Carbon Permit Prices in the European Emissions Trading System: A Stochastic Analysis

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Abstract

The Emission Trading Scheme (ETS) is a cornerstone for European efforts to reduce greenhouse gas emissions, and in its test phase will operate from 2005-2007. It is a cap-and-trade system where an aggregate cap on emissions is set by the respective government agencies to define the total number of emissions allowances. Each allowance gives the owner the right to emit one unit (usually one ton) of emissions. Covered establishments that exceeded the limits may buy emissions credits from entities with allowances they do not need to use themselves. One key feature of this system is that the amount of emissions is capped whereas the permit prices are uncertain. These permit prices are determined by economic conditions, generally, stronger economic growth means a higher permit price.

The objective of this thesis is to understand uncertainty in permit prices under the system, by determining the likelihood that permit prices will fall within a given range. This is accomplished through stochastic analysis simulation of a computable general equilibrium model of the world economy with country-level detail most of the key members of the original 15 member EU plus the 10 accession countries. Economic parameters treated as stochastic in the simulations were labor productivity growth, share of new capital vintaged, the rate of autonomous energy efficiency improvement, the elasticity of substitution between energy and non-energy composites, and oil/gas prices. Information on the likely range of future permit prices will allow operators of covered establishments to decide on the extent to which they should buy permits or invest in emissions reduction technologies possible reducing emissions below their cap, allowing them to sell allowances. While some abatement activities may involve only changes in operation and management of facilities, other may involve longer-term investment. These abatement decisions boil down to basic investment problems. How should entities affected by the ETS plan their investment policies, such that they can minimize costs? To answer this question firms need an estimate of likely future permit prices.

Results were that a zero carbon price occurred with a probability of 28-48% across variants of the Monte Carlo simulations. The mean value for the carbon prices was about $0.40 per ton of carbon, and the maximum price across the variants ranged from about $3.50 to somewhat over $6.00 per ton carbon. The implication for firms is that costly abatement investments appear difficult to justify, except to the extent that firm's are looking beyond the ETS period when carbon permit prices would rise further.

Thesis Supervisor: Dr. John Reilly
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Chapter 1   Introduction

1.1 Overview of Climate Change

Climate change is arguably the most significant environmental issue being discussed today. According to the National Academy of Sciences, the Earth's surface temperature has increased by about 1 degree Fahrenheit over the past 100 years and it is expected that the increase over the next 100 years will be more. The global mean surface temperature increased from 1880 to 2000 is shown in Figure 1. Although there is a great deal of uncertainty in global climate modeling, climate scientists today agree that a significant portion of this century's warming is due to anthropogenic emissions of greenhouse gases (GHG). Two expert assessments of the science of climate change – The Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report and the National Research Council response to the White House, confirmed that human activity has induced climate change and is projected to have potentially significant impacts on the global climate over this century. Human activities have altered the chemical composition of the atmosphere through the buildup of the greenhouse gases – primarily carbon dioxide, methane and nitrous oxide. Carbon dioxide is the most significant greenhouse gas and is released to the atmosphere when fossil fuels (oil, natural gas, and coal), and organic matter such as wood and wood products and solid waster are burned or decompose.

Figure 1: Global Temperature Changes from 1880 – 2000
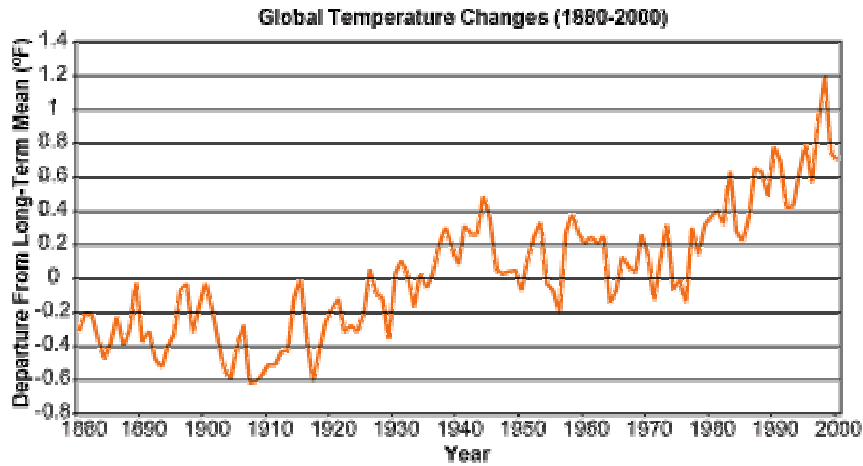
Source: US Environmental Protection Agency

Due to the global nature of the problem, attempts to reduce climate change have focused on the creation of an international environmental treaty for GHG emissions reductions, just as the Montreal Protocol did for CFCs. Hence, the Kyoto Protocol to the United Nations Framework Convention on Climate Change was negotiated in Kyoto, Japan in December 1997 and came into force on February 16 2005, following its official ratification by Russia on November 18, 2004.

The Kyoto Protocol is an amendment to the United Nations Framework Convention on Climate Change (UNFCCC), an international treaty on global warming. Developed countries, which ratified this protocol, commit to binding targets on their greenhouse gas emissions established relative to a 1990 baseline. The targets apply to the first commitment period 2008-2012. As an alternative to domestic reduction, countries can engage in emissions trading to meet their target. Developing countries that ratify the Protocol have no binding targets but there are mechanisms in the Protocol that allow their reduction to be credited against caps in developed countries. As the Kyoto Protocol is only for a five-year period, it will only have a minimal impact on climate change, but it is an important first step in reducing climate change.

1.2 Emissions Trading Scheme – Cap-and-Trade Program

Emissions trading was included in the Protocol as a mechanism that could increase economic efficiency of efforts to reduce greenhouse gas emissions. There are three basic types of emissions trading programs: reduction credit programs, averaging programs and cap-and-trade programs (Ellerman et al 2003). In this thesis, I will be looking at the cap-and-trade programs.

Cap-and-trade programs limit total emissions. In such programs, an aggregate cap on emissions is set by the respective government agencies to define the total number of emissions allowances. Each allowance gives the owner the right to emit one unit (usually one ton) of emissions. The government will then distribute the allowances to entities. These can be done in a few ways. One way is by granting the installations according to a measure of their need. Another is through a sale where the installations must purchase allowances from the government. At the end of the period, usually in a year, each installation is then required to surrender an amount of permits equal to there emissions over the period. If an installation foresees having fewer permits than emissions, they can buy permits from another installation, which has more than sufficient permits. Allowing the purchase or sale of permits means that it is not important from an economic efficiency standpoint that the allocation is exactly according to need.

The Kyoto Protocol will bind ratifying nations to a similar system, with the UNFCCC setting caps for each nation. Under the proposed treaty, nations or entities in these nations who hold allowances are able to trade their quota of GHG allowances. In view of the Kyoto Protocol, the EU has set up an emissions trading scheme that will run from 2005 through 2007. It was developed as a trial period to help Member States prepare for the Kyoto Period from 2008-2012. An example of a cap-and-trade emissions trading system is the EU emissions trading scheme (ETS). We will discuss more about the EU ETS in a later chapter.

One feature of the cap-and-trade system is that the quantity of emissions is fixed but the costs of the emissions reductions are uncertain and costs are dependent on several factors such as economic growth and world energy prices. For example, if economic growth is

high, it means that emissions-producing entities would likely use more energy and would tend to emit more GHGs. This would mean more demand for permits and a higher price. Or if the world energy prices are relatively low, installations would have less incentive to reduce energy usage, leading to higher emissions, higher demand for permits and higher permit prices.

1.3 Policy Motivation

The policy motivation for this thesis is to examine the likely permit clearing price in the EU ETS. In other words, we are trying to find out what are the possible prices an installation or entity affected by the scheme may face if they want to buy or sell their permits on the market.

Although the ETS is an EU-wide program that affects the Member States, ultimately, it is the installations or entities that come under the scheme. These entities must decide the extent to which they should buy or sell emissions permits or invest in emissions reduction technologies. This boils down to a basic investment problem. How should entities affected by the ETS plan their investment policies, such that they can minimize costs? Emissions reductions investments need to be taken upfront, given an expectation of the future price of permits. Hence, in order to make investment decisions, firms will need to estimate future prices.

As mentioned earlier, the price of permits is affected by economic factors such as economic growth or world energy prices. In the event that the permit prices are expected to be high, installations would likely invest more in emissions reduction technologies to avoid these high prices in the future.

1.4 Hypothesis

Given previous work on the ETS, I hypothesized that the probability distribution function may be shaped as in Figure 2, with a relatively high probability that the carbon price will

be zero. This is due to the fact that the ETS is a test period to prepare the EU for the Kyoto period. The member states have set relatively lax allocation caps that do not require their installations to reduce emissions by very much. Even though the most likely result may be a zero carbon price, it is important for investment decisions to know that under some conditions the price might be positive.

Figure 2: Hypothesized PDF of the Carbon Price
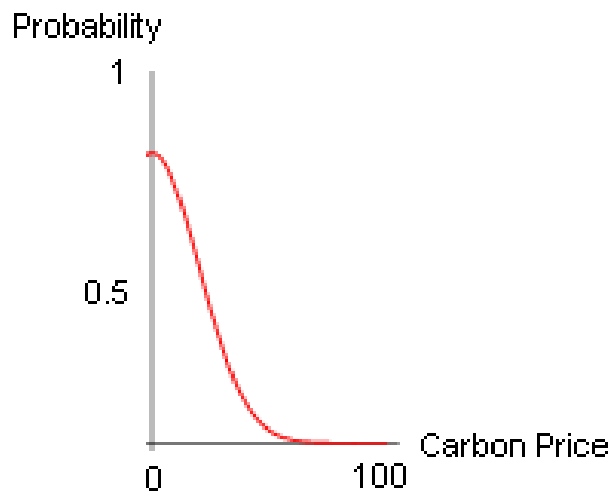
1.5 Previous Work

The aim of the report is to determine what the likely permit prices are based on economic parameters, through a stochastic analysis. The results will be in the form of a probability density function (PDF) for the permit prices. In order to achieve this, I used a Monte-Carlo analysis, simulating an economic model 250 times. Each model run uses a different value of important parameters that affect the carbon price. The different values of inputs are sampled from PDFs of the inputs in such a way as to be representative of the uncertainty in these parameters. From the 250 permit prices, I then can form a PDF describing the range of prices obtained.

The stochastic analysis conducted here builds on extensive work done by Professor Mort Webster (Webster 2000, Webster et. al. 2001) and a previous Master's thesis by Paul Cossa (Cossa, 2004). Professor Webster's study mainly addressed the issue of uncertainty

and learning in sequential decision-making in the case of climate policy (Webster et al., 2000). Parts of his thesis deal with the uncertainty in the level of greenhouse gas emissions (Webster, et al., 2001). He used a previous version of the EPPA model.

Cossa's thesis extended Professor Webster's analysis to the cost of climate change policies. He performed a sensitivity analysis on the economic parameters relevant to the analysis, in order to identify those, which have the biggest effect on the cost of climate change policies. Also, he developed a specific method to obtain experts' opinions on uncertainty on each of these parameters that allowed him to conduct his uncertainty analysis under different policy assumptions and to understand better the implications of uncertainty on climate change policies. My thesis builds on this work by examining a specific policy that has now been implemented.

1.6 Overview of Thesis

The objective of the thesis is to determine what the clearing permit prices of the EU ETS will be based on stochastic economic parameters. Chapter 2 gives a brief introduction of the EU ETS, including the driving force behind it. Chapter 3 gives an introduction of the model that I used for my analysis and the steps I took to integrate the EU ETS into the model to make the analysis as realistic as possible. Chapter 4 discusses the stochastic process used for the analysis. This includes identification of PDFs for the uncertainty parameters used for the analysis and the steps taken to obtain the samples for our model runs. Chapter 5 shows the results. These include the PDF of permit prices that were obtained. I include sensitivity analyses to show how the PDF of permits changes with different assumptions about what parameters are uncertain, whether there is correlation among GDP growth in the EU region, and whether uncertainty in these variables outside of the EU affect the EU permit clearing prices. The thesis is concluded in Chapter 6.

Chapter 2   The European Emissions Trading Scheme

2.1 Background

The European Emission Trading Scheme (ETS) is a cornerstone of the EU's plan for reducing emissions of GHGs. It establishes a framework for trading in greenhouse gas emissions across the original EU-15 nations and the 10 accession countries (Table 1).

Table 1: List of Countries taking part in the ETS

EU-15	Accession
Austria	Czech Republic
Belgium	Estonia
Denmark	Hungary
Finland	Latvia
France	Lithuania
Germany	Poland
Greece	Slovakia
Ireland	Slovenia
Italy	Cyprus
Luxembourg	Malta
Netherlands	
Portugal	
Spain	
Sweden	
UK	

The ETS runs from 2005 to 2007. This is a test phase for the trading system expected to be used by the EU during the Kyoto commitment period that runs from 2008 to 2012. The nature of emissions trading beyond 2012 is uncertain and will likely depend on international agreements on further emissions constraints.

The implementation timetable for the ETS can be seen from Figure 3. The Directive was agreed in July 2003 and entered into force on 13 October 2003.

Figure 3: Timing of national processes for implementing the ETS

Monitoring & registries guidance	Annex III guidance	Final NAPs	Approved NAPs

Aug	Sep	Oct	Nov	Dec			Mar				Jul
2003					2004						

Industry Consultation

Issue Permits

Aug				Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
					2005						

Issue 2005 EUA

Surrender allowances

Decide allocation

Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar				Jul
					2006						
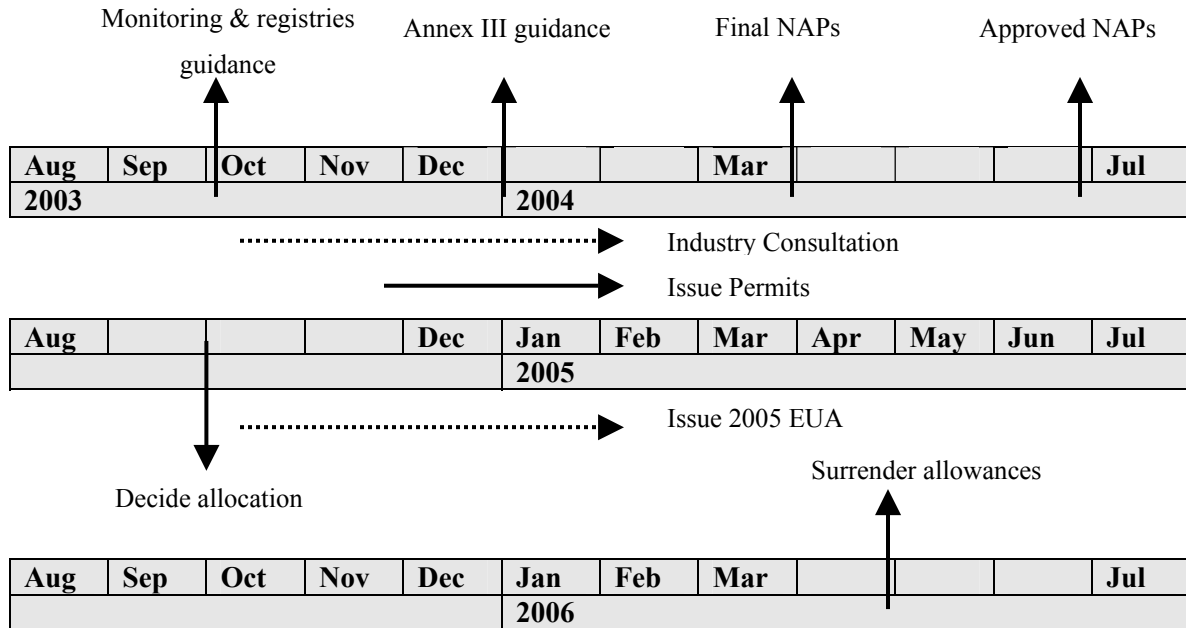
Source: Mullins 2003

The ETS is the first international trading system for CO_2 emissions in the world and covers over 12,000 companies representing close to half of Europe's CO_2 emissions. The aim of the ETS is to help EU Member States to achieve compliance with their commitments under the Kyoto Protocol. The ETS can operate independently of the Kyoto Protocol but can be linked to International Emissions Trading (IET) and other flexibility mechanisms. Emissions trading is expected to allow for cheaper compliance with the targets under the Kyoto Protocol by letting participating companies buy/sell emission credits or allowances.

