the future.

4. Costs of abatement: concepts and methods of calculation

4.1 Costs associated with emissions control

Hourcade et al. (1996) distinguish four types of costs associated with emissions control: direct, partial and general equilibrium and nonmarket costs.[18] The first classification of direct costs refers to the abatement unit used to control emissions or insulate houses or substituting high carbon content fuels with low. The partial equilibrium costs include the direct costs but take into consideration the reduction in producer and consumer surpluses caused by the increase in GHG emissions which is not traded in the economy. For instance if the price of oil increases both producers and consumers adjust to the increased price by keeping other prices constant.

The general equilibrium costs include all economic costs of GHG emissions abatement. Kolstad and Toman (2005) explain this cost distinction using as an example the sequence of an increase in the price of carbon, the expected fall in the (net of tax) price of oil, the negative effect on the oil industry and the consequences

[18] Jaffe et al. (1995) propose other costs like transaction and government administration.

for enterprises supplying inputs to oil industry, to local industry depending on the income workers earn from the oil industry. These secondary impacts from these sectoral effects are not usually elevated in the partial equilibrium costs distinction. Finally, we may have nonmarket costs outside the markets as long run unemployment due to policies that restrict GHG emissions and the human burden of unemployment includes nonmonetary factors (Kolstad and Toman, 2005).

Next let us consider the cost curves for abating emissions, the methods of constructing them before we proceed in the next session to their use in policy making.

4.2 Methods of constructing abatement cost curves

Two different approaches to energy-economy modeling exist.[19] Bottom-up or engineering models and top-down or economic models are the two modeling approaches which lead to very different properties and model results according to the analyses of emissions and abatement costs. Bottom-up modeling is based on disaggregation and technical parameters, whereas top-down modeling is based on aggregation and on macroeconomic principles. Mixture or integrated engineering and economic models may also be used to construct an abatement cost curve.

4.2.1 Bottom-up or engineering models

In this case emissions abatement objectives are defined and all potential methods to accomplish this target are listed. For each method, the costs on pollution control installation are estimated together with various other costs like initial investments, fuels used, operation and maintenance, labour and electricity, etc. Next, the total costs imposed to each firm are estimated extracting the total control cost curve.

[19] Initially a simplified method is to construct a supply abatement curve. According to Jackson (1991), Naucler and Enkvist (2009) and Kesicki (2010) a supply curve combines the options for supplying energy given demand side options in order to adopt cost effective method of reducing emissions of CO_2.

A bottom-up model as disaggregated model in order to estimate structural changes in the economy is necessary to have available data regarding technologies, the diffusion rate of facilities and the rate of use to capacity. Particularly, bottom-up models describe the demand and supply in a disaggregated way in order to estimate potentials which for example refer to substitution of technologies with low carbon emissions.

The bottom-up approach describes current and potential technologies in detail. It also describes past and present technologies using quantitative data. The purpose is to convert them to desired services and alternative technologies that can provide the same services but with less energy consumption (Wilson and Swisher, 1993; Bohringer and Rutherford, 2009; Loschel, 2002; van Vuuren et al., 2009). More specifically, it investigates how an individual technology can be applied or how can be substituted so as to provide energy services. Bottom-up models are solutions oriented in terms of trying to find a cost-effective strategy to use as little energy as possible to provide a given level of energy services (Wilson and Swisher, 1993).

The analysts of bottom-up modeling propose the substitution of technologies with more energy efficient ones. They also estimate the impacts of these investments on energy demand by developing scenarios that describe cost-effective potentials for implementing energy demand and supply side technologies. The calculation of the potential is based on summing the net costs of technology options. Hence, the technology options are ranked as the costs increase drawing graphically a marginal cost curve or supply curve of emissions reductions or conserved energy. The crucial assumptions of bottom-up modeling to take into account are the costs, total energy consumption of a country, the lifetimes of technologies and alternative technologies, fuel and electricity costs and potential rates of technologies (Wilson and Swisher, 1993).

There are various bottom-up approaches like econometric models, optimization and simulation modelling and accounting frameworks (Jacobsen, 1998). In econometric models socio-economic variables are included endogenously so as to explain the evolution of structural and behavioral changes although unexpected shocks of weather cannot be included and as a consequence the results of the analysis of the econometric relations are biased. Optimization models usually rely on linear programming and various constraints to derive the least cost ways of achieving a targeted energy demand. In this approach consumer choices are included assuming rationality in consumer's behavior and no market imperfections. Simulation modeling imitates energy users and producers using various indications like prices, incomes etc. Its purpose is to simulate variables such as energy prices and technology costs in order to calculate the potentials of energy savings and substitutions.

On the other hand accounting modelling frameworks examine explicitly the decision outcomes by considering the effects of various scenarios attaining a certain target like, for instance, the costs and benefits (in energy savings and emission reductions) in using renewable energy sources. But accounting models lack important dynamics and the changes in socio-economic variables are difficult to be assessed and interpreted. Moreover, variables that would be crucial to be circulated endogenously in the model are presumed to be exogenous.

Here we may consider the Long-range Energy Alternatives System (LEAP) as an evolution of the energy system models. LEAP is a flexible modeling environment allowing us to build applications appropriate to specific problems at different geographical levels (cities, countries, regions or globally). The model is based on accounting framework to create appropriate energy demand and supply relying on physical representation of the energy system. It also uses different scenarios to explain the appropriate possible pathways of the evolution of the energy system. [20]

The energy system in many bottom-up models is not necessarily optimal. As a consequence many cost-efficient technologies are not used because of barriers to implement them. Another weakness of this type of approach is that bottom-up models only partially represent the economy and they do not include market responses. Bottom up models characteristic is the representation of technology which allows simulating the actual sector in partial equilibrium setting (Tuladhar et al., 2009; Bohringer and Rutherford, 2008). Additionally this type of models includes an excessive number of exogenous variables something that is a factor which can cause deviations from reality. Also there is a difficulty to estimate macroeconomic costs in terms of GDP. Microeconomic costs can be calculated using cost-benefit analysis. However there is interdependence between macroeconomic and microeconomic analysis due to interdependence of indicators. These approaches often neglect the macroeconomic impact of energy policies (Tuladhar et al., 2009; Bohriger and Rutherford, 2009; van Vuuren et al., 2009).

4.2.2 Top-down or economic models

These are models relying on aggregate economic variables and their relationships as determined by the economic theory. That is the top-down approach, assuming efficient markets, uses aggregate data to assess the benefits and costs of the impact of emissions control (like GHG mitigation) on income and GDP. It also considers the changes to the economy caused by these mitigation efforts. A number of

[20] As climate change demands the consideration of very LR time periods (more than a 100 years), researchers started using LEAP model, which has been applied as the standard way in national communications for the UNFCCC reporting. In the supply-side the model uses accounting and simulation approaches in order to provide answers under alternative possible development scenarios to "what-if" type of analysis.

assumptions are required which may not correspond to real world markets. There are mainly three top-down modeling approaches: macroeconomic, input-output and computable general equilibrium.

Top-down models take into account initial distortions of the market, spillovers and income effects for households or government (Bohringer and Rutherford, 2008; 2009; Wing, 2008; van Vuuren et al., 2009; Jacobsen, 1998). This category of models can be identified into two sub-categories. The first incorporates primal simulations of an aggregate Ramsey growth model with the environmental sector to be based on historical data. For instance, DICE and RICE models belong in this category. The second type of top-down models includes dual computable general equilibrium simulations (CGE) or optimal growth model as for example the MIT Emissions Prediction and Policy Analysis (EPPA) model (Paltsev et al. 2005). CGE models are based on maximization of utility, minimization of cost and market equilibrium for goods. Top-down models greatest advantage is that assess the feedbacks effects between energy system and prices, commodity substitution, income and economic welfare (Wing, 2008).

“Top-down” CGE models divide the world into economically important regions and model demand and supply for commodities in all sectors of economy. Relationships are estimated econometrically or are calibrated. Models are solved for equilibrium before and after a shock (say introduction of carbon tax in the economy). They estimate costs of mitigation by imposing a worldwide carbon tax. Tax causes substitution of low for high carbon fuel with this cost corresponding to mitigation cost. Then by comparing the values of the associated variables in the base and shocked case, cost estimates are derived.

4.2.3 Integrated engineering-economic models

Another way to construct abatement cost curves is to rely on cost estimates as extracted by combining engineering and economic models. Recently, there is a wide effort to combine the characteristics of the two approaches into one. Hybrid modeling is the attempt to join a technological bottom-up with a top-down macroeconomic framework, in terms of integrating engineering data and macroeconomic accounts (Hourcade et al., 2006; Bohringer and Rutherford, 2008; Wing, 2008). According to Bohringer and Rutherford (2008) there are three different approaches of hybrid models. Initially bottom-up and top-down models can be combined but the two models are developed independently with the consequence of inconsistencies. Second, bottom-up models can incorporate macro-economic feedbacks or top-down models can incorporate technological explicitness (Hourcade et al., 2006). The last approach represents totally integrated models based on solution algorithms. Research as regards to hybrid modeling include Jaccard et al. (2004), Bohringer (1998), Jacobsen (1998), Koopmans and te Velde (2001), Bohringer et al. (2003), Frei et al. (2003), Kumbaroglu and Madlener (2003), McFarland et al.(2004), Bohringer and Rutherford (2008) and Wing (2008).

4.2.3.1 Bottom-up versus top-down models

Top-down and bottom-up approaches are different because of the different domain that each approach represents (IPCC, 2001). Top-down estimates of abatement costs are usually high compared to bottom-up as the latter are optimistic in determining feasible cost-effective methods to control GHGs. A number of other factors apart from technological feasibility may increase abatement costs (Kolstad and Toman, 2005; Jaffe et al., 1995). Top-down modeling may be useful in exploring the macroeconomic impact of fiscal environmental policies like environmental taxation while bottom-up modeling helps in exploring specific effects of control methods on different sectors.