The National Allocation Plans (NAPs) required under the ETS were to be submitted to the European Commission on 31 March 2004. The accession countries were given somewhat longer time frames (1 May 2004). Many countries did not meet the deadlines and some did not finish the NAPs even as the ETS began in January 2005. The objective for the NAPs was for the Member States to develop the cap for CO_2 emissions that would apply to the covered entities, mainly in the energy and industrial sectors. They also needed to develop a plan to allocate the allowances to covered installations. The NAPs determined the total quantity of CO_2 emissions that the Member State have granted to

their companies. The NAPs were developed separately by each of the Member States, which must ex-ante decide how many allowances to allocate in total for the period 2005 to 2007 and how many each installation covered under the ETS will receive. The Member States agreed to submit the NAPs to the European Commission so that they can be reviewed by the Commission and the other Member States. There were some problems that arose with regards to the NAPs (both submission and analysis problems) that will be discussed in a later section.

The ETS defines the compliance period as a calendar year with a "grace period" of 4 months. Operators are required to surrender allowances equivalent to the CO_2 they emitted in the preceding calendar year by 30 April each year. Operators with insufficient allowances face a penalty of 40 Euros per tonne of CO_2 emitted in excess of allowances they surrender during the first commitment period and 100 Euros in the second period.

2.2 Driving Force of ETS (Kyoto Protocol)

The main reason for the development of the ETS is the Kyoto Protocol. The Kyoto Protocol will come into force during 2008 to 2012 and trading may be backed by direct transfers of assigned amount units (AAUs). Under the Kyoto Protocol, AAUs define the total allowed emissions of greenhouse gases for individual Parties over the first commitment period from 2008-2012. Emissions trading, joint implementation and the clean development mechanism can be used to add or subtract to this amount. In other words, Member States that are net buyers will have their assigned amounts increased while countries that are net sellers will have their assigned amounts reduced accordingly.

Under the Kyoto Protocol, the EU is required to reduce its GHG emissions by 8%[1] from the 1990 levels during 2008 to 2012. The original EU-15 Member States' commitments of -8% from 1990 were amended in an EU burden-sharing agreement to give the national targets indicated in the table below. The accession countries were not part of the EU

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[1] The target is for all GHG (not just CO_2) and is expressed in terms of CO_2 equivalence.

when the burden sharing agreement was negotiated in the EU. Their targets, given in Table 2, were defined in the Kyoto Protocol.

Table 2: EU Member State and accession country Kyoto targets[2]

EU Member States	%	Accession Countries	%
Austria	-13	Czech Republic	-8
Belgium	-7.5	Estonia	-8
Denmark	-21	Hungary	-6
Finland	0	Latvia	-8
France	0	Lithuania	-8
Germany	-21	Poland	-6
Greece	+25	Slovakia	-8
Ireland	+13	Slovenia	-8
Italy	-6.5	Cyprus	No target
Luxembourg	-28	Malta	No target
Netherlands	-6		
Portugal	+27		
Spain	+15		
Sweden	+4		
UK	-12.5		
EU	**-8**		

Currently, only three of the original EU-15 Member States – Germany, Sweden and the UK are projected by the European Environmental Agency (EEA) to be below their Kyoto burden-sharing targets in 2010 as indicated in Figure 4. Many countries are projected to be far above their Kyoto targets. For example, France is projected to be 9%, Italy almost 15% and Spain over 30% above their targets.

Accession countries are in a very different position. From the base-year of 1990 to 2000, emissions from these countries have fell by over 35% due to economic restructuring after the collapse of the Iron Curtain. Hence, while growth of emissions in these countries have resumed, their emissions levels are expected to be well below their Kyoto targets in 2010.

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[2] These are percentage changes in emissions for 2008-2012 relative to base year (1990) levels

Figure 4: Gap between Kyoto commitments and projected greenhouse gas emissions by the EEA in 2010, with existing policies and measures (% of 1990 emissions)
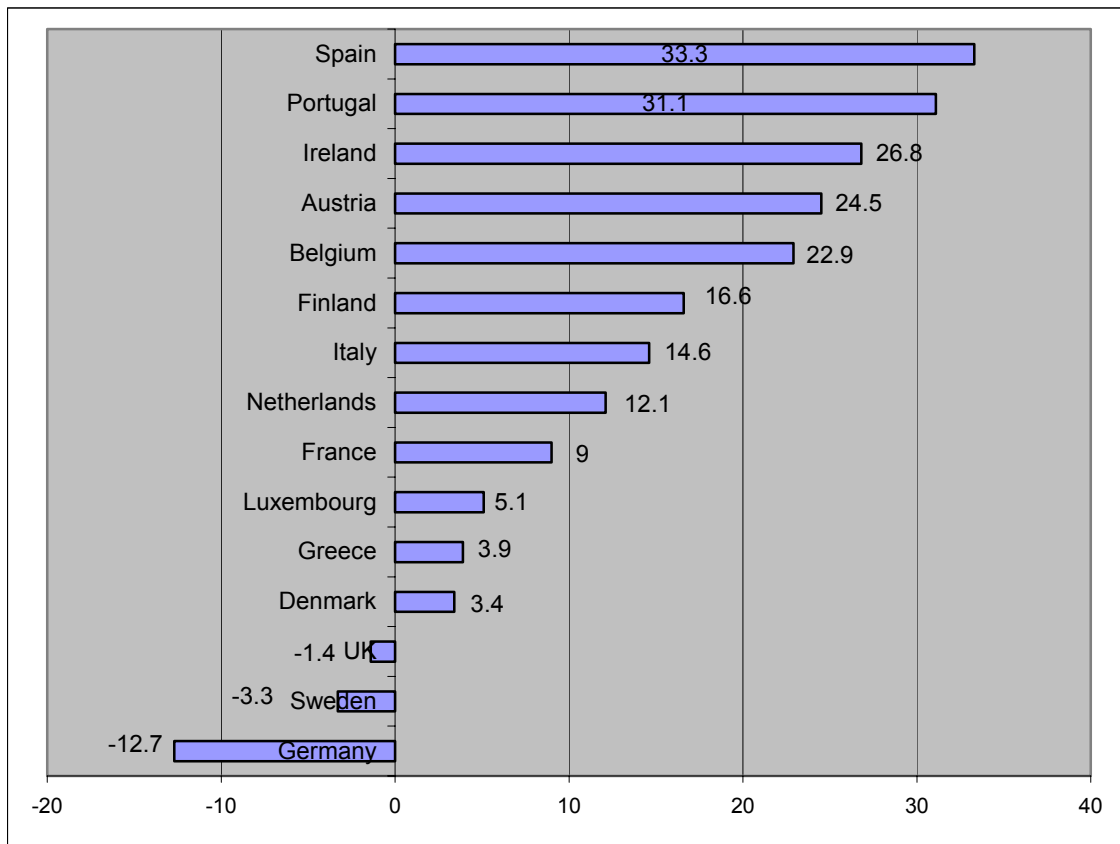
Source: EEA (2002)

Hence, while some Member States of the EU will meet their Kyoto targets, substantial further action is needed to ensure that all Member States meet their targets. In the Kyoto Protocol, mechanisms such as international emissions trading (IET)[3], Joint Implementation (JI)[4] and the Clean Development Mechanism (CDM)[5] provide additional options for Member States to fulfill their targets.

2.3 The NAPs

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[3] IET provides the trading of AAUs between Annex 1 Parties in the Kyoto Protocol
[4] JI enables Annex 1 parties to get credits for joint projects to reduce emissions
[5] CDM enables Annex 1 parties to get credit for projects resulting in emissions reductions in non-Annex 1 parties

The NAPs are a key element of the ETS. As noted, the time frame of the establishment of the EU emissions trading scheme was very tight. From the initial guidelines, the original (EU-15) Member States had only about 6 months to develop and submit their NAPs and the accession Member States, for which the deadline was May 1 2004, had 10 months. As a result, many of the Member States did not meet the deadlines. In fact, only six original Member States submitted their NAPs near the deadline (within 1 week). Some states have still not completed their NAPs even though the ETS has officially commenced. As a result, analysis of the NAPs conducted to date has been limited (Zetterberg 2004, Betz 2004). In fact, as of February 2005, according to the Environment – Climate Change website (EUROPA) that keeps track of the status of the NAPs, some of the NAPs like the Czech Republic, Greece, Italy and Poland have not been assessed by the European Commission yet, due to late submissions. Given the tight time frame to development of the NAPs, it is probably more surprising that most countries have successfully submitted their NAPs.

The definition of an installation effected in the EU ETS is the same as for Integrated Pollution Prevention and Control (IPPC)[6] that is a principal environmental regulatory directive in the EU. Installations are defined as a stationary technical unit where one or more activities covered by the EU ETS are carried out and any other directly associated activities, which have a technical connection with the activities carried out on that site and which could have an effect on emissions and pollution. This can be found in Annex I of the EU ETS Directive. This Annex lists the activities to be covered by the EU ETS.

The ETS does not cover all the installations in each Member State and the NAPs specify which installations will be covered under the ETS. There were some fundamental problems that arose initially during the identification and definition of installations. Initial estimates of the number of installations to be affected by the EU ETS was about 5000 across the EU, but it is now clear that the number will be more than 12,000 installations. This is because of the different interpretation of Annex I.

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[6] IPPC – Integrated Pollution Prevention and Control. EU legislation that seeks to limit emissions in the air, water and land from certain industrial activities.

Most Member States base the interpretation of their national implementation of the EU-Directive on the IPPC and include installations as requested by the European Commission. However, since Member States treat the implementation of the IPPC Directive differently, they will also have different treatments of Annex I of the EU ETS Directive (CEC 2003a). For example, in Germany and Poland, steam crackers and melting furnaces are not covered since the definition of combustion installation covers only activities that transform energy carriers into secondary or primary energy carriers such as electricity, heat or steam. In France, an even narrower interpretation is under consideration, which only covers combustion installations from the energy sector and no combustion installations from industry.

There are also differences in the accumulation rule. According to the Directive, capacities have to be accumulated if the same operator runs them, and if they fall under the same subheading in the same installation or on the same site (CEC 2003a). This sets the criteria governing which of the installation capacities below the 20 MW thresholds or other production threshold have to be accumulated and to be included in the EU ETS. In Germany, for example, the accumulation rule will be less stringent than expressed by the Directive because Germany requires that all criteria have to be fulfilled at the same time for an installation to be covered.

The EU Commission has threatened to report Member States that have not followed their directions to the European Court of Justice. However, this threat has had little success in convincing the offending Member States to change their approach. Most likely, the necessary harmonization of the installations covered by the EU ETS will be left to the second period 2008-2012.

In order to give a further idea of what a NAP consists of, I have provided a brief summary of the NAPs of major EU Member States, which have already been finalized and approved by the EU Commission. These summaries can be found in Annex I.

Chapter 3   Applying The EPPA Model To The ETS

3.1 Overview

The Emissions Prediction and Policy Analysis (EPPA) model simulates the world economy in order to provide scenarios of anthropogenic greenhouse gas emissions and to analyze the economic impact of climate change policies. EPPA is part of a larger Integrated Global Simulation Model (IGSM) that predicts the climate and ecosystem impacts of greenhouse gas emissions.

EPPA is a recursive dynamic multi-sector, multi-region world economy computable general equilibrium (CGE) model, with region and economic sector detail, developed at the MIT Joint Program on Science and Policy of Global Change (Yang et al., 1996, Babiker et al., 2001). As such, it models the economy as a closed loop of flows of capital and labor, goods and services, income, purchases, and taxes. Underlying the structure of the model, consumers maximize their utility, and producers maximize profits. EPPA, in its current version 4.0, extends from 1997 to 2100 in five-year periods (except for the first three year period from 1997 to 2000). For each period, the model solves for the equilibrium where goods and factor inputs clear across the entire economy, subject to the constraints of technology (represented by production functions), greenhouse gas limitations, etc. The model is initialized with production, consumption, and trade data based on GTAP-E, a comprehensive energy and economic data set (Hertel, 1997)

3.2 EPPA – European Version

The version of EPPA used here is slightly different from the EPPA version 4.0. For EPPA 4.0, the model is divided in 16 regions – United States, Canada, Mexico, Japan, Australia/New Zealand, Europe, Eastern Europe, Former Soviet Union, East Asia, China, India, Indonesia, Africa, Middle East, Latin America, and the Rest of the World). My intent is to estimate the effects of emissions trading on the EU Member States. My model

(EPPA-Euro) disaggregates the Europe and Eastern Europe regions into 13 regions so that I am able to more accurately represent details of each individual country or region.

EPPA is also divided into 11 production sectors. The model tracks carbon dioxide (CO_2) and non-CO_2 gases like methane (CH_4), nitrous oxide (N_2O), Hydrofluorocarbons (HFCs), sulfur hexafluoride (SF_6), Perfluorocarbons (PFCs), carbon monoxide (CO), Non-Methane Volatile Organic Compounds (NMVOC), and sulfur dioxide (SO_2). Finally, 11 additional new technologies (solar, synf-oil, synf-gas, renewable oil, hydrogen, wind, biomass, natural gas combined cycle with and without carbon capture, integrated gasified carbon capture with sequestration and advanced nuclear) compete with traditional technologies. One can run the EPPA model by applying a policy scenario to every region or to a subset of regions, sectors or greenhouse gases. The model will give as output, for example, the CO_2 emissions of each region, permit price, GDP, energy prices, and consumption.

Table 3 shows the regions and sectors in the EPPA-Euro model that I used.

3.3 Determining the EU Emissions Trading Sectors for EPPA

As mentioned before, the EPPA model has aggregated the economy into 11 production sectors. The production sectors in EPPA do not correspond exactly to the installations covered by the EU ETS. Hence, one of the main issues is to determine which EPPA sectors are most closely related to the ETS sectors. For example, the TRAN sector in EPPA corresponds to the transportation sector of the respective region and since the ETS does not include transportation, the allocated caps of the ETS should not cover this sector at all.

The ETS covers installations with large emissions. Sectors in EPPA that include such large installations are in the ELEC and EINT sectors. Table 4 shows the percentage of emissions in each country estimated in the NAPs to come from covered installations

(aggregated into EPPA regions) and the percentage of emissions of the EINT and ELEC sectors for the year 2000.

Table 3: Regions and Sectors in EPPA-Euro

Regions		Production Sectors	
Annex B		**Non-Energy**	
USA	United States	**AGRI**	Agriculture
CAN	Canada	**EINT**	Energy Intensive
MEX	Mexico	**OTHR**	Other Industries
JPN	Japan	**SERV**	Services
ANZ	Australia/New Zealand	**TRAN**	Transportation
FSU	Former Soviet Union		
EUR_FIN	Finland	**Energy**	
EUR_FRA	France	**OIL**	Crude Oil
EUR_DEU	Germany	**ROIL**	Refined Oil
EUR_GBR	UK	**COAL**	Coal
EUR_ITA	Italy	**GAS**	Natural Gas
EUR_NLD	Netherlands	**ELEC**	Electricity Production
EUR_ESP	Spain		
EUR_SWE	Sweden	**Consumption**	
EUR_REU[7]	Rest of Europe	**FD**	Non-Industrial Consumption
EUR_EFT[8]	EFTA		
EET_HUN	Hungary		
EET_POL	Poland		
EET_XCE[9]	Rest of EET		
Non Annex B			
CHN	China		
IND	India		
IDZ	Indonesia		
ASI	Asia		
MES	Middle East		
LAM	Latin America		
AFR	Africa		
ROW	Rest of the World		

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[7] REU: Denmark, Austria, Belgium, Switzerland, Greece, Ireland, Portugal
[8] EFT: Iceland and Norway
[9] EET: Romania, Czech Republic, Bulgaria, Slovakia and Slovenia

Table 4: Percentage of national GHG and CO_2 emissions covered by EU ETS and the EINT and ELEC sectors from EPPA

		REU	FIN	FRA	DEU	GBR	ITA	NLD	ESP	SWE	HUN	POL	XCE
% of GHG	NAP	41	50	20	50	38	47	44	41	28	-	70	52
	EPPA	37	53	23	44	36	39	35	36	29	46	56	53
% of CO_2	NAP	53	59	29	58	46	61	54	54	30	52	80	65
	EPPA	46	63	32	52	45	47	42	47	34	59	69	72

Source: National Allocation Plans of Member States and EPPA-Euro
*all figures rounded to the nearest integer

As can be seen, the results show that there is a similarity between the EU ETS sectors and the EINT and ELEC sectors in EPPA.

3.4 Determining Sectorial Caps for each Member State

We corrected for the differences in Table 4 by proportionately changing the absolute cap as stated in the NAP for each Member State, so that the percentage reduction of emissions will be the same in EPPA as in the NAP.

As an example, Finland's ETS cap is 45.5mmt CO_2-eq/year for the ETS sectors. However, we cannot use the 45.5mmt cap for the EINT and ELEC sectors. This is because the cap applies to 59% of total CO_2 emissions in Finland whereas the EINT and ELEC sectors cover 63% of total CO_2 emissions. Hence, the cap that we use in our analysis when running the EPPA model should be higher since the EPPA sectors cover a higher percentage of national CO_2 emissions.

Table 5 shows the allocation of credits by Member States and also the breakdown into EPPA sectors.

Table 5: National Allocation Plan Caps within EU

Member State	Installations	NAP Cap (mmt/year)
Austria	205	32.9
Belgium	363	63.3
Denmark	362	33.5
Finland	533	45.5
France	1392	153.55
Germany	1860	495
Greece	141	71
Ireland	143	22.33
Italy	2100	279
Netherlands	180	76
Portugal	239	39
Spain	927	188.2
Sweden	499	22.9
UK	1078	252
Czech Republic	450	107.66
Hungary	300	30
Poland	1200	286.2
Slovakia	209	30.5
Slovenia	78	8.75

Source: Cozijinsen, 2005

In order to obtain the appropriate cap for the EPPA sectors, we will need to determine what the differences between the ETS sectors and the EPPA sectors are, in terms of percentage of national emissions. Since the ETS is concerned primarily with CO_2 emissions, we decided to concentrate on the CO_2 emissions differences.

Table 6 below shows the allocation caps to be used for the EINT and ELEC sectors in EPPA.

Table 6: Allocation Caps by EU regions as applied in EPPA compared with those in NAPs

	REU	FIN	FRA	DEU	GBR	ITA	NLD	ESP	SWE	HUN	POL	XCE
Original	262	45.5	153.6	495	252	279	76	188.2	22.9	30	286.2	301.86
New	227	49	172	446	246	214	60	163	26	34	247	339

*all figures rounded to the nearest integer

I use these adjusted allocation caps for the sectorial policy when applied in the EPPA EU and Eastern Europe regions, specifically for the ELEC and EINT sectors.

I apply these caps in EPPA as if they are national caps where only the two sectors are participating in emissions trading. EPPA does not require these caps to be further allocated to each sector. In economic theory, what matters in terms of trading and economic efficiency is the market clearing permit price. How permits are allocated does not affect these outcomes because all permits have opportunity cost even if they are given away for free. In EPPA this opportunity cost is represented by the permit price. The cap and trade system is thus modeled as if all permits were purchased from the government and all revenue is distributed in a lump sum manner to the representative consumer. In the real world, the allocation will affect the distribution of income, depending on the extent to which different consumers own equity of firms affected by the cap. Since EPPA has a single consumer who owns all assets, we cannot estimate this effect. We also cannot estimate the potential distortionary effects of non-lump sum distribution of some of the permits (those that under some countries' NAPs are retained for new entrants).

Chapter 4   Stochastic Analysis of the EU ETS

4.1 Stochastic Analysis: Research Methodology

One can model the uncertainty faced by installations with respect to carbon prices that they will face as driven by the uncertainty in the input parameters of the EPPA model. The basic idea is to obtain an estimate of the uncertainty in these parameters in the form of a probability density function (PDF). Sampling from these allows me to then perform a Monte Carlo simulation to determine the possible range for the permit prices.

The first step is to identify those economic parameters in the EPPA model to which the permit prices are most sensitive. For each of these parameters, one must then estimate a PDF, quantifying its degree of uncertainty. The PDF can be determined either by using historical data or through expert elicitation, as done by Cossa (Cossa, 2004). One must then sample the PDFs of each parameter to obtain 250 different sets of inputs. The EPPA model is then run once for each parameter set in a Business-As-Usual (BAU) scenario. The caps of each Member State are then applied. The 250 sets of inputs will thus result in 250 different permit prices, which we can be represented as a PDF of the permit price. Lastly, I will conduct a sensitivity analysis to determine which uncertainty parameter has the most effect on the permit prices. Figure 5 shows the steps that I took for my research methodology.

Figure 5: Research Methodology

```
┌─────────────────────────┐
│   Identify the Economic  │
│        Parameters        │
└─────────────────────────┘
            │   E.g Labor Productivity Growth
            ▼
┌─────────────────────────┐
│    Develop the PDFs      │
│    for Each Parameter    │
└─────────────────────────┘
            │   Either using historical data or expert elicitation
            ▼
┌─────────────────────────┐        ┌─────────────────────────┐
│   Sample the PDFs of each│        │  Obtain appropriate emissions│
│   parameter 250 times as │        │  caps for each European region│
│      inputs to model     │        │       in EPPA-Euro       │
└─────────────────────────┘        └─────────────────────────┘
            │   250 Input Files              │   Allocation Caps
            ▼                                 │
┌──────────────────────────────────────┐     │
│  Run EPPA 250 times to generate 250 BAUs│  │
└──────────────────────────────────────┘     │
            │                                 ▼
            ▼                    ┌─────────────────────────┐
            └───────────────────▶│ Run EPPA 250 times to estimate costs of│
                                 │           p     y        │
                                 └─────────────────────────┘
                                              │
                                              ▼
                                 ┌─────────────────────────┐
                                 │     Extract the results  │
                                 └─────────────────────────┘
                                              │   250 Permit Prices
                                              ▼
                                 ┌─────────────────────────┐
                                 │   Construct the PDF of   │
                                 │      Permit Prices       │
                                 └─────────────────────────┘
                                              │
                                              ▼
                                 ┌─────────────────────────┐
                                 │    Sensitivity Analysis  │
                                 └─────────────────────────┘
```

4.2 Stochastic Parameters Used

There are hundreds of parameters in the EPPA model but it is not numerically feasible to investigate uncertainty in all of them. Experience with uncertainty analysis indicates that most of the uncertainty in a particular outcome can be traced to a few parameters. Important parameters are those for which the outcome of interest is sensitive and for which there is relatively large uncertainty. A parameter for which the outcome was highly uncertain but that was known with complete certainty obviously could not contribute to uncertainty in the outcome. Similarly a parameter that was very uncertain but which had little or no effect on the outcome of interest would not be important in determining that outcome but could contribute to uncertainty in other outcomes. Cossa (2004) conducted a complete sensitivity analysis of EPPA, examining which parameters most affected the cost of carbon policy. He identified a set that was most important in the nearer term (2010), and a different set that was important in the longer run (2050 and beyond). Because I am interested in the near term effects of the ETS, I chose the set of parameters that Cossa (2004) determined were important for short run costs. This set included the Vintaging Coefficient, Elasticity of Substitution between Energy and Non-Energy Composites, Labor Productivity Growth, and the Autonomous Energy Efficiency Improvement (AEEI).

For the Vintaging Coefficient, Elasticity of Substitution between Energy and Non-Energy Composites, and the Autonomous Energy Efficiency Improvement (AEEI), I used PDFs that Cossa (2004) developed. He derived these PDFs using an expert elicitation process (Cossa 2004). For the labor productivity growth, I be developed the PDFs myself, using historical economic growth.

Besides these parameters that Cossa recommended, I expanded the analysis to include stochastic world oil and gas prices. These prices are highly volatile especially in the short term and likely affect the costs of emissions reductions, thereby affecting the permit prices. As normally run, energy prices are determined endogenously in EPPA based on a description of supply of energy and demand. Short run energy price dynamics are often

determined by political and other factors, unrelated to long rum supply considerations. EPPA thus includes a feature whereby energy prices can be set exogenously. I thus used this feature of EPPA.

In the next sections, I describe how each of these parameters is modeled in EPPA. I then describe how I estimated PDFs for labor productivity growth and oil and gas prices.

4.2.1 Vintaging Coefficient (VINT)

Once capital like a factory or machine has been put into place there is a limited ability to change its characteristics. Economists refer to "putty-putty" versus "putty-clay" capital investment formulations. In a "putty-putty" formulation all capital remains malleable, as if it were completely new investment. In a "putty-clay" formulation capital is only malleable when the investment is first made. EPPA allows a share of capital to become clay and the rest to remain malleable, approximating the reality that there is some ability to alter old capital, but not as much as with completely new investment. The vintaging coefficient is the share of malleable capital (new investment plus previous malleable capital) that becomes clay, and thus becomes "vintaged." If the coefficient is 1.0, it means that all capital becomes "clay" and it cannot be retrofitted. If it is 0.0, it means that all capital is "putty" and can be retrofitted and redeployed in each period.

4.2.2 Elasticity of Substitution between Energy and Non-Energy Composites (ELAS)

Each sector in EPPA is modeled as a constant elasticity of substitution (CES) function that is composed of several different parts. The elasticity between energy and non-energy composites is one of them and it measures the ease of substituting switch between energy and non-energy composites (capital and labor). It thus models the extent to which the energy efficiency characteristics of new capital can differ because of changing energy prices relative to the composite price of other inputs, inclusive of any taxes or of carbon prices.

4.2.3 Autonomous Energy Efficiency Improvement (AEEI)

The AEEI represents the decrease in the amount of energy required to produce one unit of output that is not explained by price changes. It was used in the Edmonds-Reilly model (Edmonds & Reilly 1983) and also in the Global 2100 model (Manne & Richels, 1990). It is a simple formulation that captures the overall improvement in energy efficiency that has occurred even when energy prices have been falling. In other words, the AEEI represents the change in technology that results in a change in the efficiency of energy use.

AEEI is introduced in EPPA through a decrease in the effective energy required in non-energy sectors, consumption (CONS), government (GOVT) and investment (INV). The non-energy sectors include Agriculture, Energy-intensive Industries, Other Industries, Services and Savings Good. AEEI enters EPPA as:

$$E_j^e(t) = \frac{E_j(t)}{AEEI_j(t)} \quad j \in (ne, cons, govt, inv)$$

where $E_j^e(t)$, $E_j(t)$ and $AEEI_j(t)$ are respectively the effective and physical energy inputs and the AEEI factor in sector j at time t.

4.2.4 Labor Productivity Growth (LPG)

Labor productivity indicates how productive a worker is. In order to obtain the amount of effective labor supply available in period t+1, the effective labor in period t is multiplied by the productivity index:

$$Labor_{t+1}(R) = Labor_t(R) \times prod_{t+1}(R)$$

where $Labor_{t+1}(R)$ and $prod_{t+1}(R)$ represent the effective labor supply available and the productivity index at time t in region R respectively. The evolution of $prod_{t+1}(R)$ over time is determined by LPG:

$$prod_{t+1}(R) = prod_t(R) * (1 + lpg_t(R))$$

where $lpg_t(R)$ is the labor productivity growth rate at time t in region R. In EPPA, LPG in t is determined by an initial rate and a terminal rate that are each set exogenously. Its evolution over time is modeled as a decreasing negative exponential from its value in 1997 to its value in 2100.

$$lpg_t(R) = (1 + \alpha) \times \frac{lpg_0 - lpg_{100}}{1 + \alpha \exp[\beta(t-1)]} + lpg_{100}$$

where $\alpha = 0.1$ and $\beta = 0.07$. lpg_0 and lpg_{100} are the values of LPG in 1997 and 2100.

4.2.5 Oil and Gas Prices

Normally EPPA endogenously calculates oil and gas prices that clear markets, equating supply with demand. Given a production function describing production of energy from the resource base, the supply of energy in any period is a function of technical change and gradual depletion of fossil resources. Short-run changes in oil and gas prices can be driven by political events and other things mostly unrelated to these long run forces. EPPA thus includes a feature that allows users to over-ride the endogenous price process, to set oil and gas prices at any level. Quantity demanded is determined by this price, and it is assumed that that sufficient supply is available to meet that demand. I used this feature of EPPA in my analysis.

4.3 Uncertainty for Labor Productivity Growth

Labor Productivity Growth is a major determinant of economic growth in the EPPA-Euro model. Economic growth is a key economic factor that affects the permit prices. In general, if the economic growth of a particular Member State is relatively strong, it is expected that the emissions by an installation in the country will increase as well. In situations whereby there is generally strong economic growth among all Member States,

the permit prices are expected to be high as most installations affected by the ETS will demand more permits to meet their emissions levels.

I analyzed the uncertainty in historical economic growth in the EU countries. Based on the relationship between LPG and economic growth, I was able to determine a PDF for LPG that produced in EPPA the desired variability in economic growth. In my case, this meant matching it to the historical variability I observed. I retained the reference values in EPPA as the mean of the distribution and matched the variability to that of historical economic growth. Table 7 shows the reference labor productivity values in EPPA from 2000 to 2020 for the European regions.

The historical economic growth rates were obtained from Professor Mort Webster from University of North Carolina at Chapel Hill. This data included the annual economic growth for most Member States from 1950 – 2000, with the exception of some Eastern European nations like Romania and Poland, for which the data extend back only to the late 1980s to 2000.

Since EPPA solves on multi-year time steps, I was not interested in annual variability but instead on the variability in GDP growth over succeeding multi-year periods. I thus calculated the historical variation of the economic growth values in three-year time periods. We did not use five-year periods as used in EPPA-Euro because the data series was too short to generate enough observations of successive 5-year growth rates.

Table 7: Reference Labor Productivity Values in EPPA

	2000	2005	2010	2015	2020
EUR_FIN	0.02	0.052	0.05	0.047	0.044
EUR_FRA	0.02	0.052	0.05	0.047	0.044
EUR_DEU	0.02	0.052	0.05	0.047	0.044
EUR_GBR	0.02	0.052	0.05	0.047	0.044
EUR_ITA	0.02	0.052	0.05	0.047	0.044
EUR_NLD	0.02	0.052	0.05	0.047	0.044
EUR_ESP	0.02	0.052	0.05	0.047	0.044
EUR_SWE	0.02	0.052	0.05	0.047	0.044
EUR_REU	0.02	0.052	0.05	0.047	0.044

EUR_EFT	0.02	0.052	0.05	0.047	0.044
EET_HUN	0.071	0.059	0.057	0.054	0.050
EET_POL	0.071	0.059	0.057	0.054	0.050
EET_XCE	0.071	0.059	0.057	0.054	0.050

Source: EPPA_Euro

To apply the variations of the historical economic growth to the LPG values of each Member State, I normalized the historical growth rates of each country such that the mean was 1. Hence, a value of 1.19 for Finland means that for that period, Finland's economic growth was 19% more than the average economic growth from 1950 – 2000 and this translate into a 19% increase in LPG for Finland over its reference values in the EPPA model.

From the normalized historical economic growth, I obtained a PDF, for each Member State in which the labor productivity varies. This was done with the software @RISK, which is widely used for uncertainty analysis. @RISK makes it possible to find among 20 different types of distributions, one that best fits the data.