GHGs mitigation may lead to benefits from the reduced damages. In Stern’s (2007) review, the high climate scenario among various scenarios shows increasing damages of the climate change in the case of BAU policy. Specifically, by the year 2200 the GNP losses are expected at a level of almost 14%.

Various researchers apply energy economic models to estimate the costs of CO_2 control options (Morthorst, 1994; Maya and Fenhann, 1994; Amous et al., 1994; Mahgary et al., 1994; Halsnses et al., 1994). Mosnaim (2001) applies a bottom-up approach to estimate the costs of CO_2 emissions abatement and sequestration alternatives in Clile. Ribbenhed et al. (2007) using a bottom-up approach rank abatement options to reduce CO_2 emissions in the Swedish iron ore-based steelmaking sector. Hasanbeigi et al. (2010) constructed a bottom-up CO_2 abatement cost curve for the Thai cement industry to determine the potentials and costs of CO_2 abatement, taking into account the costs and CO_2 abatement of different technologies. According to Blok et al. (2001) an integrated modelling analysis of the energy system and the associated emissions with the PRIMES model developed by the National Technical University of Athens (or 'top-down approach'), and an engineering-economic analysis of individual emission reduction options(or 'bottom-up approach'), based on sector studies performed by Ecofys and AEA technology and analysed with the GENESIS database.

Moreover the paper of Novikova (2009) aims to address this gap in knowledge and summarizes the results of research aimed at quantifying the potential to improve electric efficiency and reduce electricity-associated CO_2 emissions from the Hungarian tertiary sector up to the year 2025 as a function of cost of conserved CO_2.

To achieve the research purpose, a database of CO_2 mitigation technologies and practices has been created and a bottom-up model has been developed to estimate the baseline final electricity consumption and associated CO_2 emissions from Hungarian tertiary buildings and conduct individual and incremental assessment of mitigation options in terms of their potential for CO_2 emission abatement and costs resulted from deployment of these mitigation options in the sector.

4.3 Marginal Abatement Cost curves

Marginal abatement cost (**MAC**) curves is a key tool which has been developed since the early 1990s to illustrate the costs associated with carbon mitigation and to contribute to determining optimal level of pollution control (Halkos and Kitsou, 2014; Beaumont and Tinch, 2004; McKintrick, 1999). Policy makers try to introduce and implement a concrete and consistent policy to achieve the desirable emissions reduction. The authorities or the decisions makers seek to maximize control efforts under their budget constraints.

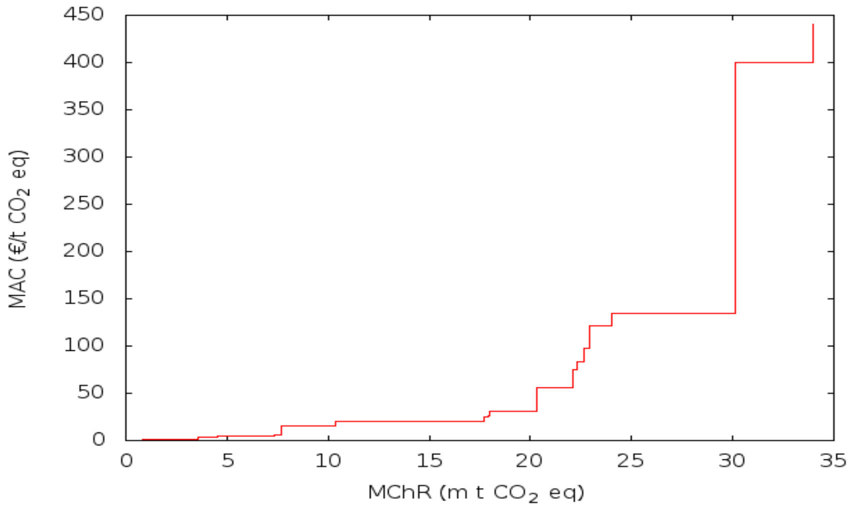
More specifically, an abatement cost curve as a graph depicts the cost of the emissions reduction. Marginal costs increase as we switch between abatement methods with the abatement rising to the maximum feasible level. In this way the MAC curve is a discontinuous step function presenting a staircase shape with each step representing a specific control method. That is each step of this stepwise curve represents solely one technological option and the level of each step shows the additional cost of an abatement method relative to the maximum incremental amount of the pollutant abated by introducing that method (Halkos, 1992; 1995; 2010). The height of each step represents the cost of € per tone of CO_2 abated and the width refers to the magnitude of emission reduction for each mitigation option. The sequence of cost-effective abatement methods provides us with the long-run MAC.

As with any pollutant, the challenge is to reduce GHG emissions in a cost-effective way with the total annualized cost divided by the annual tonnes of emissions removed to be minimized. Assuming "cost-effectiveness" in the potential application of the abatement techniques for a given method in a given pollution source implies achievement of the highest reduction at the lowest cost. Thus cheaper options have to be preferred compared to more costly ones as it would be inefficient to use the most costly abatement methods first if there are cheaper alternatives. In this way national abatement cost curves exhibit non-decreasing marginal costs and the most cost-effective techniques will be the appropriate control methods for the national decision maker.

Control methods may differ in applicability as well as in costs. Abatement costs are independent of the order of application and technologies applied for the abatement of emissions are scale specific. That is constant returns to scale are assumed with fixed abatement coefficients over the abatement range at which each abatement method is efficient. At the same time, both fuel use and costs are assumed given independently of abatement policy with the existence of a competitive market for abatement methods which is accessible to all European countries at the same conditions. Moreover, the mitigation options are assessed for a specific year.[21] Figure 2 presents an example of the marginal abatement cost curve for F-gases control for the EU-27 in 2020 (Halkos, 2010).

[21] This approach however includes flaws such as not taking into account neither the potential interdependencies between the options in the system nor the intertemporal dynamics nor the indirect costs such as implementation, search cost or financial costs (Ekins et al., 2011; Kesicki, 2010; Morthorst, 1994).

Figure 2: F-gases abatement cost curve for EU-27 in 2020



Source: Halkos (2010).

Following Halkos (1992, 1995; 1996a,b) the abatement cost of an emission control method (say Fluidized Bed Combustion) is given by the total annualized cost (TAC) of a control method, including capital and operating cost components. That is:

$$TAC = \left\{ (TCC) \left[\frac{r}{1-(1+r)^{-n}} \right] \right\} + VOMC + FOMC \qquad (1)$$

where TCC represents the total capital cost (using investments as a measure for total capital cost); VOMC and FOMC: variable and fixed operational and maintenance cost respectively; $r/[1 - (1 + r)^{-n}]$ reflects the capital recovery factor at a real discount rate r, converting a capital cost to an equivalent stream of equal annual future payments, considering the time value of money (represented by r). Finally, n is the economic life of the asset (in years). For the economic and technical assumptions in cost calculations see Halkos (1992; 1995; 2010). The calculation of annual operating and maintenance costs requires the availability of the pollutant's content in fuel used (e.g. content of pollutant in coal used in an industrial unit), the annual operating hours, the assumed abatement efficiency of the installed abatement unit, as well as country specific conditions like fuel prices, capacity/vehicles utilization and emission factors. Growth rates in industrial productivity and in population are important factors of abatement costs in controlling GHGs.

Alternatively we can use USEPA's (2006) methodology in order to construct a MAC curve. USEPA defines as the abatement method's breakeven price the carbon price where a method's costs equal to benefits. The calculation of the breakeven price is presented below (modified from USEPA, 2006):

$$P = \frac{CC}{(1-t)*PR*\sum_{n=1}^{N}\frac{1}{(1+d)^n}} + \frac{RC-TR}{PR} - \frac{CC}{n*PR}*\frac{t}{(1-t)} \qquad (2)$$

Where P represents the breakeven price of the option (€/tCO2eq); CC is the one-time capital cost of the option (€); t represents the tax rate (%); PR stands for the pollutant's emissions reduction achieved by the method applied ($MtCO_2eq$); RC is the operating and maintenance cost of the adopted method (€/year); TR reflects the total revenues generated from energy production (scaled on regional energy prices) or sales of abatement by-products or change in agricultural commodity prices (€); N is the method's lifetime (in years); and d stands for the discount rate.