The best-fitting distributions for countries turned out to be either the Logistic distribution, the Extreme Value distribution or the Normal Distribution. A brief introduction of all three distributions can be found in the Annex II. Table 8 shows the distributions for all the European regions and Figures 6 - 18 show the Cumulative Density Function (CDF) of the regions fit to the raw data.

Table 8: PDF of LPG for European Regions

Region	Function	Parameters	
		α	β
EUR_FIN	Logistic	1.076	0.42
EUR_FRA	Logistic	1.005	0.307
EUR_DEU	Logistic	1.007	0.338
EUR_GBR	Logistic	1.034	0.26
EUR_ITA	Extreme Value	0.73	0.48
EUR_NLD	Extreme Value	0.723	0.519
EUR_ESP	Normal	1	0.725
EUR_SWE	Logistic	1.098	0.294

EUR_REU	Logistic	1.018	0.285
EUR_EFT	Logistic	1.04	0.195
EET_HUN	Logistic	2.215	2.542
EET_POL	Extreme Value	-0.414	2.664
EET_XCE	Extreme Value	-2.588	7.231

Figure 6: Finland's CDF of LPG
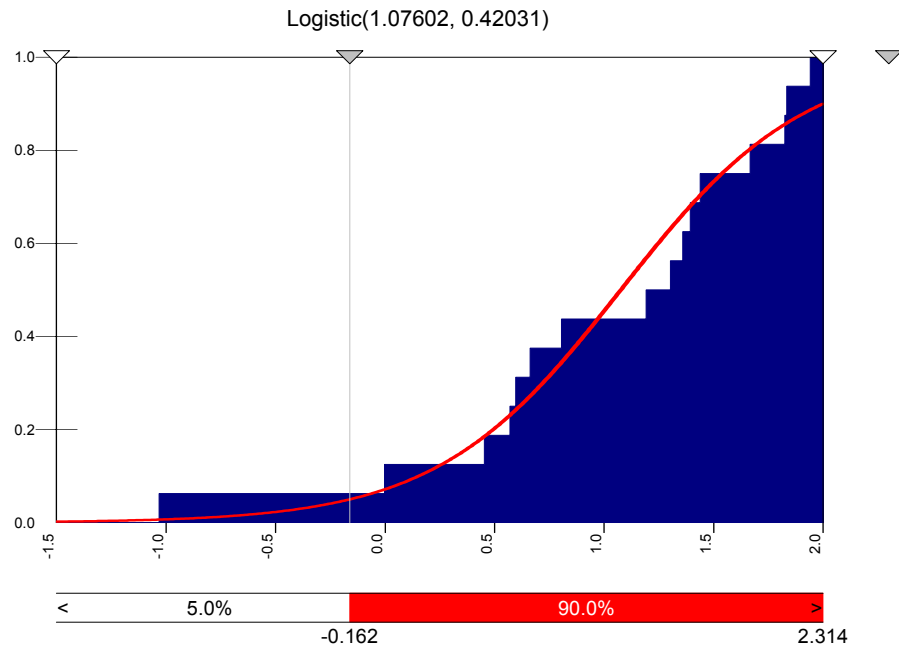
Figure 7: France's CDF of LPG

Logistic(1.00544, 0.30716)

90.0%

0.101   1.910
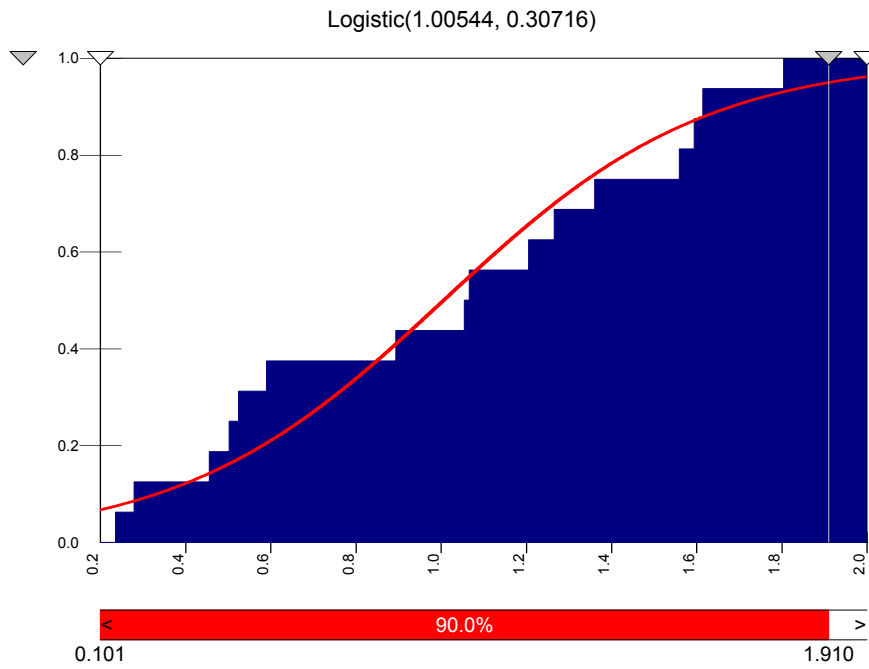
Figure 8: Germany's CDF of LPG

Logistic(1.00672, 0.33757)

90.0%

0.013   2.001
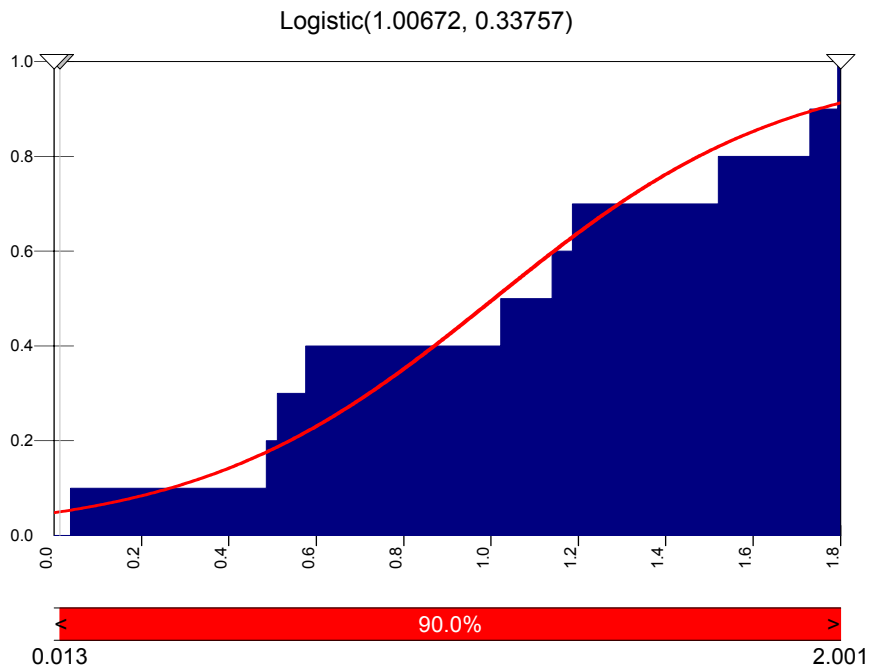
Figure 9: UK's CDF of LPG

Logistic(1.03373, 0.26007)
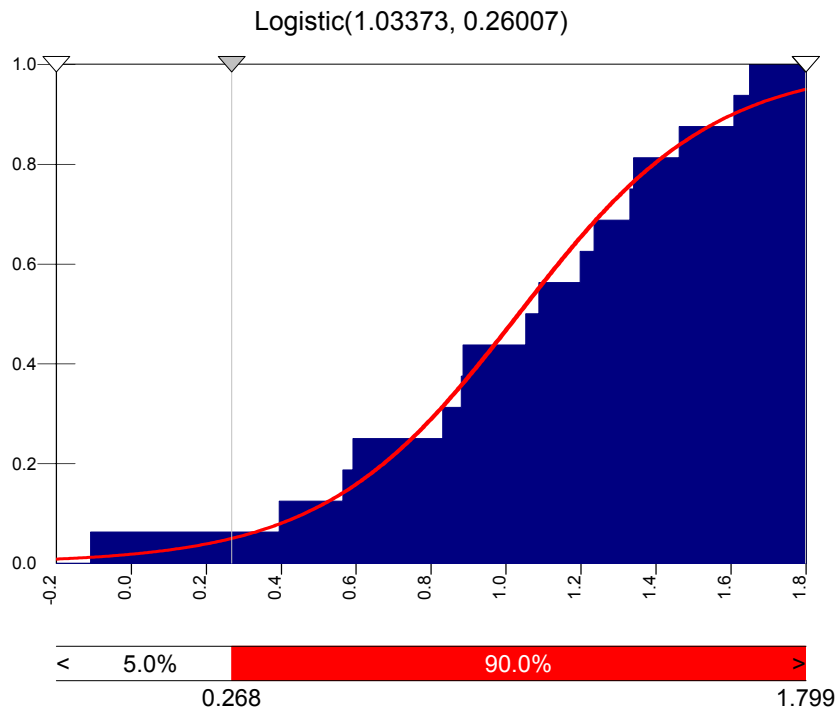
Figure 10: Italy's CDF of LPG

ExtValue(0.73036, 0.48044)
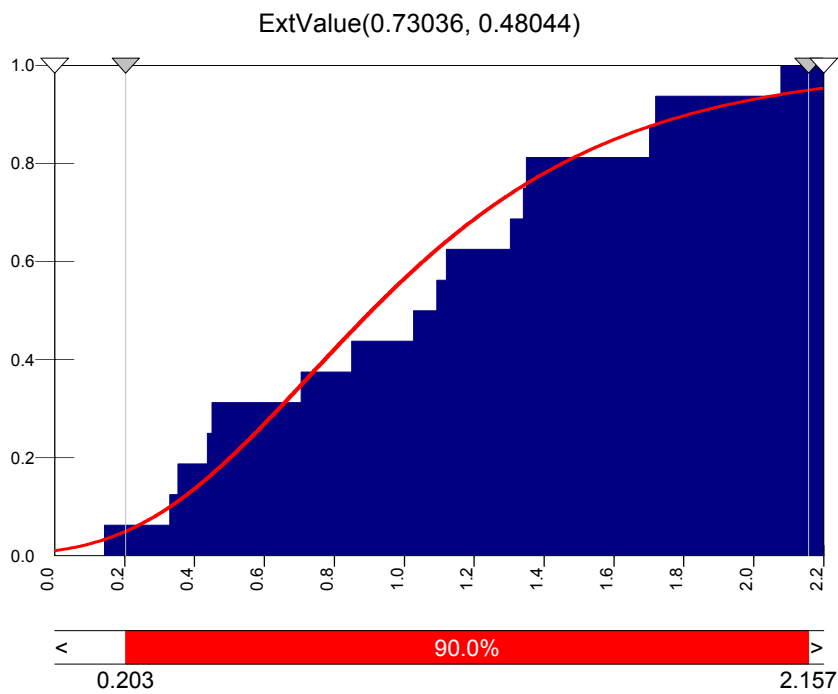
Figure 11: Netherlands's CDF of LPG

ExtValue(0.72287, 0.51887)
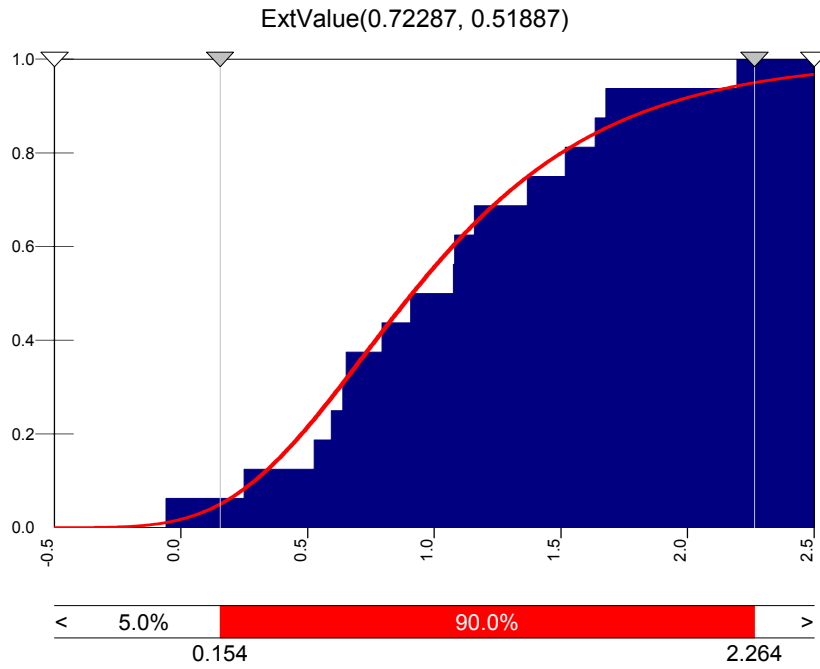
Figure 12: Spain's CDF of LPG

Normal(1.00000, 0.72524)
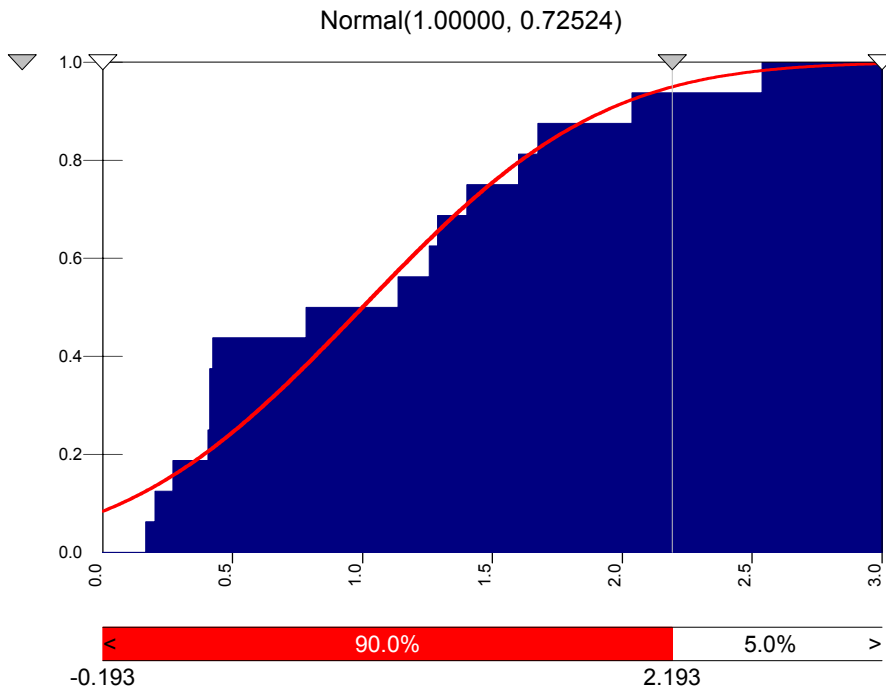
Figure 13: Sweden's CDF of LPG

Logistic(1.09761, 0.29428)

<	5.0%		90.0%	>
		0.231		1.964

Figure 14: REU's CDF of LPG

Logistic(1.01830, 0.28512)

<	90.0%	>
0.179		1.858
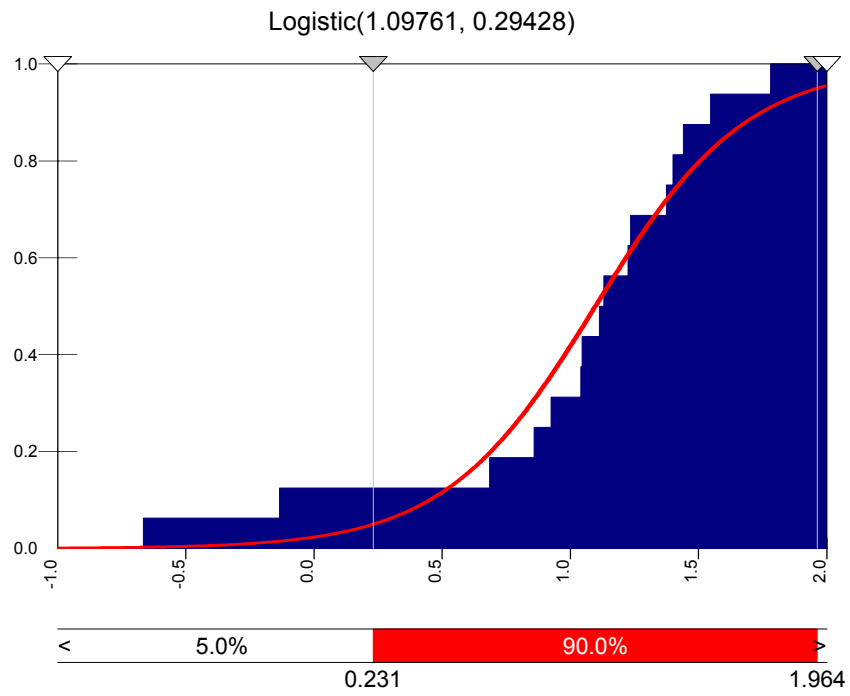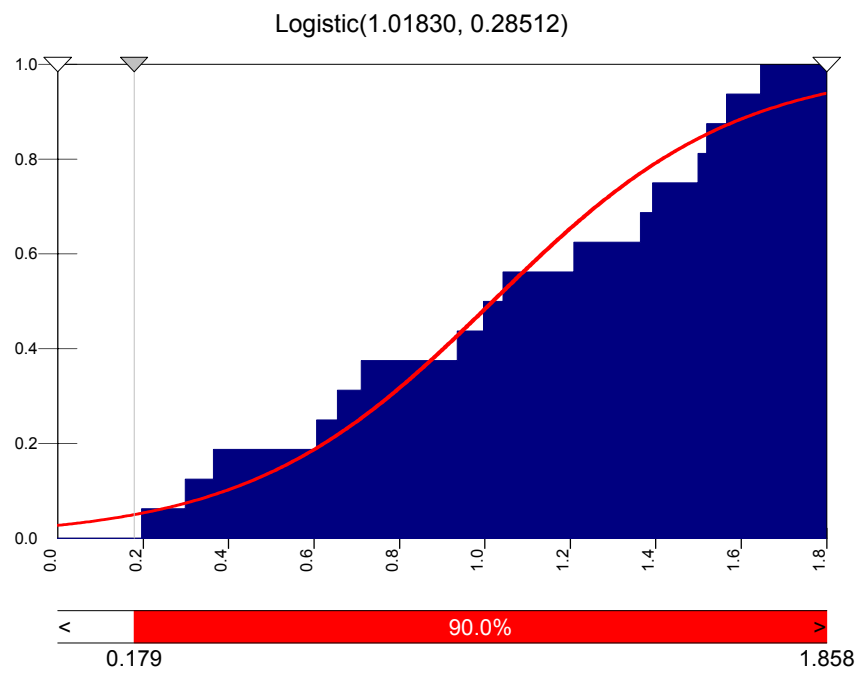
Figure 15: EFT's CDF of LPG

Logistic(1.03959, 0.19501)
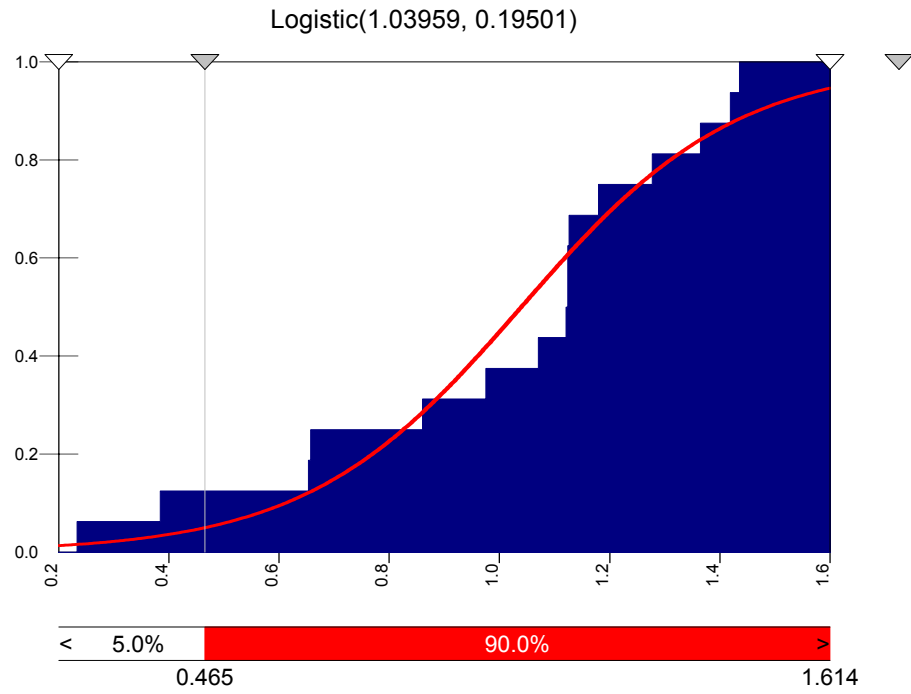
Figure 16: Hungary's CDF of LPG

Logistic(2.2146, 2.5420)
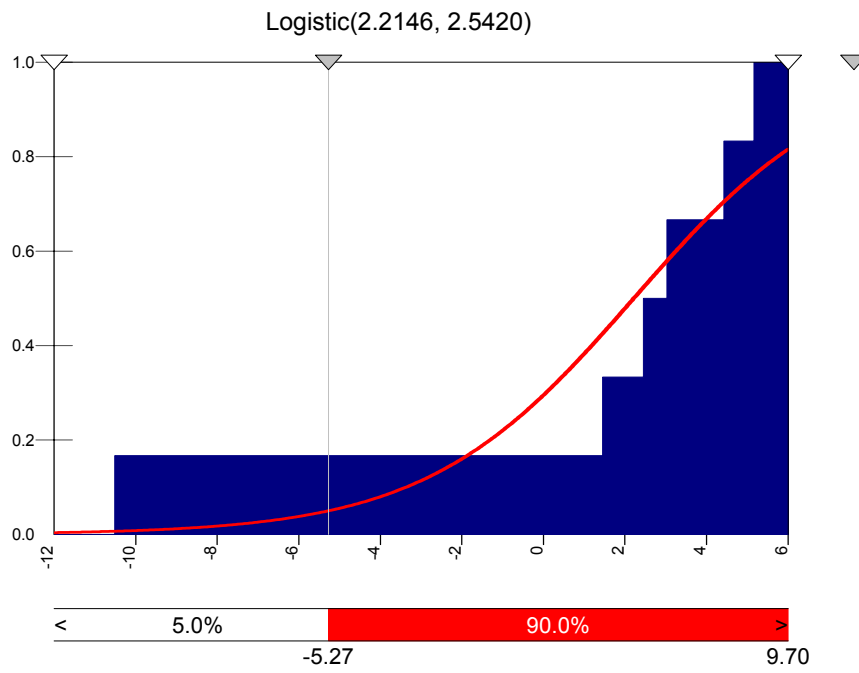
Figure 17: Poland's CDF of LPG

ExtValue(-0.41480, 2.6644)

Figure 18: XCE's CDF of LPG

ExtValue(-2.5885, 7.2308)
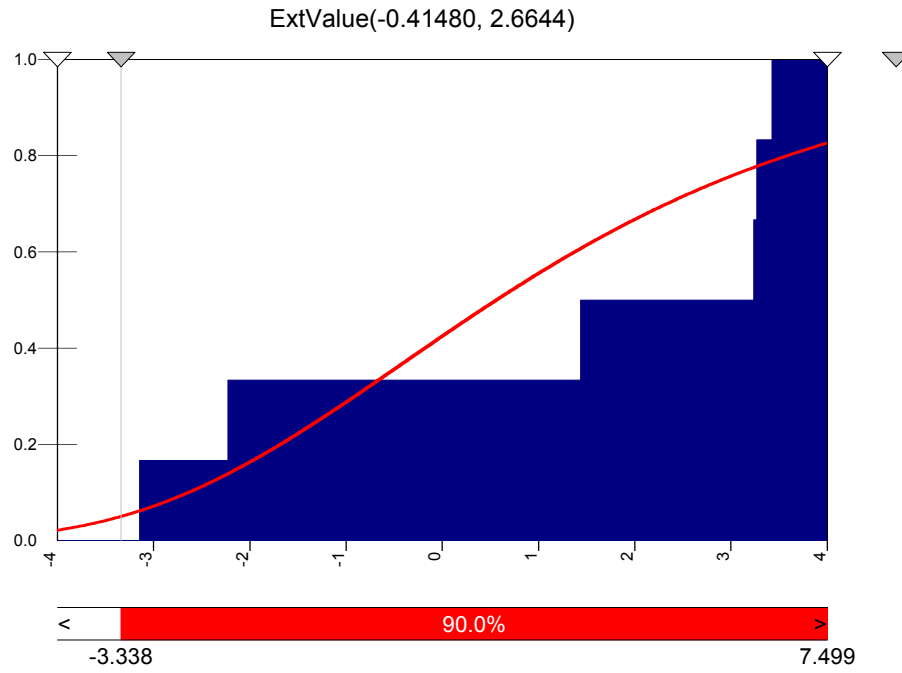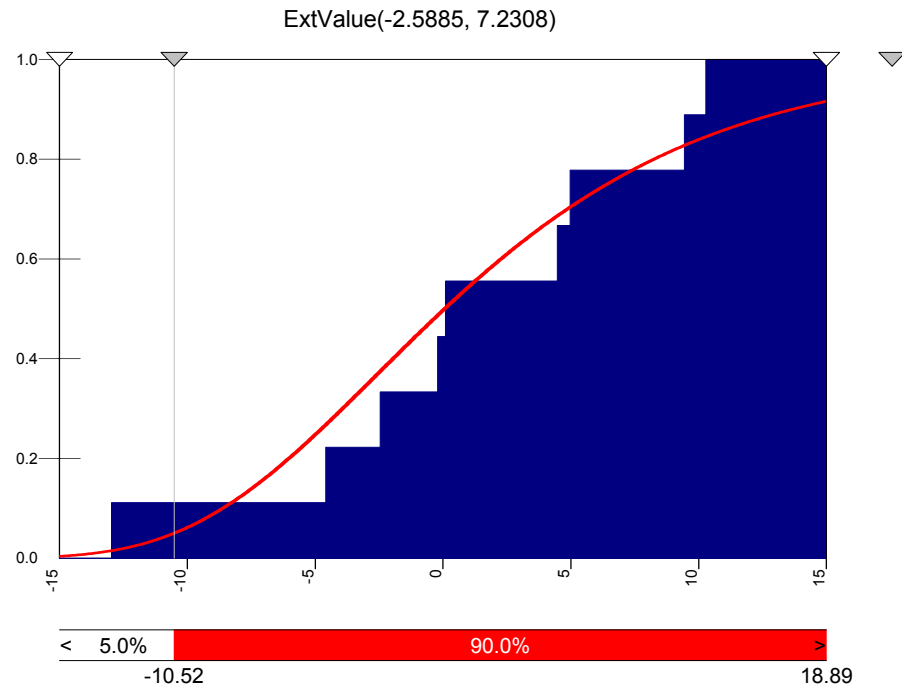
These PDFs were then used to simulate 6000 sample normalized economic growth values for each region. The normalized sample was then multiplied by the reference labor productivity values to obtain 6000 stochastic samples of LPG for the 13 European regions in EPPA. The 6000 samples produces a discrete approximation of the limiting distribution from which it is then possible to sample the 250 values needed for the Monte Carlo simulations. The frequency of LPG values drawn is determined by the PDF.

Table 9 shows one set of sampled LPG values for the different European regions for the years 2000 to 2020. This can be compared with the reference values from the table above, in order to see the differences in the LPG inputs.

Table 9: Partial Sample of the File Generated – New LPG inputs to EPPA

	2000	2005	2010	2015	2020
EUR_FIN	0.0131	0.067	0.0324	0.0579	0.0468
EUR_FRA	0.0245	-0.0045	0.0545	0.0288	0.0509
EUR_DEU	0.0273	0.0574	0.0691	0.0523	0.0289
EUR_GBR	0.057	0.0543	0.0377	0.0602	0.0726
EUR_ITA	0.0256	0.0507	-0.0195	0.1216	0.0662
EUR_NLD	0.016	0.0749	0.1178	0.0466	0.0358
EUR_ESP	0.0187	0.0657	0.0173	0.0614	0.05
EUR_SWE	0.0319	0.0804	0.0329	0.0477	-0.0006
EUR_REU	0.0117	0.0609	0.0387	0.0791	0.0615
EUR_EFT	0.0162	0.0632	0.0371	-0.0059	0.0349
EET_HUN	0.0267	0.5289	0.1925	0.1693	-0.0138
EET_POL	-0.4727	0.1415	0.7827	-0.7748	0.3879
EET_XCE	0.092	-0.1155	1.9257	0.1216	1.5351

It must be noted that EPPA solves in 5-year periods. Hence, we made the assumption that the 1997 values correspond to LPG values from 1997 - 1999, 2000 values correspond to LPG values from 2000 - 2004, the 2005 values correspond to the 2005 - 2007 EU ETS period and the 2010 values correspond to the 2008-2012 Kyoto Protocol. Because LPG values from 1997 – 1999 is historical, we do not represent these years as uncertain. The year 2010 has full uncertainty according to the variation from the PDFs generated. The period 2005 has limited uncertainty. Because I assume 2005 is representative of the 2005-2007 period, I assume that the first 2 years of the 5 year period are know with certainty because they are historical years, but that the last 3 are uncertain. In fact, 2003 and 2004

are already historical years and we are well into 2005, but the modeled 2005 to represent the 2005-2007 period, the simulations are done as if 2003, 2004 and 2005 are as yet unknown. Hence, we assumed that the uncertainty in the year 2005 is only 3/5 of the variation in the PDFs.

4.4 Uncertainty for World Oil and Gas Prices (OIL/GAS)

In order to obtain stochastic data for both the world oil and gas prices, we used expert elicitation process as described by Cossa, (2004). The experts where Professor Henry Jacoby, Dr John Reilly and Professor Denny Ellerman of the Joint Program. I elicited their views on what the average oil and gas prices will be from 2005 – 2007. I also elicited views on the correlation between oil and gas prices, leading me to assume that is was 0.7.

The results of the expert elicitation are shown in Tables 10 and 11.