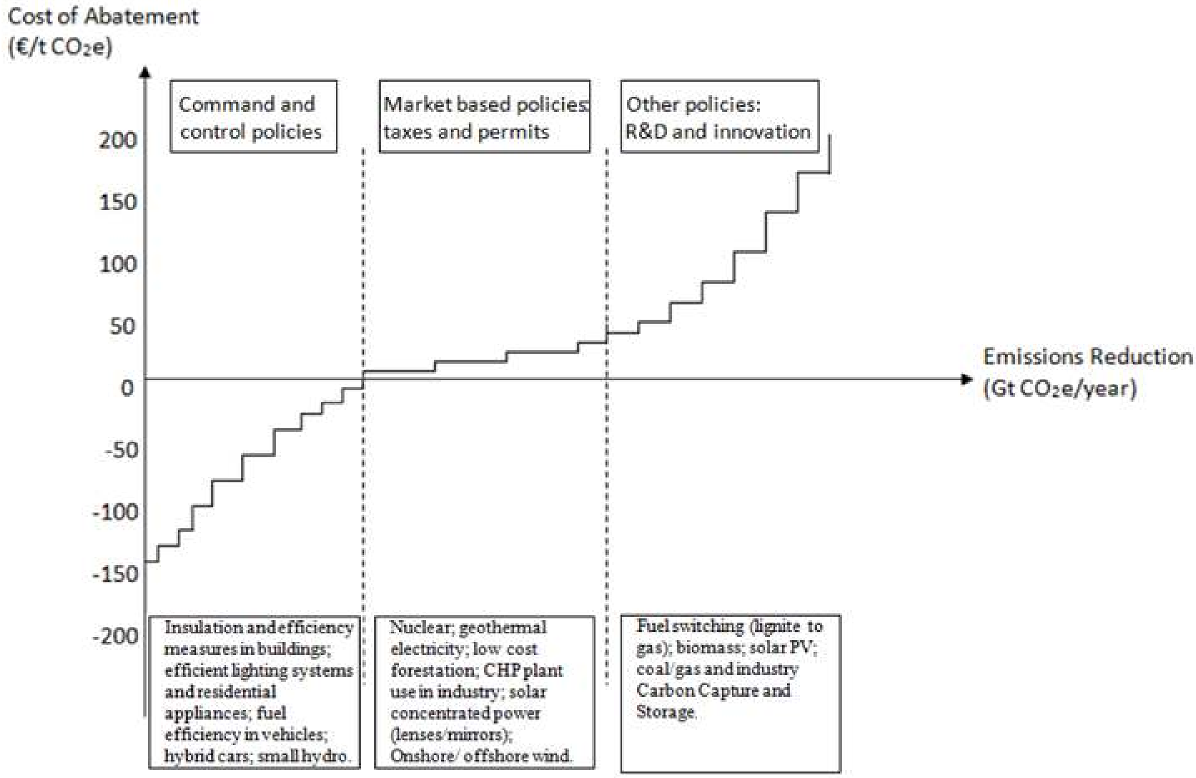
Figure 3 presents a hypothetical abatement cost curve for global CO_2 emissions reduction.[22] Specifically, it presents a hypothetical calculation of the maximum potential abatement of some possible and feasible control methods. Their order of introduction may change according to country conditions and requirements. As can be seen Figure 3 shows significant amounts of negative costs. That is the abatement cost curve (as in McKinsey and Company's and Kesicki's abatement cost curves) does not only include positive costs but presents also negative costs. Many of negative cost opportunities involve energy efficiency measures while some may

[22] Examples of constructed abatement cost curves can be fount in McKinsey and Company's global GHG abatement cost curve beyond business as usual for the year 2030 and in Kesicki (2011, p. 3) with an expert based derived CO_2 abatement cost curve.

involve land use, especially in countries with large tropical forest areas. The abatement options with negative cost may be defined in the literature as no regrets mitigation options. The existence of negative costs means that the society benefits from the specified mitigation actions.

Ekins et al. (2011) mention that in the case of the McKinsey abatement cost curve as the project costs are correctly estimated, the explanation of these negative costs may be based on the insufficient definition of the extensive cost, the implementation of non-financial barriers or inconsistent discount rates. Further, they note that markets are not perfect and suffer from various imperfections. So, the cost curve cannot assume rational agents, perfect information and no transaction costs. Ackerman and Bueno (2011) present an overview of the McKinsey and Company's results and discuss the controversy about the meaning of the negative abatement costs. They mention that for this phenomenon McKinsey is not alone as there are bottom-up studies for energy savings and emission reductions which have negative cost options.

Figure 3: A hypothetical CO_2 abatement cost curve



In order to avoid the academic controversy about the interpretation of negative cost investment opportunities they offer a new method. Their method obtains estimates which are in some respects comparable to other bottom-up analysis of energy costs. Finally, they note that, according to Brown (2001, p. 1199) there are a range of market failures (like distortionary fiscal and regulatory policies, unprized costs and benefits, imperfect information) and market barriers (like low attention to energy issues, capital market barriers and incomplete markets for energy efficiency) that explain the existence of an efficiency gap. This disparity is the difference between the actual energy efficiency level of investment and the higher potential cost-beneficial level from the consumer's side.

5. Basic policy approaches for reducing GHGs

The construction of abatement cost curves increases the environmental awareness of firms in terms of giving insight into the most cost-efficient measures to abate emissions (Beaumont and Tinch, 2004). Furthermore, they provide knowledge regarding command and control regulations to tackle market imperfections in the field of energy efficiency, conservation in buildings, industry and transport (Kesicki, 2010).

GHGs abatement costs are uncertain and differ among countries. Various studies have been carried out determining the marginal abatement cost of controlling GHGs by calculating a carbon tax imposed on the carbon content of the fossil fuels burned. In the USA the carbon tax ranges from \$94 - \$400 /t of carbon (2000 US \$) to reduce GHGs to 93% of 1990 levels by 2010 (satisfying the Kyoto Protocol target) (IPCC, 2001). Similarly in the case of European OECD countries the tax on carbon to reduce emissions ranges from \$25 to \$825 / t of carbon.

Looking again at Figure 3 and following Kesicki (2011, p. 12) and McKinsey and Company (2009, p. 57) it can be seen that the derived MAC curve may be used by decision makers to establish effective policies to tackle global warming.[23] The left part of the figure requires attention to coping with market imperfections by imposing appropriate regulations. The middle part of the MAC may lead to the effective policies by the adoption of market-based policies (taxes and tradable permits) while the right part of the curve may require more innovation and RandD.

In general we may have direct regulations, provision of financial incentives, taxation on polluters equivalent to the marginal external social costs (in the concept of Pigou taxation), allocation of property rights (Coasean approach) linked with emissions trading with the economic instruments (carbon tax or tradable permits) necessary to drive to a low carbon economy. A regulatory standard fixes neither however it provides the framework where the firms operate (Ellerman, 2000). Environmental taxes were widely used in order to achieve environmental objectives, but the last years tradable permits are quickly gaining ground. The growing popularity of tradable permits is an outcome of the economic advantages they offer because they have the ability to equalize marginal abatement costs among all controlled sources and they assure least-cost compliance with a particular environmental goal (Egenhofer, 2007). Next we discuss the emissions trading scheme and the experience with their applications so far.

[23] Halkos and Kevork (2014) claim that percentiles estimation is important in decision making. They show the significance in analyzing the effects of various environmental policies in different percentiles of the marginal distribution of an environmental variable like the CO_2 annual emissions intensity avoiding the usual problems arising from using the mean as the only statistical parameter. In this way the constructed confidence intervals are more realistic and can be used effectively by the decision makers in their environmental policies.

5.1 Emissions Trading Schemes

Emissions trading schemes could provide the framework for international cooperation among countries because in the GHG emissions problem the location of the polluter country is irrelevant as it is a cross-border issue. The principal problem of GHG emissions is that they diffuse quickly in the atmosphere, so that a tone of CO_2 emitted contributes the same in global emissions regardless the location of the emitter country (Solomon and Lee, 2000).

In an emissions trading framework, an environmental authority sets a target or a cap on total emissions and then issues emission permits, where the total number of permits equals the cap. In order to establish a market for emissions permits, the environmental authority has to decide about: who will participate in the market, the number of emissions permits that will be available in the market and how the permits will be allocated (Kruger et al., 2007). The last decision can be done either by auctioning or by grandfathering or a combination of them. Emissions trading is used as a means of an interchange and can take two forms which are “allowance-based trading or cap-and-trade” and “credit-based trading”. *Allowance-based trading* assumes a fixed cap on aggregate emissions and tradable emission rights while *credit-based trading* is about trading of emission rights (Ellerman, 2000). Emissions trading can be seen as a means towards the reduction of any possible inefficiency of the defined standards. However, emission permits have received much criticism about their immoral nature with the main objection being that permits give someone the “right to pollute”.

Emissions’ trading scheme is an American institutional innovation in environmental regulation. Among other trading schemes, the American Trading Scheme for SO_2 was the first successful Trading Scheme. The value of SO_2

allowances that issued per year was up to €2.8-8.7 billion while other trading schemes such as American NO_X trading programs issued allowances up to €1.1 billion (Grubb and Neuhoff, 2006). United States has brought emissions trading into Kyoto Protocol discussions which met the firm opposition from the European Union (Ellerman and Buchner, 2007). However, as we will present later, the EU has adopted the emissions trading as its core element of the European environmental policy.

The first major step towards the global adoption of emissions trading schemes was made by the commitment of countries in the Kyoto protocol. The commitment that every country has signed in Kyoto protocol is to limit its GHG emissions to some percentage of 1990 emissions on an average annual basis over a five-year of the First Commitment Period (2008-2012). This commitment can be fulfilled by any means but the protocol favors emissions trading. Although "emission permits" are not referred in the Protocol, it includes "assigned annual amounts" which is basically the same and they may be acquired or transferred. In addition it provides a framework for these permits where Annex-B countries (the countries that signed the Kyoto Protocol) can re-allocate the permits among themselves. Furthermore, as shown in sub-section 2.1, the Protocol promotes two very important mechanisms, the Joint Implementation (JI) and the Clean Development Mechanism (CDM). In JI a country finances an emissions reduction project in another country and in CDM trading can take place with a non-Annex B country.

The European Union Emissions Trading Scheme (**EU ETS**) is the largest emissions trading scheme and the first large scale emissions trading scheme for carbon dioxide emissions. The EU has committed to reduce the GHGs emissions by 8% according to 1990 levels under the Kyoto Protocol (Bredin and Muckley, 2011). The principal idea of the EU ETS system is an overall cap on total emissions in all 30 member states that is equal to the target of Kyoto Protocol in order to meet the EU commitments. The EU ETS deals with the CO_2 emissions by creating a framework for the energy-intensive industrial plants and electric utilities in EU to trade emission permits for CO_2 (Kruger et al., 2007). These emissions permits are called European Union Allowances (EUAs) and the three main markets for these allowances are: Powernext, Nord Pool and European Climate Exchange (Daskalakis et al., 2009). The EU ETS is a ‘‘bottom-up’’ and decentralized scheme, with each of the member states responsible for the allocations, the registry and the compliance. The EU ETS is covering approximately 13,000 sources and the value of the EUAs distributed is equal to about €22-66 billion (Grubb and Neuhoff, 2006).

The EU ETS is divided into three periods. First is the trial trading period (2005–2007) which is not part of any commitment under the Kyoto Protocol. The second EU ETS trading period (2008–2012) coincides with the first five-year commitment period under the Kyoto Protocol. Finally, in the post-2012 period no commitment has been made but the EU ETS is expected to continue regardless of what happens to the Kyoto Protocol. Anger (2008) studies the possibility to link EU ETS with other non-European schemes such as Canadian, Australian or Japanese. The author argues that this linkage should be the desirable global environmental goal as it would be beneficial for both energy-intensive and non-energy-intensive countries yielding lower adjustment and compliance costs and a larger emissions market. There are some notable differences among the phases such as that in the trial period countries are allowed to auction up to 5% of their total EUAs and 10% during the second phase. In addition, in the trial period the EU ETS only covers CO_2 emissions from large emitters in the heat and power generation industry and in selected energy-intensive industrial sectors (Ellerman, 2008).

The price of the EUAs is defined by the member states and naturally the bigger the share of a country, the bigger the influence it has on the price. The five member states with the highest shares at the trial period are Germany, the UK, Poland, Italy and Spain (Convery and Redmond, 2007). The non-compliance with EU ETS results in penalty fines. Thus, enterprises which emit more than the EUAs they hold at the end of the accounting period must pay a fine which is 40€ for each metric ton of CO_2 during the trial period and 100€ during the second period (Kettner et al., 2007).

A number of studies investigate the problems and drawbacks of the EU ETS. Jepma (2003) argues that EU ETS has no clear link with the environmental policies of the EU countries. In addition, the author considers the possibility the EU ETS to distort the competition in EU and questions the future perspective of the scheme. Ellerman (2008) signifies the importance of a central coordinating organization for the EU ETS. Additionally, the mechanism should incorporate a number of benefits for compliance in order to encourage the participation in the scheme. Last but not least, the author points to a number of issues such as harmonization, differentiation and stringency. Also, a number of studies question the level of stringency in the mechanism. Demailly and Quirion (2008) investigate the impact of the mechanism's stringency and find that no negative effect emerges from the level of stringency.

The EU ETS covers about 45% of total EU CO_2 emissions (Betz and Sato, 2006). This percentage is not sufficient for EU to meet the Kyoto targets and therefore, member states are encouraged to adopt national environmental strategies in order to accomplish the Kyoto targets (Bohringer et al., 2006). For instance, the Norwegian environmental policy relies entirely on emissions trading in order to meet the Kyoto targets. The Norwegian Emissions Trading Scheme is a more comprehensive system than the EU ETS because it includes all GHGs. The Norwegian scheme is set to begin at the start of the second EU ETS period at 2008. There is a debate in Norway about the allocation of the permits with quite interesting results. The majority of the parties (six out of eleven) recommended auctioning. The second recommendation was about grandfathering while the third opinion was undecided (Ellerman, 2000).

The UK Emissions Trading Scheme is also inspired by the Kyoto Protocol but it is not as tied to the UK's obligations as the Norwegian scheme. The UK environmental authorities use additional policies in order to meet the UK objectives such as environmental tax on natural gas, coal and electricity, namely the Climate Change Levy and the Negotiated sectoral Climate Change Agreements (Smith and Swierzbinski, 2007). The Emissions Trading Scheme allows both allowance-based and credit-based emissions trading. The essence of the UK trading scheme is to reduce the environmental taxes and to provide incentives for the emitters to voluntarily take the cap (Ellerman, 2000). The Danish Electricity Sector Emissions Trading Scheme is in effect from 2001 and includes 1/3 of the Danish CO_2 emissions and aims for a 10% reduction in CO_2 emissions below 1988 levels. The mechanism is about electricity generation companies and the emissions permits are grandfathered. The penalty for non-compliers is up-to $22 per ton of carbon (Ellerman, 2000).

In contrast to the aforementioned schemes the Swedish Flex-Mechs Emissions Trading Scheme has started as an open discussion. The mechanism has a very large coverage including almost all sectors and most of the GHGs. The idea of the scheme is to replace the CO_2 tax and to substitute least-cost solution with best-available-control technology. In addition, the system promotes JI and CDM (Ellerman, 2000). France was one of the major countries (along with Germany) which criticize the emission trading schemes. However, a shift in French environmental policy resulted in the French Emissions Trading Scheme. The mechanism incorporates voluntary negotiated five-year agreements between the government and fossil-fuel intensive sectors which account for 80% of industrial CO_2 emissions and other GHGs. The scheme also promotes JI and CDM. Just like in France, Germany shifted its environmental policy towards an emissions trading scheme. The German Emissions Trading Scheme has limited scope and concerns only large industrial firms. The Dutch Emissions Trading Scheme has also limited scope. It targets JI projects in Central and Eastern Europe.

6. Adaptation

Adaptation to climate change may take place locally. Following Burton (1996) and IPCC (2001) a number of adaptation measures can be applied to cope with climate change risks such as bearing, sharing or preventing losses, modifying the threat, encouraging research for new methods and techniques and changing use, location and behavior through education and appropriate regulations. OECD (2009) provides examples of adaptation for various sectors. Specifically in agriculture we may prevent the loss by investing in new capital or removing market distortions and by changing use in crops and altering farming practices; in coastal zones we may prevent losses by upgrading drainage systems, increasing habitat protection and planning land use; in water we may prevent losses by increasing capacity, using water permits and pricing and by encouraging the change in behavior seeking for rational water use or by collecting rainwater.[24]

[24] For detailed information see Agrawala et al. (2010).

In general all IAMs pay attention mainly to the relationship between damage caused by climate change and the cost of mitigation with adaptation to be either ignored or considered as part of the damage estimation (Fisher et al., 2007; Fankhauser et al., 1999). The first research modeling adaptation in an IAM's set-up is by Hope et al. (1993) who using PAGE they consider two policies of adaptation: no adaptation and aggressive adaptation. They find that the latter should be used as it is more beneficial.

Tol (2008) models adaptation in the FUND model. Relying on Fankhauser (1994) he uses coastal protection as a continuous decision variable and provides useful information on the dynamics of adaptation showing that adaptation is an important way to tackle the effects of sea level rise. What is important is the adverse relationship in the use of mitigation and adaptation as more mitigation may result to fewer resources left to invest in measures of adaptation. Tol claims that very high abatement levels will more likely lead to adverse influence as less adaptation will be used resulting to higher net climate change degradation.

IPCC has included adaptation in every Assessment Report but took 10 years to organize a workshop on adaptation to climate change in Costa Rica in 1998 (Klein and Maciver, 1999) while it has been proved that adaptation is more difficult to be treated compared to mitigation. Kates (1997) refers to the IPCC 2nd volume of 1995 Assessment Report dedicating a few pages to adaptation (around 4% of the pages of the full report). Kates ascribes this to the presence of two schools of thought: the "preventionists" and the "adaptationists". The former consider adaptation as weakening societies' willingness to control GHGs while the latter believe that little adaptation is needed as climate change takes place slowly for nature and the societies to amend easily (Stern et al., 2013).

Use of adaptation may lead to the so-called maladaptation (Mendelsohm, 2000) with Barnett and O'Neil (2010) to put forward several types of maladaptation like reductions in incentives for adaptation and shift in costs to poor and coexisting emissions of GHGs. Moreover, maladaptation may increase costs with no associated benefits and may result to worse environmental conditions. Smit and Wandel (2006) classify four approaches adopted by researchers in their consideration of adaptation: composite indexes; scenarios and statistical and equilibrium modeling; cost-benefit and cost-effectiveness analyses; and "bottom-up" studies in cases of analysis.[25]

Table 5 presents adaptation cost estimates provided by World Bank (2006), Stern (2007), Oxfam (2007), UNDP (2007), UNFCCC (2007) and World Bank (2009). The costs refer to necessary investment levels for adaptation to climate change in developing countries. Additionally, the UNFCCC (2007) reported a total cost for global adaptation by 2030 in the range of $49-171 billion yearly. Specifically, for the developed countries the range of the cost is between $22-105 while for the developing countries is within $27-66 billion per year. IIED (2009) claims that UNFCCC estimates is perhaps underestimated by a factor of between 2 and 3 for the sectors considered and could be much higher with more sectors included.

Table 5: Adaptation cost estimates in developing countries for the years 2010-2015 (in billion US$/year)

World Bank (2006)	9-41
Stern (2007)	4-37
Oxfam (2007)	>50
UNDP (2007)	86-109
UNFCCC (2007)	27-66
World Bank (2009)	75-100

Source: Agrawala and Fankhauser (2008); IIED (2009); Chesney et al. (2013).

[25] For more details see Stern et al. (2013).

7. Conclusions and policy implications

There are various policies to cope with the climate change problem. A number of measures may be adopted to tackle its effects. We may have increasing energy efficiency per unit of output using less energy-intensive methods and demanding products with lower energy intensity or to have reductions in production of high cost carbon intensive products together with increasing sequestration through reforestation and prevention of deforestation. We may store CO_2 (or C) practicing sequestration like storing carbon in trees and plants as planting trees and managing effectively forests are important steps in coping with the problem. We may also use geoengineering increasing the Earth's ability to reflect radiation. The latter may be achieved by using mirrors in space, by large balloons or by painting houses' roofs white. Oceans may play a significant role in dissolving part of CO_2 and other GHGs emissions.