Table 10: Expert Elicitation of World Oil Prices

	Expert 1		Expert 2		Expert 3	
	2005	2010	2005	2010	2005	2010
5% Percentile	70	70	80	100	60	55
50% Percentile	33.65	33.65	40	50	40	35
95% Percentile	15	15	25	30	20	15

Table 11: Expert Elicitation of World Gas Prices[10]

	Expert 1		Expert 2		Expert 3	
	2005	2010	2005	2010	2005	2010
5% Percentile	12	12	12	14	10	8.5
50% Percentile	6.5	6.5	6	8	6.5	5.5
95% Percentile	3	3	4	5	3	2.5

I combined these by equally weighting each expert to obtain PDFs for both the world oil and gas prices, similar to what we was done with the labor productivity growth using the

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[10] US$ per million British Thermal Units (Btu)

@Risk software and then generated 250 samples of stochastic world oil and gas prices to be incorporated into the EPPA model. The PDFs of the world oil and gas prices are shown in Figures 19 - 22.
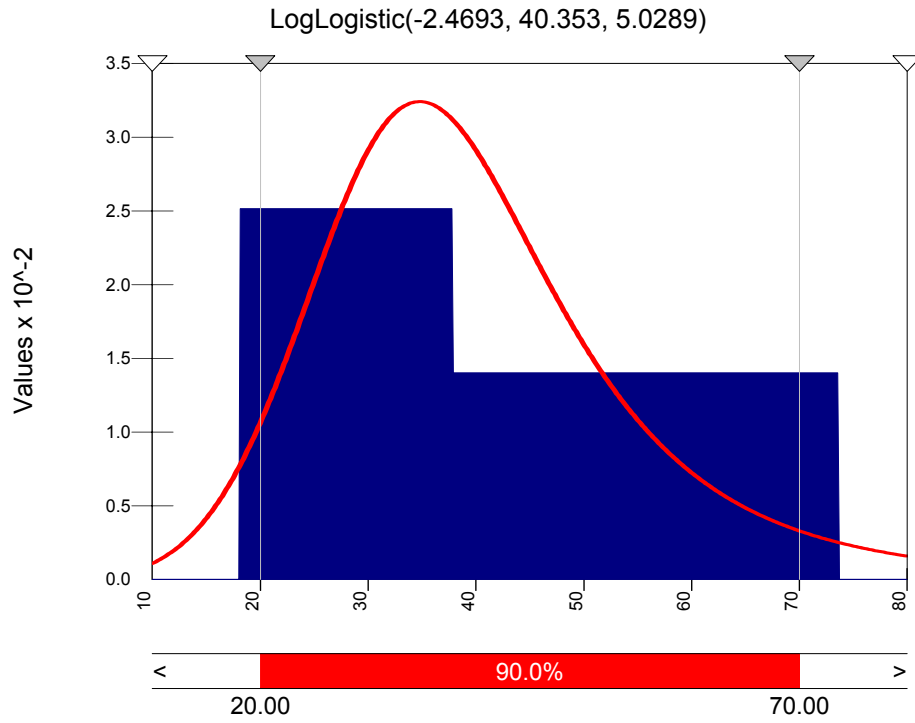
Figure 19: PDF of 2005 Oil Prices

LogLogistic(-2.4693, 40.353, 5.0289)

Figure 20: PDF of 2010 Oil Prices

LogLogistic(-4.0379, 43.588, 4.9474)
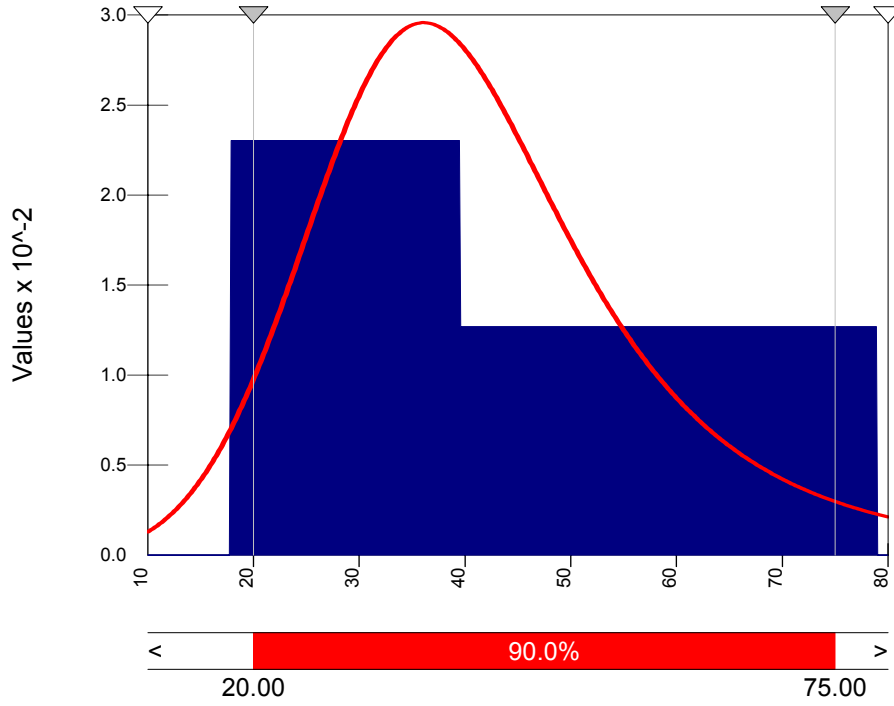
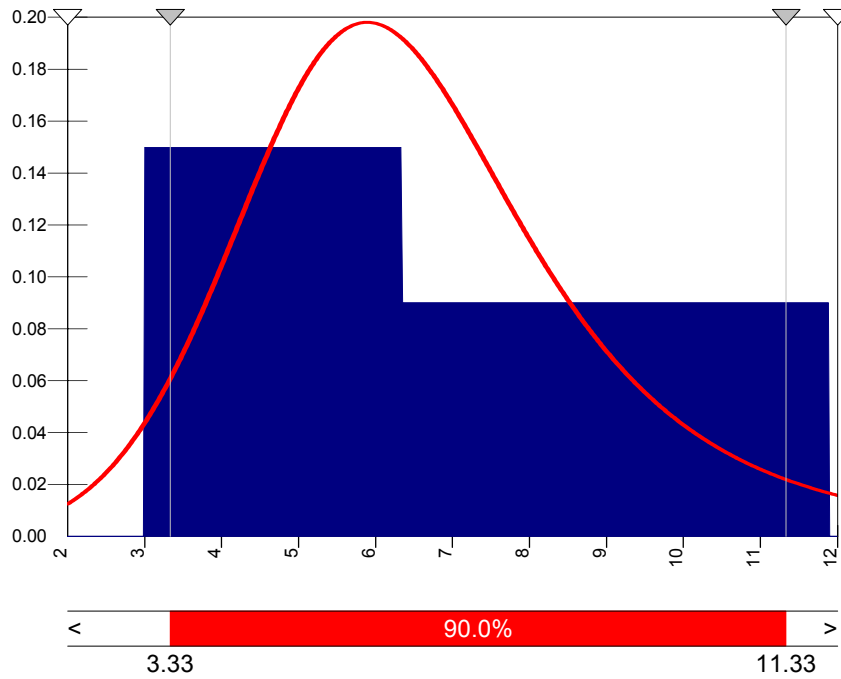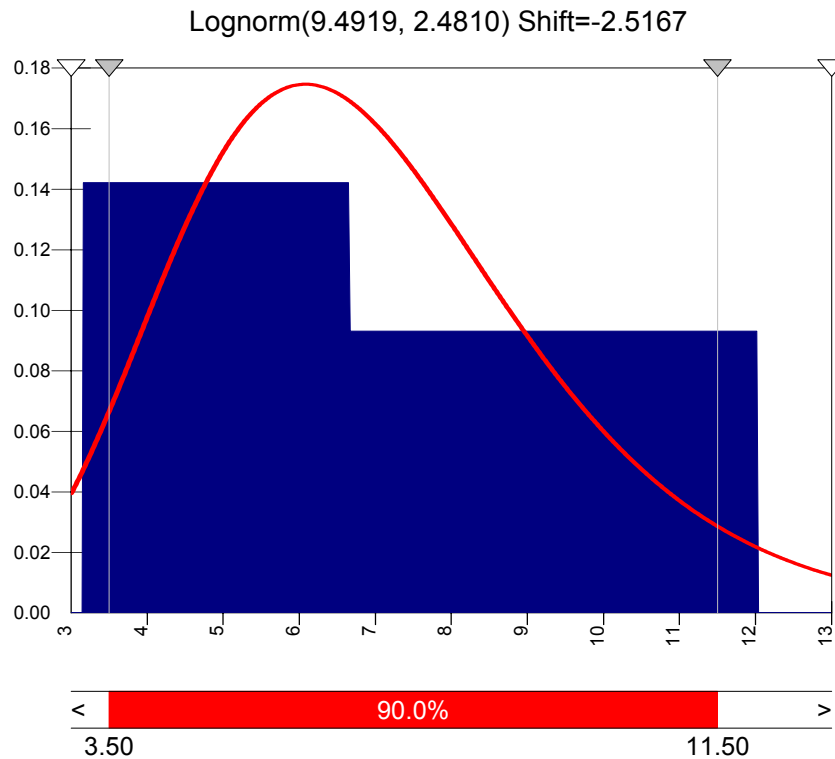# Figure 21: PDF of 2005 Gas Prices

LogLogistic(-1.1667, 7.5000, 5.7641)

Figure 22: PDF of 2010 Gas Prices

Lognorm(9.4919, 2.4810) Shift=-2.5167

4.5 Correlation of Economic Growth between EU Member States

Observations on GDP growth in the EU were too limited to generate statistically significant estimates of the correlation in growth among the countries. Moreover the historical relationship among growth rates may underestimate correlation in the future because of the increasing economic integration of the EU. Hence, I assumed that the correlation between economic growths of Member States is 0.8. I used this correlated economic growth to determine the uncertainty values for the LPG.

Chapter 5   Results

5.1 Uncertainty in Permit Prices under the ETS

The main result of this work is to estimate uncertainty in permit price under the EU ETS. This was derived from a Monte Carlo analysis, varying the share of vintaged capital, the elasticity of substitution between energy and non-energy inputs, labor productivity growth, the rate of autonomous energy efficiency improvement, and oil and gas prices. My main result also enforces a 0.8 positive correlation among countries in terms of labor productivity growth to represent the increasing integration of the EU countries, and positive correlation of 0.7 between oil and gas prices, representing the judgment of experts I consulted. It also includes uncertainty in all regions in EPPA, including the non-European regions as depicted by 'All regions'.

The results of the stochastic analysis are shown in Figure 23 and Table 12.

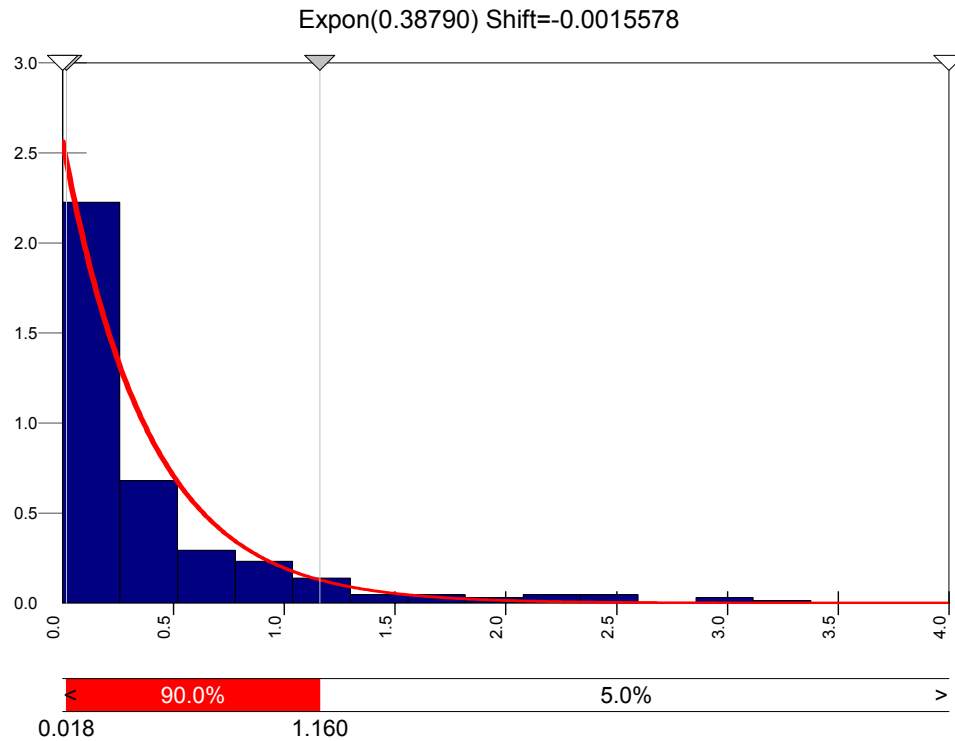**Figure 23: PDF of permit prices during EU ETS (All regions, LPG, AEEI, Vint, Elas, Oil/Gas, with correlation)**

Expon(0.38790) Shift=-0.0015578

Table 12: Key Statistics (All regions, LPG, AEEI, Vint, Elas, Oil/Gas, with correlation)

	Original
Data Points used	250
Probability(Price = 0)	43.0%
Mean Price	$0.38790
Max Price	$3.6372

From the graph, it can be seen that the range of permit prices is between $0 - $3.64/tC[11], with 43% of the cases showing a permit price of zero. The mean price is $0.39. This indicates that the best estimate is that the EU ETS will have some effect, but it may easily be the case that the overall target will not be binding at all. Many Kyoto-type studies found carbon prices of $50, $100, or $200/tC or more for if the EU were to meet its domestic Kyoto target. In comparison, the ETS goal is far less restrictive.

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[11] All permit prices will be in terms of /tC in this paper.

The results are not surprising because as mentioned earlier, the EU ETS is a trial period for the EU region to prepare its Member States for their Kyoto targets. Member States proposed their own emissions cap independently, subject to approval by the Commission. Individual Member State worried that if they set the emissions cap to be too low, it would differentially penalize firms in their county compared with other EU countries. Overall, this favored each country choosing a loose cap, and an overall loose cap for the EU as a whole, and thus a low carbon price. In fact, the chance of a zero carbon price would have been much higher if the European Commission overseeing the ETS and development of the NAPS had not forced some countries to revise downward the original caps they proposed.

5.1.1 Current Market (25 April 2005)

As of 25 April 2005, the carbon price in the EU was trading at €17.42/mmt CO_2 which translate to about US$82.77/tC. There is a huge difference from these results. It is many times higher than even the highest prices in any of the 250 runs. This seems indicate that either we are not capturing something in our model or the market is not focusing on fundamentals and instead relying on sentiments and misinformed expectations. One reason could be due to the fact that because the ETS has just started, very little information is been available. As noted earlier, the short period over which the NAPs were developed has prevented any serious analysis the possible carbon prices given the actual caps. With no history of the market, and little information this creates a situation of great uncertainty. Operators of installations are unsure whether they will be able to meet their allocated target at the end of the year and also as a result, may expect that the demand for the permits will be very high as there may be more demand to meet targets by other installations. Extremely risk-averse behavior may be driving firms to buy permits now, thereby pushing the prices up. However, at the end of the period, as installations get more and more experienced with the EU ETS, they may find that the caps are not very stringent and can easily be reached. Other installations who expect to have extra permits may wait to sell until they are sure they are extra. The actual number of trades

occurring in these early days may be fairly small, and so in the end these high prices may not have much weight.

As noted earlier, not all the countries have finalized their NAPS, and perhaps the expectation is that the remaining NAPs will be very tight. However, I have tried to represent these countries with constraints that are similarly binding to countries with completed NAPs. The remaining countries seem highly unlikely to propose very tight NAPs for themselves, and it seems unlikely the Commission would force them to do much more than other countries.

The ETS allowances cannot be banked forward into the Kyoto period under the current rules of the ETS. It may be possible, however, that firms have an expectation that this will change, and thus might wish to accumulate excess credits on the basis that they will actually be able to apply them during Kyoto when they expect that carbon constraint will be much tighter. An interesting set of research would be estimate the ETS permit price if there were banking of allowances into the Kyoto period.

Of course, it also may be the case that the EPPA model is not adequate to model the relatively short-term market behavior of permit prices, and these results are simply misleading. Interesting research once the ETS is over would thus be to try to reconcile the real average price with the projections made here.

Given these results contradict current market evidence, and to understand better the impact of individual variables, I performed a set of sensitivity analyses described in the next section to see how my results might change.

5.2 Expanding the Stochastic Analysis

The next step for us is to conduct a sensitivity analysis to determine which uncertainty parameter has the most effect on the permit prices, if any. In order to do this, I remove one parameter at a time from the set of uncertain parameters and conduct another set of

250 BAU and policy runs to obtain a new PDF of permit prices. The objective is to determine the effect of including more or fewer uncertain parameters. Because the marginal contribution will depend on the order of this operation, one cannot infer the "importance" of individual parameters from this. I am interested, however, in using this exercise to understand what difference adding other parameters to the uncertain set might make. As noted earlier, most experience with uncertainty analysis suggests that the few most important parameters can capture most of the uncertainty. This is a test of that finding for my case.