Reducing GHG emissions by controlling emissions from the burning of fossil fuels may be achieved by applying abatement methods (like scrubbers) to control GHG emissions or by reducing the carbon content of the fuels used or using instead of fossil fuels various alternatives energy sources like renewables. Investments in low carbon energy may rely on RES increasing their participation in the global electricity supply.

To be more specific, planning efficient policies requires careful consideration of each sector. Specifically, in power generation we may have fuel switching to less carbon-intensive fuels (like natural gas for oil), and use of nuclear and renewable energy resources like wind, solar photovoltaic, biomass co-firing, geothermal power and small hydroelectric power. In both power generation and industry we may have energy efficiency and use of combined heat and power and carbon capture and storage. In transport we may have policies to increase vehicles' efficiencies, use of new technologies with more hybrid vehicles, careful fuel switching and more effective pricing mechanisms (taxation on gasoline, charging for using the roads, etc). In households we may have higher energy efficiency (associated with human behavioral changes) leading to substantial reductions in energy consumption and pollutants' emissions. The latter may be related to buildings insulation and use of combined heat and power. In general, agriculture and forestry have a great potential in reducing emissions with options related to forestry and to the international framework of Reducing Emissions from Deforestation and forest Degradation (REDD).

The latter may face institutional problems. Generally, the institutional framework is important in the imposition of appropriate policies to cope with or prevent the problem. Halkos and Tzeremes (2013) examined countries' CO_2 emissions and governance relationship using six governance measures (voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, rule of law and control of corruption) as defined in World Governance Indicators from the World Bank. They find a highly nonlinear non-monotonic relationship between CO_2 emissions and governance measures and it seems that countries' higher governance quality does not always result to lower CO_2 emissions.

As control costs of abating GHGs are not certain and may differ among countries, economic analysis may identify the appropriate policy instruments for mitigation. Different policy instruments (like carbon taxes, control subsides, quotas in emissions, performance standards and permits) are required to cope with the problem either directly to emissions or indirectly to pollution related products (like subsidizing a control method or taxing fuels). For some countries taxes may work better compared to permits. Domestically tradable permits may be used to satisfy national targets. The Kyoto Protocol includes international policy tools like the "assigned amounts" concerning national control targets. If a system of international tradable permits is adopted this may reduce costs by 50% (Olmstead and Stavins, 2007) whereas the inclusion of developing countries could lower by half again the costs (Edmonds et al., 1994). As Olmstead and Stavins (2007) propose, for effectiveness, trading has to take place between firms and not countries with international carbon trading markets to be vulnerable to the problems faced by any other market and with serious obstacles imposed by high transaction costs or by the concentration of permits by some firms (countries). This makes initial allocation of permits quite important (Halkos, 1993).

Obviously adaptation and mitigation have to be used together and efficiently. These arguments imply that different forms of mitigation are necessary together with ways to avoid free-riding. Additionally more investments in RandD are required together with developed countries financing mitigation efforts. Measures of adaptation have to be planned in such a way that they can be modified when new information is available. Markandya (2013) incorporates this with the use of option values in CBA or cost-effectiveness analysis. Markandya (2014) claims that delivering adaptive measures requires structural steps including all actions demanding sector-wide changes (physical regulations as well as economic or fiscal incentives). Both public and private sectors have to co-finance some activities and the international community to support the development of market and institutional mechanisms for an efficient level of adaptation.

It is worth mentioning that societies have to understand the ethics of sustainability. To enhance greenhouse effect and the ethics of sustainability, Spash

(2002, p. 223) identifies four rules of ethics in the case of the existing greenhouse effect: the elitist, the egalitarian, the Paretian and the neoclassical utilitarian rules. The first demands that welfare of the best-off are to be improved. The second rule opposes this requiring that the welfare of the worst-off are to increase (max-min principle). The Paretian rule in the lines of the Pareto efficiency reallocates resources in such a way as to find the point where the improvement of a generation's welfare cannot be better off without making someone worse-off. Finally the neoclassical utilitarian rule maximizes utility for all generations by reallocating resources. We may think of the elitist rule as our generation considered as elite and us living now.

References

Ackerman F. and Bueno R. (2011). *Use of McKinsey abatement cost curves for climate economics modeling*. Stockholm Environment Institute. Working Paper WP-US-1102.

Agrawala S. and Fankhauser S. (eds) (2008). *Economic Aspects of Adaptation to Climate Change. Costs, Benefits and Policy Instruments*. OECD, Paris.

Agrawala S., Bosello F., Carraro C., de Bruin K., De Cian E., Delink R. And Lanzi E. (2010). *Plan or react? Analysis of adaptation costs and benefits using Integrated Assessment Models*. OECD Environment Working Papers No. 23, Paris.

Alcamo J., Leemans R. and Kreileman E. (eds) (1998). *Global Change Scenarios of the 21st Century. Results from the IMAGE 2.1 Model*. Pergamon Press, Oxford.

Alcamo J., Shaw R. and Hordijk L. (eds) (1990). *The RAINS Model of Acidification: Science and Strategies in Europe*. Dordecht, The Netherlands: Kluwer Academic Publishers.

Amann M., Bertok I., Borken J., Cofala J., Heyes C., Hoglund L, Klimont Z., Purohit P., Rafaj P., Schoepp W., Toth G., Wagner F. and Winiwarter W. (2008). *GAINS – Potentials and costs for greenhouse gas mitigation in Annex I countries*. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, http://gains.iiasa.ac.at/

Amous S, Revet D and Sokona Y. (1994). Greenhouse gas abatement in Senegal. *Energy Policy,* 22(II), 947-954.

Anger N. (2008). Emissions trading beyond Europe: Linking schemes in a post-Kyoto world. *Energy Economics*, 30, 2028-2049.

Arrow K.J. (2007). Global Climate Change: A challenge to policy. *The Berkley Electronic Press* www.bepress.com.ev

Babiker M.H., Reilly J.M., Mayer M., Eckaus R.S., Wing I.S. and Hyman R.C. (2001). The MIT Emissions Prediction and Policy Analysis (EPPA) model: Revisions, sensitivities and comparison results, MIT Joint Program on the Science and Policy of Global Change, Report No 71.

Barnett J. and O'Neill S. (2010). Maladaptation. *Global Environmental Change,* 20, 211–213.

Barrett S. (2007). Proposal for a new climate change treaty system. *The Berkley Electronic Press* www.bepress.com.ev

Beaumont N.J. and Tinch R. (2004). Abatement cost curves: a viable management tool for enabling the achievement of win-win waste reduction strategies? *Journal of Environmental Management,* 71(3), 207-215.

Betz R. and Sato M. (2006). Emissions trading: lessons learnt from the 1st phase of the EU ETS and prospects for the 2nd phase. *Climate Policy*, 6, 351-359.

Blok K., De Jager D. and Hendriks C. (2001). Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change—Summary Report for Policy Makers. Ecofys, Utrecht, The Netherlands.

Boden T.A., Marland G. and Andres R.J. (2012). Global, Regional, and National Fossil-Fuel CO_2 Emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., USA DOI: 10.3334/CDIAC/00001_V2012

Boehringer C., Hoffmann T. and Loeschel A. (2003). Dismantling Nuclear Power in Europe: Macroeconomic and Environmental Impacts. ZEW Discussion Paper, vol. 03–15. Center for European Economic Research, Mannheim.

Böhringer C., Hoffmann T. and Manrique-de-Lara-Penate C. (2006). The efficiency costs of separating carbon markets under the EU emissions trading scheme: A quantitative assessment for Germany. *Energy Economics*, 28, 44-61.

Böhringer C. (1998). The synthesis of bottom-up and top-down in energy policy modeling. *Energy Economics*, 20, 13 233–48.

Böhringer C. and Rutherford T.F. (2008). Combining bottom-up and top-down, *Energy Economics,* 30(2), 574-596.

Böhringer C. and Rutherford T.F. (2009). Integrated assessment of energy policies: Decomposing top-down and bottom-up. *Journal of Economic Dynamics and Control*, 33(9), 1648-1661.

Bosello, F., Carraro, C., and E. De Cian (2010) Climate policy and the optimal balance between mitigation, adaptation and unavoided damage. *Climate Change Economics,* 1, 71–92.

Bosello F., Eboli F. and Pierfederici R. (2012). Assessing the economic impacts of climate change. *Review of Environment Energy and Economics*, 1–9.

Bredin D. and Muckley C. (2011). An emerging equilibrium in the EU emissions trading scheme. *Energy Economics*, 33, 353-362.

Brown M.A. (2001). Market failures and barriers as a basis for clean energy policies. *Energy Policy,* 29, 1197-1207.

Burton I. (1996). The growth of adaptation capacity: Practice and Policy. In: Smith J.B., Bhatti N., Menzhulin G., Benioff R., Budyko M., Campos M., Jallow B. and Rijsherman F. (eds), *Adapting in Climate Change: An International Perspective,* Springer, New York, pp. 55-67.

Capros P. et al. (1995). GEM-E3: Computable general equilibrium model for studying economy-energy-environment interactions, EUR 16714 EN, European Commission DG XII, Brussels.

Capros P. et al. (1997). *The GEM-E3 Model: Reference Manual*. National Technical University of Athens, Greece.

Chesnaye F., Harvey R., Kruger D. and Laitner J. (2001). Cost-effective reductions of non-CO2 greenhouse gases. *Energy Policy*, 29, 1325-1331.

Chesney M., Gheyssens J. and Taschini L. (2013). *Environmental Finance and Investment.* Springer.