Analysis 1: All regions + LPG + AEEI + Vintaging + Elasticity(Energy & Non Energy) + Correlation

In this analysis, world oil/gas prices are endogenous and the prices are certain and the mean are different from that obtained from the expert elicitation. As can be seen from Figure 24 and Table 13, it seems that the permit prices are sensitive to world oil/gas prices. There seems to be a lower probability that the permit prices are zero. This is because in the EPPA-Euro model, world oil/gas prices are lower. In the expert elicitation, the stochastic oil/gas prices are much higher, with the judgment of the experts possibly affected by the recent sharp increase in oil/gas prices. With lower oil/gas prices, this means that installations have a less incentive to reduce energy use in the BAU and hence, this results in higher emissions in the BAU, and makes the caps tighter. This will increase the demand for permits and hence, there is a lesser probability that the permit prices will be zero. This is also indicated by the higher mean price and the higher maximum price for Analysis 1.

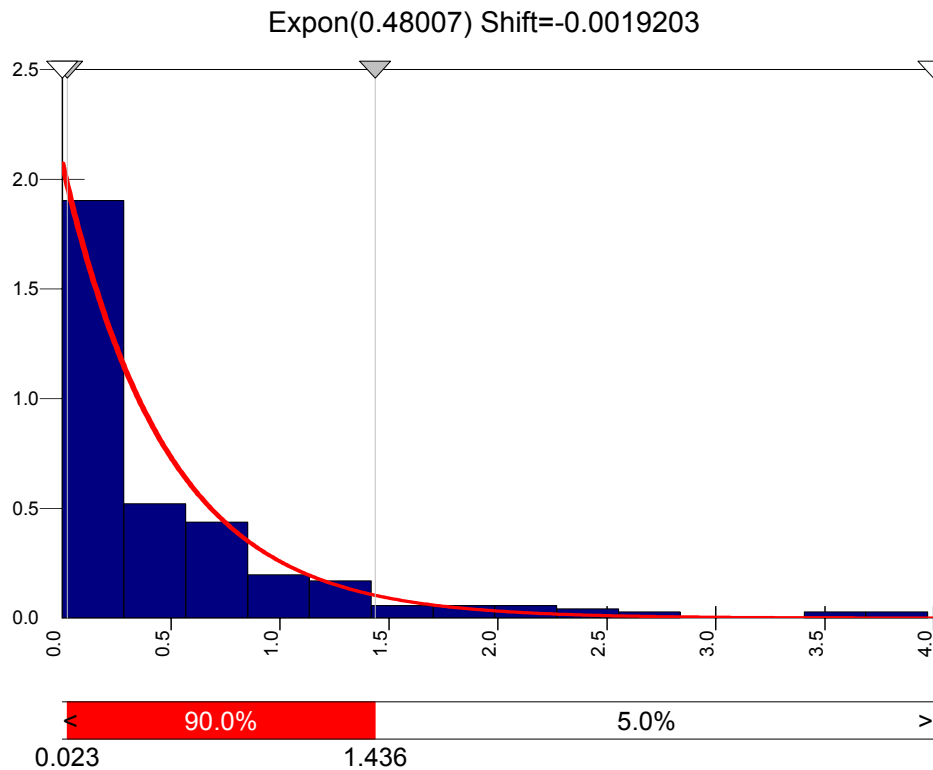**Figure 24: PDF of permit prices during EU ETS (All regions, LPG, AEEI, Vint, Elas, with correlation)**

Expon(0.48007) Shift=-0.0019203

Table 13: Key Statistics (All regions, LPG, AEEI, Vint, Elas, with correlation)

	Analysis 1	Original
Data Points used	250	250
Probability(Price = 0)	35.6%	43.0%
Mean Price	$0.48007	$0.38790
Max Price	$3.9725	$3.6372

Analysis 2: All regions + LPG + AEEI + Vintaging + Elasticity(Energy & Non Energy)

Analysis 2 involves removing the correlation in economic growth among Member States. As might be expected, correlation also has a relatively significant impact on permit prices as can be seen in Figure 25 and Table 14. Without correlation, there is a lower probability that the permit prices are zero. This is because without correlation, it is less likely to get sets of inputs where the LPG values of the Member States are all low, thereby reducing

the chance that the permit prices will be zero. On the other hand, it is also less likely to get sets of inputs where the LPG values of all Member States are all high. This means lower permit prices, as indicated by the lower mean price for Analysis 2. The maximum price is higher without correlation, which is a counter-intuitive result. But the imposition of correlation remains a statistical process and so nothing conclusive can be derived from a single observation, which is there is a chance even without correlation that our sample accidentally contains a parameter input set that has high LPG for several regions. In this sample, it seems that FRA, DEU, GBR, ITA, NLD, ESP and XCE all have higher LPG.

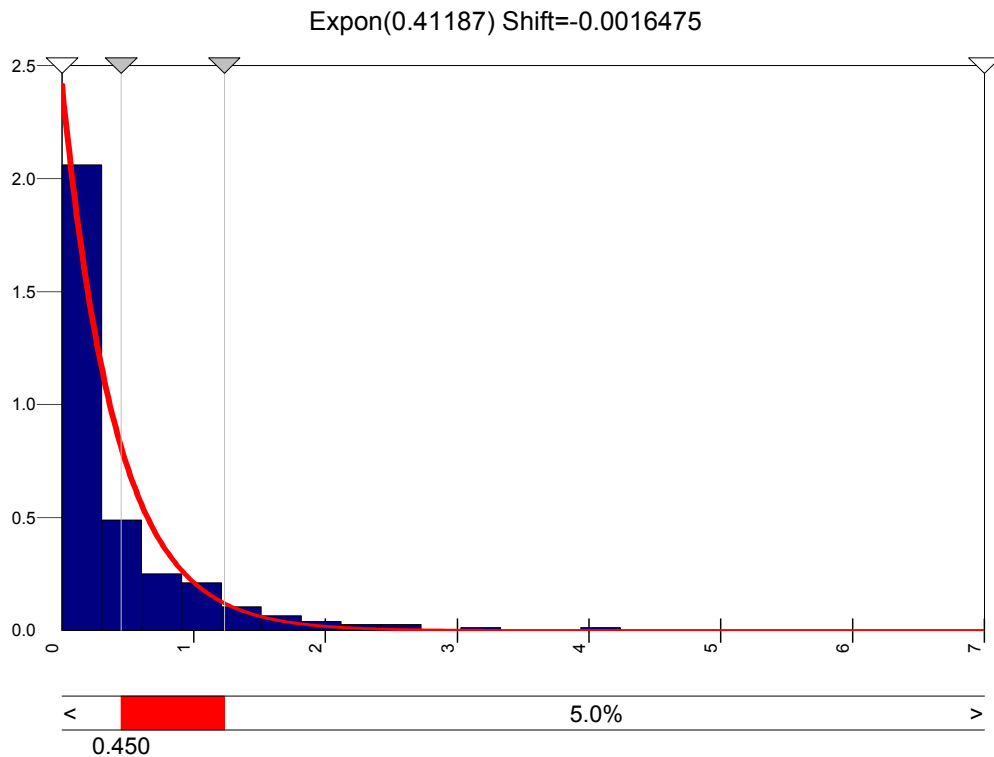**Figure 25: PDF of permit prices during EU ETS (All regions, LPG, AEEI, Vint, Elas)**

Expon(0.41187) Shift=-0.0016475

Table 14: Key Statistics (All regions, LPG, AEEI, Vint, Elas)

	Analysis 2	Analysis 1
Data Points used	250	250
Probability(Price = 0)	24.0%	35.6%
Mean Price	$0.41187	$0.48007
Max Price	$4.238	$3.9725

Analysis 3 involves the AEEI parameter being removed from the analysis. As can be seen from Figure 26 and Table 15, removing the AEEI did not have a very big impact on permit prices and the PDFs and key statistics of both Analysis 3 and 2 are very similar.

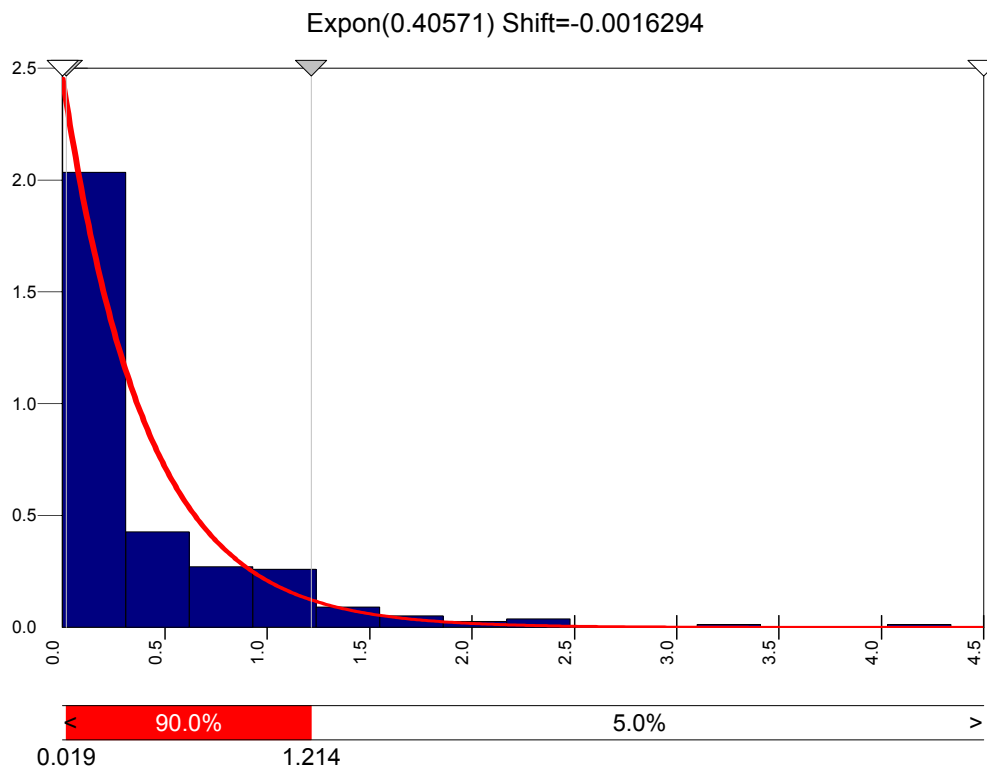**Figure 26: PDF of permit prices during EU ETS (All regions, LPG, Vint, Elas)**

Expon(0.40571) Shift=-0.0016294

Table 15: Key Statistics (All regions, LPG, Vint, Elas)

	Analysis 3	Analysis 2
Data Points used	250	250
Probability(Price = 0)	24.1%	24.0%
Mean Price	$0.40571	$0.41187
Max Price	$4.3396	$4.238

Analysis 4: All regions + LPG + Elasticity(Energy & Non Energy)

Analysis 4 involves the Vintaging coefficient being removed from the analysis. As can be seen from Figure 27 and Table 16, it seems that removing vintaging does have some impact on permit prices, though not as much as oil/gas prices. As expected there is a higher probability that permit prices will be zero and the mean price is lower. However, the maximum price is higher. This impact is similar to Cossa's analysis. Cossa found that vintaging has the highest impact on short-term permit prices (Cossa 2004).

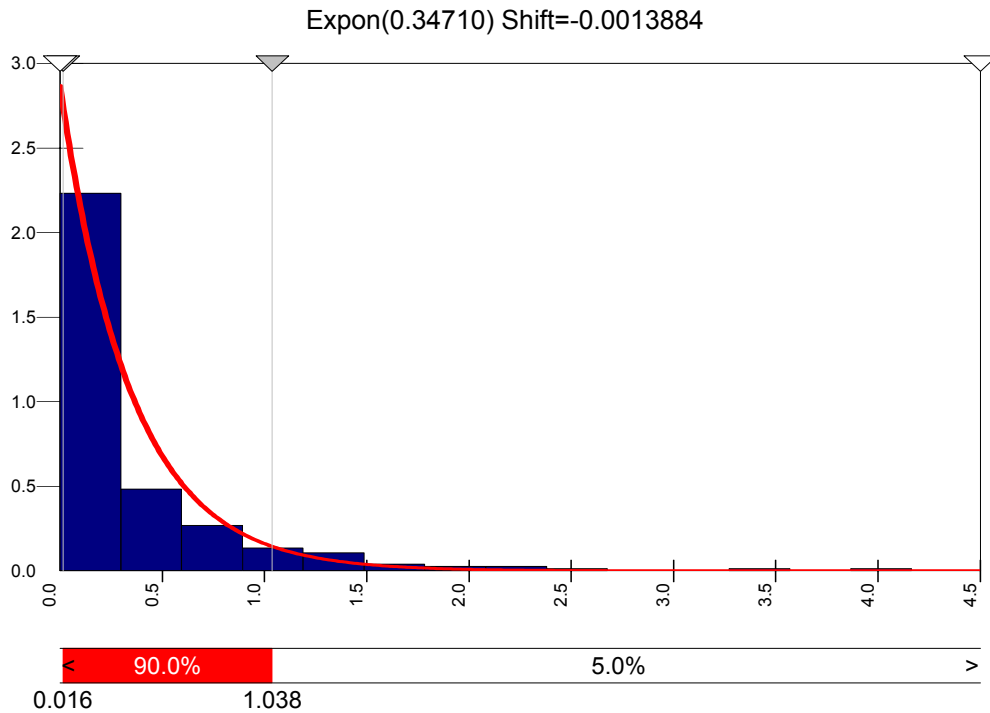**Figure 27: PDF of permit prices during EU ETS (All regions, LPG, Elas)**

Table 16: Key Statistics (All regions, LPG, Elas)

	Analysis 4	**Analysis 3**
Data Points used	250	250
Probability(Price = 0)	28.4%	24.1%
Mean Price	$0.34710	$0.40571
Max Price	$4.6410	$4.3396

Analysis 5: All regions + LPG

Analysis 5 involves the Elasticity between energy and non-energy composites being removed from the analysis. As can be seen from Figure 28 and Table 17, removing ELAS does not have much impact on permit prices, since most of the key statistics between Analysis 5 and 4 are relatively similar.