Convery F. and Redmond L. (2007). Market and price developments in the European Union Emissions Trading Scheme. *Review of Environmental Economics and Policy*, 1, 88-111.

Daskalakis G., Psychoyios D. and Markellos R.N. (2009). Modeling CO_2 emission allowance prices and derivatives: Evidence from the European trading scheme. *Journal of Banking and Finance*, 33, 1230-1241.

de Bruin K., Dellink R.B., Ruijs A., Bolwidt L., van Buuren A., Graveland J., de Groot R.S., Kuikman P.J., Reinhard S., Roetter R.P., Tassone V.C., Verhagen A., and van Ierland E.C. (2009). Adapting to climate change in The Netherlands: an inventory of climate adaptation options and ranking of alternatives. *Climatic Change,* 95(1-2), 23-45.

Demailly D. and Quirion P. (2008). European Emissions Trading Scheme and competitiveness: A case study on the iron and steel industry. *Energy Economics*, 30, 2009-2027.

Du L., Wei C. and Cai S. (2012). Economic development and carbon dioxide emissions in China: Provincial panel data analysis. *China Economic Review,* 23, 2371-384.

Edmonds J.A. and Reilly J.M. (1985). *Global Energy: Assessing the Future*. Oxford University Press, New York.

Edmonds J., Wise M.A. and MacCracken C.N. (1994). *Advanced Energy Technologies and Climate Change: An Analysis Using the Global Change Assessment Model (GCAM)*. Richland, Wash.: Pacific Northwest Laboratory.

Egenhofer C. (2007). The making of the EU Emissions Trading Scheme: Status, prospects and implications for business. *European Management Journal*, 25, 453-463.

Ekins P., Kesicki F. and Smith A.Z.P. (2011). *Marginal Abatement Cost Curves: A call for caution*. UCL Energy Institute. London, UK.

Ellerman A.D. (2000). Tradable permits fro greenhouse gas emissions: A primer with particular reference to Europe. MIT Joint Program on the Science and Policy of Global Change. Report No 69.

Ellerman A.D. (2008). The EU's emissions trading scheme: A prototype global system?. MIT Joint Program on the Science and Policy of Global Change. Report No 170.

Ellerman A.D. and Buchner B.K. (2007). The European Union Emissions Trading Scheme: Origins, allocation and early results. *Review of Environmental Economics and Policy*, 1, 66-87.

Fankhauser S. (1994). The economic costs of global warming damage: a survey. *Global Environmental Change*, 4(4), 301–309.

Fankhauser S. (1995). *Valuing Climate Change: The Economics of the Greenhouse*, 1st ed. EarthScan, London.

Fankhauser S., Smith J.B. and Tol R.S.J. (1999). Weathering climate change: some simple rules to guide adaptation decisions. *Ecological Economics* 30, 67-78.

Fisher B.S., Nakicenovic N., et al. (2007). Issues related to mitigation in the long term context Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change.

Fuglestvedt J., Berntsen T., Godal O., Sausen R., Shine K. and Skodvin T. (2003). Metrics of climate change: Assessing radiative forcing and emission indices. *Climatic Change*, 58, 267-331.

Golub A., Narita D. and Schmidt M.G.W. (2011). Uncertainty in integrated assessment models of climate change: alternative analytical approaches. 2011.02 Fondazione Eni Enrico Mattei Working Papers.

Granados J.A.T., Ionides E.L. and Carpintero Ó. (2012). Climate change and the world economy: short-run determinants of atmospheric CO_2. *Environmental Science and Policy,* 2150-62.

Grubb M. and Neuhoff K. (2006). Allocation and competitiveness in the EU emissions trading scheme: policy overview. *Climate Policy*, 6, 7-30.

Hackett S.C. (2011). *Environmental and Natural Resources Economics: Theory, Policy and the Sustainable Society*. 4th Edition, M.E. Sharpe Inc. New York.

Halkos G. (1992). *Economic Perspectives of the Acid Rain Problem in Europe.* DPhil thesis, Department of Economics and Related Studies, University of York, UK.

Halkos G. (1993). An evaluation of the direct costs of abatement under the main desulphurisation technologies, MPRA Paper 32588, University Library of Munich, Germany.

Halkos G. (1995). Evaluation of the direct cost of sulphur abatement under the main desulfurization technologies. *Energy Sources*, 17, 391-412.

Halkos G. (1996a). Evaluating the direct costs of controlling NOX emissions in Europe. *Energy Sources*, 20(3), 223-239,

Halkos G. (1996b). Evaluating the direct costs of controlling NOx emissions in Europe, MPRA Paper 33253, University Library of Munich, Germany.

Halkos G. (2010). Construction of abatement cost curves: The case of F-gases, MPRA Paper 26532, University Library of Munich, Germany.

Halkos G. and Tzeremes N. (2011). Does the Kyoto Protocol Agreement matters? An environmental efficiency analysis, MPRA Paper 30652, University Library of Munich, Germany.

Halkos G. (2012). Environmental pollution and economic development: Explaining the existence of an environmental Kuznets curve. *Journal of Applied Economic Sciences*, 6(18), 148-159.

Halkos G. and Tzeremes N. (2013). Carbon dioxide emissions and governance: A nonparametric analysis for the G-20, *Energy Economics*, 40(C): 110-118.

Halkos G. and Kevork I. (2014). Confidence intervals for percentiles in stationary ARMA processes: An application using environmental data. MPRA Paper 56134, University Library of Munich, Germany.

Halkos G. and Kitsou D. (2014). Uncertainty in optimal pollution levels: Modeling the benefit area. *Journal of Environmental Planning and Management* DOI:10.1080/09640568.2014.881333

Halkos G. and Tzeremes N. (2014). Measuring the effect of Kyoto protocol agreement on countries' environmental efficiency in CO_2 emissions: An application of conditional full frontiers. *Journal of Productivity Analysis*, 41(3): 367-382.

Halsnæs K., Mackenzie G.A., Swisher J.N. and Villavicencio A. (1994). Comparable assessment of national GHG abatement costs. *Energy Policy*, 22(11), 925-934.

Hamilton L., Goldstein G., Lee J., Manne A., Marcuse W., Morris S. and Wene C.O. (1992). NARKAL-MACRO: An overview, Brookhaven National Laboratory, BNL-48377.

Harmelink, M.G.M., Blok, K., Ter Avest, G.H., (2005). Evaluation of non-CO_2 greenhouse gas emission reductions in the Netherlands in the period 1990–2003. *Environmental Science*, 2(2/3), 339–349.

Hasanbeigi, A., Menke, C, Therdyothin, A. (2010). The Use of Conservation Supply Curves in Energy Policy and Economic Analysis: the Case Study of Thai Cement Industry. *Energy Policy*, 38, 392–405.

Heal G.M. and Kriström B. (2002). Uncertainty and climate change. *Environmental and Resource Economics,* 22, 3-39.

Hope C.W., Anderson J. and Wenman P. (1993). Policy analysis of the greenhouse effect-an application of the page model. *Energy Policy*, 15, 328-338.

Hope C.W. (2006). The marginal impact of CO2 from PAGE2002: an integrated assessment model incorporating the IPCC's five reasons for concern. *The Integrated Assessment Journal*, 6(1), 19-56.

Hope C.W. (2009). How Deep Should the Deep Cuts Be? Optimal CO_2 Emissions Over Time Under Uncertainty. *Climate Policy*, 9, 3-8.

Hourcade J.C., et al. (1996). A review on mitigation cost studies. In: Bruce J.P., Lee H. and Haites H. (Eds). *Climate Change 1995: Economic and Social Dimensions of Climate Change*. University of Cambridge Press, New York pp. 263-366. Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change.

Hourcade J.C. and Shukla P. (co-ordinating lead authors) et al. (2001). Global, Regional, and National Costs and Ancillary Benefits of Mitigation. In: *IPCC (Intergovernmental Panel on Climate Change), Climate Change 2001: Mitigation*, Cambridge University Press, Cambridge, UK, pp. 499–559.

Hourcade J.C., Jaccard M., Bataille C. and Ghersi F. (2006). Hybrid Modeling: New Answers to Old Challenges - Introduction to the Special Issue of The Energy Journal. *Energy Journal*, 27, 1-11.

Hyman R.C., Reilly J.M., Babiker M.H., De Masin A., Jacoby H.D. (2002). Modeling non-CO2 greenhouse gas abatement. *Environmental Modelling and Assessment* 8(3), 175–186.

Ibrahim M.H. and Law S.H. (2014). Social capital and CO_2 emission—output relations: A panel analysis. *Renewable and Sustainable Energy Reviews* **29:** 528-534.

IIED (2009). Annual report 2009. International Institute for Environment and Development. Accessible at: http://www.iied.org/annual-report-2009

Interagency Working Group on Social Cost of Carbon (2010). *Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866*. Final Rule Technical Support Document: Energy Efficiency Program for Commercial and Industrial Equipment: Small Electric Motors. Appendix 15A. US Department of Energy, Washington, DC.

IPCC (1990). *Climate change. The IPCC scientific assessment; intergovernmental panel of climate change.* World Meteorological Organization and United Nations Environmental Programme, Cambridge University Press, Cambridge.

IPCC (2001). *Climate Change 2001: The Scientific Basis*. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

Kainuma M., Matsuoka Y. and Morita T. (eds) (2002). *Climate Policy Assessment*. Springer, Berlin.

Kann A. and Weyant J.P. (2000). Approaches for performing uncertainty analysis in large-scale energy/economic policy models. *Environmental Modelling and Assessment*, 5, 171-197.

Kates R.W. (1997). Climate change 1995–impacts, adaptations, and mitigation. *Environment*, 39(9), 29-33.

Kesicki F. (2010). Marginal Abatement Cost Curves: Combining Energy System Modelling and Decomposition Analysis. International Energy Workshop 2010. Stockholm.

Kesicki F. (2011). Marginal abatement cost curves for policy making– expert-based vs. model-derived curves. UCL Energy Institute. Accessible at: http://www.homepages.ucl.ac.uk/~ucft347/Kesicki_MACC.pdf

Kelly D.L. and Kolstad C.D. (1999). Integrated assessment models for climate change control. In: Folmer and Tietenberg (eds) *International Yearbook of Environmental and Resource Economics 1999/2000*, Cheltham, UK: Edward Elgar, pp. 171-197.

Kettner C., Koppl A., Schleicher S.P. and Thenius G. (2007). Stringency and distribution in the EU Emissions Trading Scheme: The 2005 evidence. Fondazione Eni Enrico Mattei.

Klein, R.J.T. and Maciver D.C. (1999). Adaptation to climate variability and change: methodological issues. *Mitigation and Adaptation Strategies for Global Change*, 4(3–4), 189–198.

Kolstad C.D. and Toman M. (2005). The economics of climate policy. In: K.G. Mäler and J.C. Vincent (Eds.), *Handbook of Environmental Economics*, vol. 3. Elsevier, Amsterdam, pp. 1561–1618.

Kruger J., Oates W.E. and Pizer W.A. (2007). Decentralization in the EU Emissions Trading Scheme and lessons for global policy. *Review of Environmental Economics and Policy*, 1, 112-133.

Jaccard M., Rivers N. and Horne M. (2004). *The Morning After: Optimal Greenhouse Gas Policies for Canada's Kyoto Obligations and Beyond*. C.D. Howe Institute Commentary 197. Toronto: C.D. Howe Institute.

Jackson T. (1991). Least-cost greenhouse planning supply curves for global warming abatement. *Energy Policy*, 19, 35-46.

Jacobsen H.K. (1998). Integrating the bottom-up and top-down approach to Energy-Economy modelling: the case of Denmark. *Energy Economics,* 20, 443-461.

Jaffe A.B., Peterson S.R., Portney P.R. and Stavins R.N. (1995). Environmental regulation and the competitiveness of U.S. manufacturing: what does the evidence tell us? *Journal of Economic Literature* 33, 132-163.

Jepma C.J. (2003). The EU emissions trading scheme (ETS): how linked to JI/CDM? *Climate Policy*, 3, 89-94.

Kolstad C.D. (1998). Integrated Assessment Modelling of Climate Change. In: W.D. Nordhaus (eds.) *Economics and Policy Issues in Climate Change*, Resources for the Future, Washington, D.C., pp. 263-286.

Koopmans C.C. and te Velde D.W. (2001). Bridging the energy efficiency gap: using bottom-up information in a top-down energy demand model. *Energy Economics*, 23, 57–75.

Kumbaroglu G. and Madlener R. (2003). Energy and Climate Policy Analysis with the Hybrid Bottom-Up Computable General Equilibrium Model SCREEN: The Case of the Swiss CO_2 Act. *Annals of Operations Research*, 121(1–4), 181–203.

Loschel A. (2002). Technological change in economic models of environmental policy: a survey. *Ecological Economics,* 43(2-3), 105-126.

Loulou R. and Labriet M. (2008) ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure. *Computational Management Science*, 5, 7-40.

Loulou R. (2008). ETSAP-TIAM: the TIMES integrated assessment model. part II: mathematical formulation. *Computational Management Science*, 5, 41-66.

Lucas P.L., Den Elzen M.G.J. and van Vuuren D.P. (2005). Multi-gas abatement analysis of the Kyoto Protocol. Report no. 550006001. Netherlands Environmental Assessment Agency (MNP), Bilthoven, The Netherlands.

Maddison, D.J. (2003). The amenity value of the climate: the household production function approach. *Resource and Energy Economics*, 25 (2), 155–175.

Maddison D. and Rehdanz K. (2011). The impact of climate on life satisfaction. *Ecological Economics*, 70(12), 2437–2445.

Mahgary Y.El, Ibrahim A.F., Shama M.A.F., Hassan A., Rifai M.A.H., Selim M., Gelil A., Korkor H., Higazi A., Amin A., Bedewi F. and Forsstrom J. (1994). Costs of CO_2 abatement in Egypt using both bottom-up and top-down approaches. *Energy Policy,* 22(11): 935-946.

Manne A. (1981). ETA-MACRO: A User's Guide, EA-1724. Electric Power Research Institute, Palo Alto, CA.

Manne A., Mendelsohn R. and Richels R. (1995). MERGE: a model for evaluating regional and global effects of GHG reduction policies. *Energy Policy*, 23(1): 17–34.

Manne A. and Rishels R. (1993). *Buying Greenhouse Insurance: The Eco-Emission Limits*, 2nd edn (MIT Press, Cambridge, MA.

Manne A. and Richels R. (1995). AMERGE: A model for evaluating regional and global effects of GHG reduction policies. *Energy Policy,* 23, 17–34.

Manne A. and Richels R. (2001). An alternative approach to establishing trade-offs among greenhouse gasses. *Nature*, 5, 675–677.

Manne A. and Richels R. (2005). MERGE: an integrated assessment model for global climate change. In: R. Loulou J., Waaub P. and Zaccour G. (Eds.), *Energy and Environment*, Springer, USA.

Markandya A. (2013). Impacts of Climate Change and Adaptation to Climate Change: Current State of the Art. *bc*[3] Basque Centre for Climate Change. Accessible at:

http://dce-conference.au.dk/fileadmin/dce-conference.au.dk/Presentation/Markandya.pdf

Markandya A. (2014). Policies and Instruments to Leverage Private and Multilateral Flows for Climate Finance. Paper resented in the Bank of Greece. Accessible at: http://www.bankofgreece.gr/BogDocumentEn/Markandya_Climate_Finance.pdf

Maya R.S. and Fenhann J. (1994). Methodological lessons and results from UNEP GHG abatement costing studies. *Energy Policy,* 22(II) 955-963.

Mastrandrea, M.D. (2010). Representation of climate impacts in integrated assessment. In: Gulledge J., L.J. Richardson, L. Adkins, and S. Seidel (eds.) *Assessing the Benefits of Avoided Climate Change: Cost Benefit Analysis and Beyond.* Proceedings of Workshop on Assessing the Benefits of Avoided Climate Change, March 16–17, 2009. Pew Centre on Global Climate Change: Arlington, VA, p. 85–99. Available at: http://www.pewclimate.org/events/2009/ benefitsworkshop

McFarland J.R., Reilly J.M. and Herzog H.J. (2004). Represen ting energy technologies in top-down economic models using bottom-up information. *Energy Economics*, 26, 685–707.

McKibbin W.J. and Wilcoxen P.J. (2002). The role of economics in climate change policy. *Journal of Economic Perspectives*, 16, 107–29.

McKibbin W.J. and Wilcoxen P.J. (2005). The role of Economics in Climate Change Policy. In: R.N. Stavins (Ed), *Economics of the Environment: Selected Readings*. Chapter 25 pp. 479-502. 5th Edition, W.W. Norton and Company.

McKinsey and Company (2009). Pathways to a Low-Carbon Economy - Version 2 of the Global Greenhouse Gas Abatement Cost Curve.

McKinsey and Company (2010). Impact of the financial crisis on carbon economics: Version 2.1 of the global gas abatement cost curve.

McKitrick R. (1999). A Derivation of the Marginal Abatement Cost Curve. *Journal of Environmental Economics and Management*, 37, 306-314.

Mendelsohn R. (2000). Efficient Adaptation to Climate Change. *Climatic Change,* 45, 583-600.

Mendelsohn R.O., Morrison W.N., Schlesinger M.E. and Andronova N.G. (2000a). Country-specific market impacts of climate change. *Climatic Change,* 45(3–4), 553–569.

Mendelsohn R.O., Schlesinger M.E. and Williams L.J. (2000b). Comparing impacts across climate models. *Integrated Assessment,* 1(1), 37–48.

Messner S. and Strubegger M. (1995). User's Guide for MESSAGE III. WP95 ‐ 69,

International Institute for Applied Systems Analysis, Laxenburg, Austria.

Morita T., Robinson J., Adegbulugbe A., Alcamo J., Herbert D., Lebre la Rovere E., Nakicenivic N., Pitcher H., Raskin P., Riahi K., Sankovski A., Solkolov V., de Vries H.J.M. and Zhou, D. (2001). Greenhouse gas emission mitigation scenarios and implications. In: Metz, B., Davidson, O., Swart, R., Pan, J. (Eds.), *Climate Change 2001: Mitigation*. Cambridge University Press, Cambridge.

Morthorst P.E. (1994). Constructing CO_2 reduction cost curves: The case of Denmark. *Energy Policy*, 22(11), 964-970.

Mosnaim A. (2001). Estimating CO2 abatement and sequestration potentials for Chile. *Energy Policy,* 29(8), 631–640.

Naucler T. and Enkvist P. A., (2009). Pathways to a Low-Carbon Economy - Version 2 of the Global Greenhouse Gas Abatement Cost Curve. McKinsey and Company.

Nordhaus W.D. (1979). *The Efficient Use of Energy Resources*. Yale University Press, New Haven, CT.

Nordhaus W.D. (1994a). Expert opinion on climate change. *American Scientist,* 82(1), 45–51.

Nordhaus W.D. (1994b). *Managing the Global Commons: The Economics of Climate Change*. The MIT Press, Cambridge.

Nordhaus W.D. (2006). Geography and macro economics: new data and new findings. *Proceedings of the National Academy of Science*, 103(10), 3510–3517.

Nordhaus W.D. (2007). The Challenge of Global Warming: Economic Models and Environmental Policy. Available at:

http://nordhaus.econ.yale.edu/dice_mss_072407_all.pdf

Nordhaus W.D. (2008). *A Question of Balance: Weighing the Options on Global Warming Policies*. Yale University Press, New Haven.

Nordhaus W.D. (2011). The economics of tail events with an application to climate change. *Review of Environmental Economics and Policy*, 5(2), 240–257.

Nordhaus, W.D. and J.G. Boyer (2000). *Warming the World: Economic Models of Global Warming* The MIT Press, Cambridge, Massachusetts—London, England.

Novikova A. (2009). Potential for carbon dioxide mitigation in the Hungarian residential buildings. In Proceedings of the International Conference on Energy Efficiency in Domestic Appliances and Lighting (EEDAL) 2009, Berlin.

OECD (2009). Integrating Climate Change Adaptation into Development Co-operation POLICY GUIDANCE. OECD.

OECD/IEA (2013). CO_2 emissions from fuel combustion: Highlights. International Energy Agency.

Olmstead S.M. and Stavins R.N. (2007). A Meaningful Second Commitment Period for the Kyoto Protocol. *The Economists' Voice*, 4(3), 1-5.

Oxfam (2007). Adapting to Climate Change. What is Needed in Poor Countries and Who Should Pay? Oxfam Briefing Paper 104.

Paltsev, S., J. M. Reilly, H. D. Jacoby, R. S. Eckaus, J. McFarland, M. Sarofim, M. Asadoorian and M. Babiker (2005). The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4. Cambridge, MA, MIT Joint Program on the Science and Policy of Global Change.

Parson E.A. (1995). Integrated Assessment and Environmental Policy Making. *Energy Policy*, 23(4/5), 463-475.

Peterson S. (2006). Uncertainty and economic analysis of climate change: A survey of approaches and findings. *Environmental Modelling and Assessment,* 11(1), 1-17.

Pizer W.A. (2003). *Climate change catastrophes. 2003. Resources for the Future Working Paper 03–31, May 2003.*

Pizer W. A. (2006). The evolution of a global climate change agreement. *American Economic Review*, 96(2), 26-30.

Perman R., Ma Y. and McGilvray J. (2003). *Natural Resource and Environmental Economics*, Third Edition, Longman.

Peters G.P., Marland G., Le Quere C., Boden T., Canadell J.G. and Raupach M.R. (2012). Rapid growth in CO_2 emissions after the 2008-2009 global financial crisis. *Nature Climate Change*, 2(1), 2–4.

Prinn R. et al. (1996). Integrated Global System Model for climate policy analysis: I. Model framework and sensitivity studies. Tech. Rep. 7, MIT Joint Program on the Science and Policy of Global Change, June1996.

Rehdanz K. and Maddison D.J. (2005). Climate and happiness. *Ecological Economics,* 52(1), 111–125.

Rotmans J. and de Vries B. (1997). *Perspectives on global change: The TARGETS approach*. London: Cambridge University Press.

Rotmans J. (1998). Methods for IA: The Challenges and Opportunities Ahead. *Environmental Modeling and Assessment*, 3, 155-180.

Rotmans J. and Dowlatabadi H. (1998). Integrated Assessment of Climate Change: Evaluation of Methods and Strategies. In: S. Rayner and E. Malone (eds.), Human Choice and Climate Change: An International Social Science Assessment, Battelle Press, Washington, USA.

Roughgarden T. and Schneider S. H. (1999). Climate change policy: quantifying uncertainties for damages and optimal carbon taxes. *Energy Policy,* **27:** 415-29.

Schmalensee R., Stoker T.M. and Judson R.A. (1998). World Carbon Dioxide Emissions: 1950–2050. *Review of Economics and Statistics*, 80(1), 15-27.

Smith S. and Swierzbinski J. (2007). Assessing the performance of the UK Emissions Trading Scheme. *Environmental and Resource Economics*, 37, 131-158.

Solomon B.D. and Lee R. (2000). Emissions trading systems and environmental justice, *Environment*, 42, 32-45.

Spash C.L. ((2002). *Greenhouse Economics: Values and Ethics*. Chapter 9. London and New York. Routledge.

Stern D.I., Jotzo F. and Dobes L. (2013). The Economics of Global Climate Change: A Historical Literature Review, CCEP Working Papers 1307, Centre for Climate Economics and Policy, Crawford School of Public Policy. The Australian National University.

Stern N. (2007). *The Economics of Climate Change: The Stern Review*. Cambridge and New York: Cambridge University Press.

Stiglitz J.E. (2006). A new agenda for global warming. *Economist Voice. The Berkley Electronic Press* www.bepress.com.ev

Tol R.S.J. (1995). The damage costs of climate change toward more comprehensive calculations. *Environmental and Resource Economics*, 5(4), 353–374.

Tol R.S.J. (2002a). Estimates of the damage costs of climate change: part 1: benchmark estimates. *Environmental and Resource Economics,* 21(1), 47–73.

Tol R.S.J. (2002b). Estimates of the damage costs of climate change: part ii: dynamic estimates. *Environmental and Resource Economics*, 21(2), 135–160.

Tol, R. S. J. (2005). Adaptation and mitigation: trade-offs in substance and methods, *Environmental Science and Policy*, 8, 572-578.

Tol R.S.J. (2013). Targets for global climate policy: An overview. *Journal of Economic Dynamics and Control,* 37, 911–928.

Tóth F.L., Bruckner T., Fssel H.M., Leimbach M., Petschel-Held G. and Schellnhuber H.J. (1997). The tolerable windows approach to integrated assessments, in: Intergovernmental Panel on Climate Change, Climate Change and Integrated Assessment Models (IAMs)–Bridging the Gaps, Proc. of the IPCC Asia-Pacific Workshop on Integrated Assessment Models (United Nations University, Tokyo, Japan, 1997), CGER-Report, No. I029-'97 pp. 403–430.

Tuladhar, S. D., Yuan, M., Bernstein, P., Montgomery, W. D. and Smith, A. (2009). *A top–down bottom–up modeling approach to climate change policy analysis. Energy Economics*, 31, S223-S234.

UNDP (2007). *Human Development Report 2007/08*. New York: Palgrave McMillan.

UNFCCC (2007). *Investment and Financial Flows to Address Climate Change*. Bonn.

USEPA (2006). *Global Mitigation of Non-CO_2 Greenhouse Gases*. Washington, DC, United States Environmental Protection Agency.

van Vuuren D.P., Den Elzen M.G.J., Berk M.M., Lucas P.L., Eickhout B., Eerens H., and Oostenrijk R. (2003). Regional costs and benefits of alternative post-Kyoto climate regimes: comparison of variants of the multi-stage and per capita convergence regimes. Report no. 728001025. National Institute for Public Health and the Environment, Bilthoven, The Netherlands.

van Vuuren D.P., Weyant J.P., De la Chesnaye F.C. (2006). Multigas scenarios to stabilise radiative forcing. *Energy Economics,* 28, 102–120.

van Vuuren D, den Elzen M, Lucas P, Eickhout B, Strengers B, van Ruijven B, Wonink S. and van den Houdt R (2007) Stabilising greenhouse gas concentrations at low levels. An assessment of reduction strategies and costs. *Climate Change*, 81, 119–159.

van Vuuren D. P., Hoogwijk M., Barker T., Riahi K., Boeters S., Chateau J., Scrieciu S., van Vliet S., Masui T., Blok K., Blomen E. and Kram T. (2009). Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials. *Energy Policy,* 37(12), 5125-5139.

Wang Z., Zhu Y. and Peng Y. (2013) Carbon emissions trends with optimal balanced economic growth of China and the USA and some abatement options for China. *Journal of Geographical Sciences,* 23, 6991-1004.

Warren R. et al. (2008). Development and Illustrative Outputs of the Community Integrated Assessment System (CIAS), a Multi-Institutional modular Integrated Assessment Approach for Modelling Climate Change. *Environmental Modeling and Software,* 23, 592 ‐ 610.

Wayne C. (2008). The Economics of Global Warming. Economics 268 Environmental Economics. University of Wisconsin-Eau Claire Accessible information in: www.uwec.edu/carrolwd/Classes/Econ268/GlobalWarming.ppt

Weyant J.P. and de la Chesnaye F.C. (2006). Overview of EMF-21: multigas mitigation and climate change. *Energy Journal* Multi-Greenhouse Mitigation and Climate Policy Special Issue, 1-32. Climate Change Secretariat.

Weyant J.P., Davidson O., Dowlatabadi H., Edmonds J.A., Grubb M.J., Parson E.A., Richels R.G., Rotmans J., Shukla P.R., Tol R.S.J., Cline W.R. and Fankhauser S. (1996). Integrated Assessment of Climate Change: An Overview and Comparison of Approaches and Results, In: J. P. Bruce, H. Lee, and E. F. Haites, eds. (eds.), *Climate Change 1995: Economic and Social Dimensions* -- Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 367-396.

Wilson D. and Swisher J. (1993). Exploring the gap. Top-down versus bottom-up analyses of the cost for mitigating global warming. *Energy Policy*, 21, 249-263.

Wing S.I. (2008). The Synthesis of Bottom-Up and Top-Down Approaches to Climate Policy Modeling: Electric Power Technology Detail in a Social Accounting Framework. *Energy Economics,* 30, 547-573.

World Bank (2006). *World Development Indicators 2006 Online*. The World Bank, Washington, DC.

World Bank (2009). *World Development Indicators 2009*. The World Bank Washington, DC.