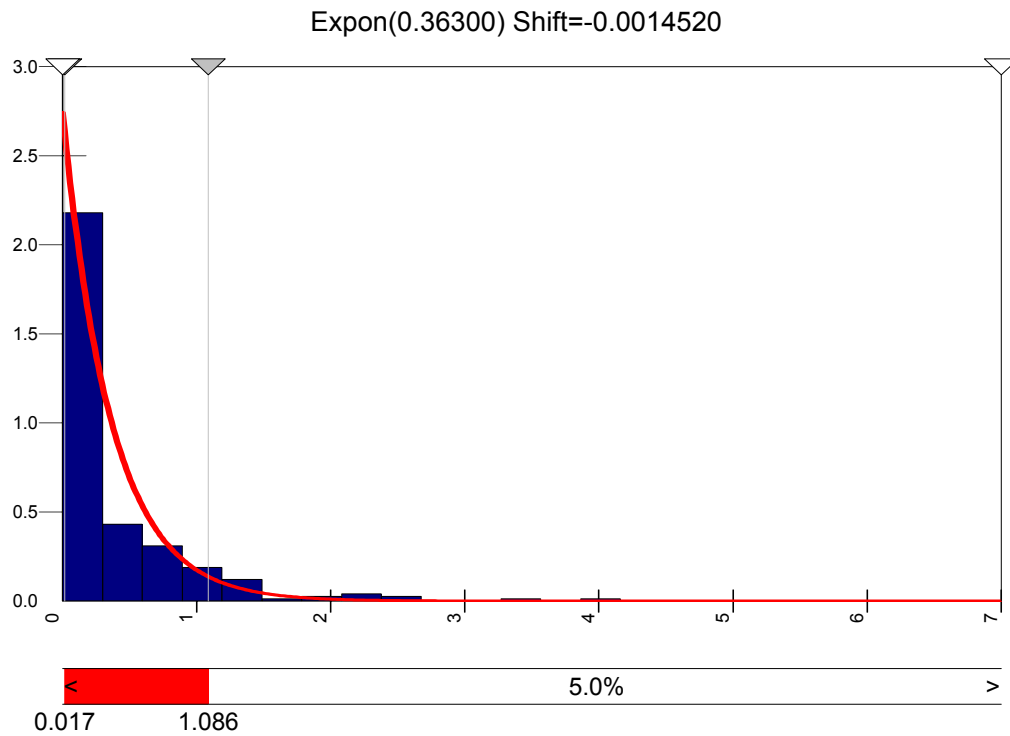**Figure 28: PDF of permit prices during EU ETS (All regions, LPG)**

Expon(0.36300) Shift=-0.0014520

Table 17: Key Statistics (All regions, LPG)

	Analysis 5	Analysis 4
Data Points used	250	250
Probability(Price = 0)	28.0%	28.4%
Mean Price	$0.363	$0.34710
Max Price	$4.1599	$4.6410

Analysis 6: LPG

Analysis 6 involves only uncertainty values in the European regions in EPPA-Euro. The rest of the regions are using reference values. As can be seen from Figure 29 and Table 18, it seems that having uncertainty in all regions compared with only in the European regions do not have a big impact on the permit prices within the EU. Note that there is no emission trading with regions outside the EU. To the extent there are impacts, it would be through international trade in other goods.
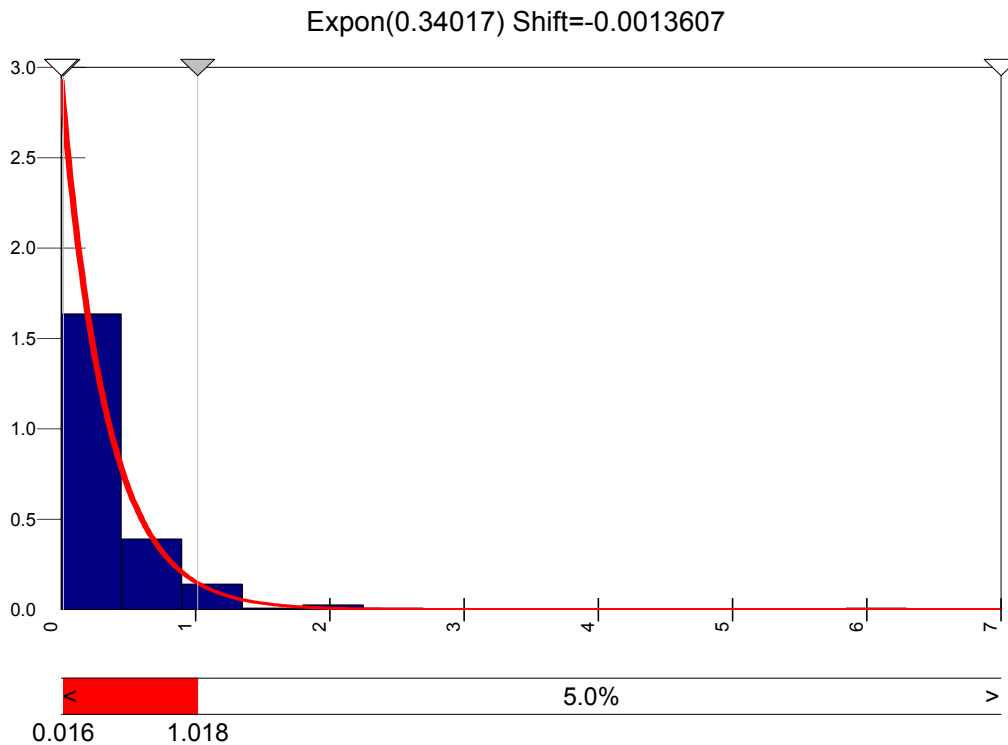
Figure 29: PDF of permit prices during EU ETS (LPG)

Expon(0.34017) Shift=-0.0013607

Table 18: Key Statistics (LPG)

	Analysis 6	Analysis 5
Data Points used	250	250
Probability(Price = 0)	28.4%	28.0%
Mean Price	$0.34017	$0.363
Max Price	$6.2943	$4.1599

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5.2.1 Sensitivity Analysis Implications

The three main implications of the sensitivity analysis are that: (1) Even with LPG as the only uncertain parameter, the resulting PDF on permit prices is not that notably different than with all of the parameters uncertain. This suggests, unless the sensitivity analysis failed to identify some very critical parameters, that adding additional parameters beyond the set I studied would not have a significant impact on the distribution. The proportion of cases with zero prices did change fairly substantially ranging from 43 percent in my reference analysis, to under 30 percent in some of the sensitivity analyses. (2) Correlation among growth of regions has the expected result of creating a somewhat more extreme high end. (3) None of these different results generate prices that include the current ETS market price in the distribution. It remains a puzzle as to what is behind this large difference. The small effect of adding additional parameters beyond LPG is likely mostly the nature of the random sampling procedure. Any one important parameter creates uncertainty. When adding additional uncertain parameters, values for them in any particular one of the 250 parameter sets are as likely to offset the effect of the particular LPG value on the permit price as to amplify it. This is why enforcing correlation is somewhat more important. This has the effect of making it more likely that when one country is growing fast (slow) all the other countries are also growing fast (slow), thus broadening out the distribution of EU growth overall, and creating more case where the cap is either much more binding, or where growth is so slow that there is no net demand for permits.

5.3 Policy Implications

These results show that based on the national caps determined by the individual EU Member States, the permit prices for the EU ETS are most likely to be relatively low. I expected this result because the EU ETS is a trial period and Member States seemed unwilling to impose stringent caps for fear that it would disadvantage industries in their own country compared to other countries.

The policy implications for installation operators is that it does not appear worthwhile on the basis of these results for the ETS to make major costly investments to abate greenhouse gases. It is likely that installations will only have to pay a relatively small price to meet their emissions targets by purchasing permits in the market. However, because the eventual goal is to achieve the EU Kyoto target of 8% reduction from the 1990 levels, Member States may eventually have to lower the national allocation in order to meet their Kyoto targets. This, coupled with the expected increase in emissions from 2005 till 2008 due to economic growth, will result in the prices of permits rising for the Kyoto period.

Toward that end of considering the ETS in light of the Kyoto targets, I conducted similar policy runs to determine the range of permit prices during the Kyoto Protocol period[12], with combinations of uncertainty in the LPG, AEEI, Vintaging Coefficient, Elasticity between energy and non-energy composites parameters, world oil/gas prices, as well as correlated economic growth between the Member States. I assumed that the caps and sectors covered remained the same, and that there is no trading with other Kyoto Parties.

Comparing Figures 30, 31 and 32 and Table 19 and Table 20, it can be seen that even when the national caps are held constant, the permit prices during the Kyoto Period are still expected to be higher than the EU ETS period and the probability of permit prices to be zero is significantly lower. This is due to growth of emissions over time in the BAUs. As a result, installations will most likely face a higher permit price and hence, it may be more worthwhile that installations invest more in abatement (through emissions reduction technologies or improving efficiency) rather than rely mostly on buying permits in the market.

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[12] Because EPPA runs in 5 year periods, we assumed that year 2010 in EPPA represents the Kyoto period

Figure 30: PDF of the Permit Price during Kyoto Commitment Period (All regions, LPG, AEEI, Vint, Elas, Oil/Gas with correlation)
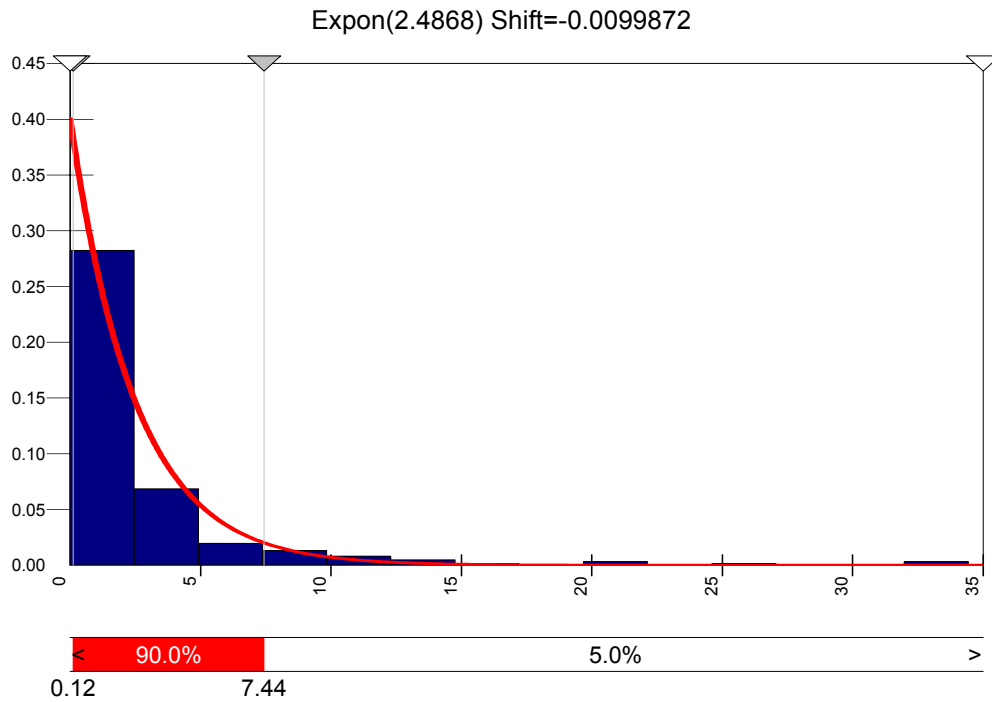

Expon(2.4868) Shift=-0.0099872

Figure 31: PDF of Analysis 2 during Kyoto (All regions, LPG, AEEI, Vint, Elas)

Expon(2.9003) Shift=-0.011601
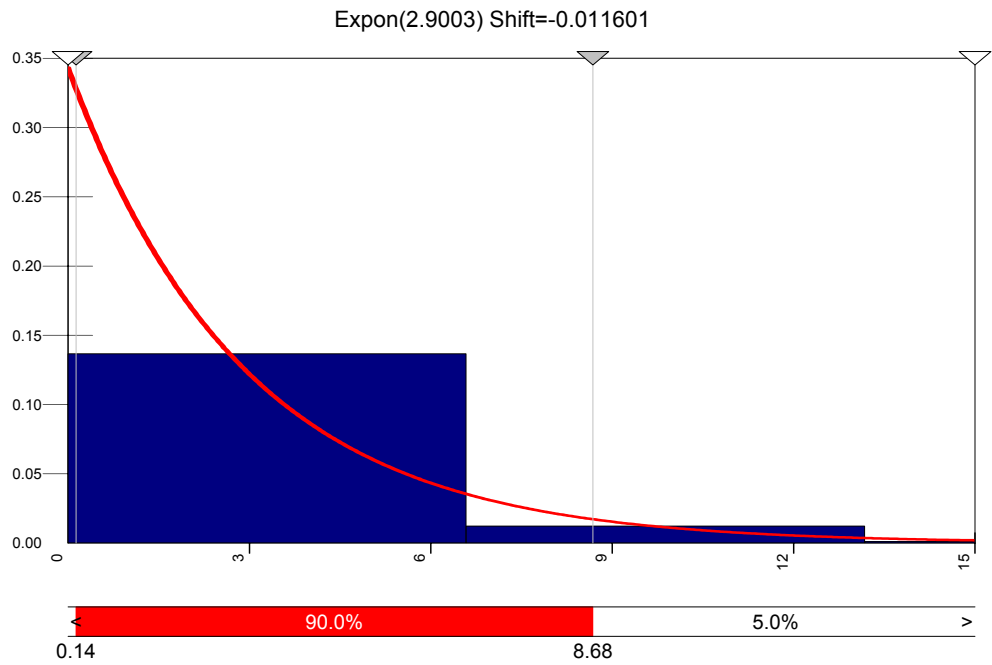
Figure 32: PDF of Analysis 5 during Kyoto (All regions, LPG)

Expon(2.0743) Shift=-0.0084666
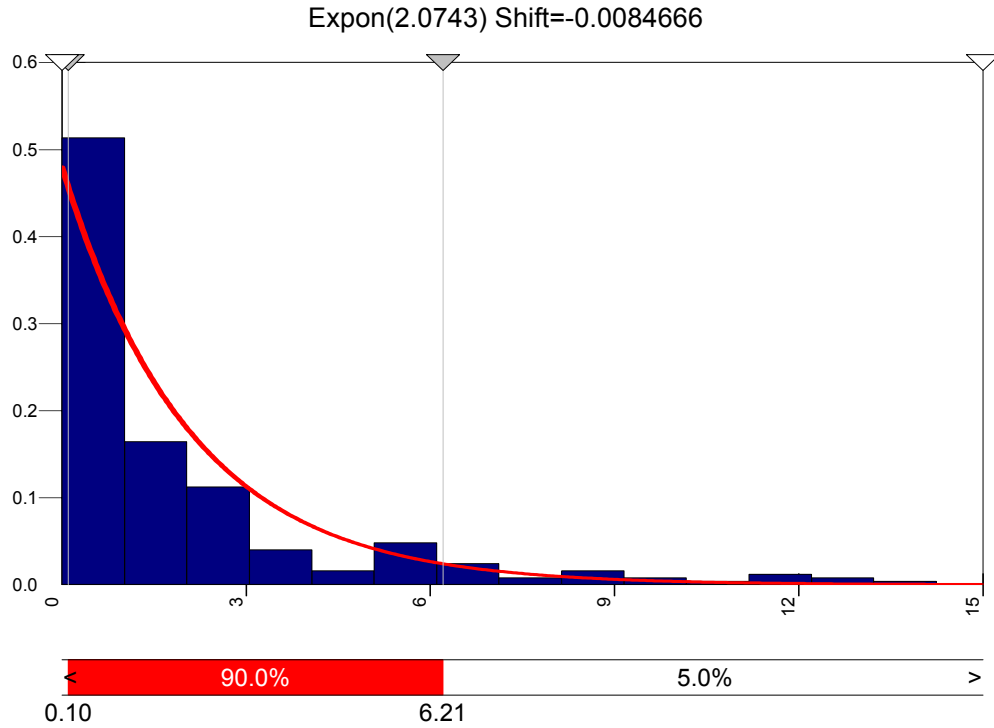
Table 19: Key Statistics of Kyoto Period Permit Price PDF

	Original	Analysis 2	Analysis 5
Data Points used	250	250	250
Probability(Price = 0)	28.8%	9.6%	8.4%
Mean Price	$2.49	$2.90	$2.07
Max Price	$34.44	$92.21	$14.24

Table 20: Key Statistics of ETS Period Permit Price PDF

	Original	Analysis 2	Analysis 5
Data Points used	250	250	250
Probability(Price = 0)	43.0%	24.0%	28.0%
Mean Price	$0.39	$0.412	$0.36
Max Price	$3.64	$4.24	$4.16

From these results it seems likely that firms should be more concerned about the implications for these caps in the Kyoto period than in the ETS period. If the ETS is considered only a trial period, one might expect the caps to be tightened further, in which case, the PDFs I have estimated would shift to higher overall prices. Moreover, if the cap

expands to other more rapidly growing sectors such as transportation in order to assure that the EU meets its overall Kyoto targets, the permit prices could be higher still. On the other side, if there is access to allowances from Russia, that could reduce the price. Useful further analysis would consider these types of scenarios.

Chapter 6   Conclusion

My purpose was is to determine what the range of permit prices are most likely to result from the caps applied in the EU Emissions Trading Scheme (ETS). These results may help operators of covered installations determine whether to invest in costly abatement or enter the permit market and purchase allowances.

Because the EU ETS period is a 'trial' period to prepare the EU as a whole for the Kyoto Protocol during 2008-2012, I hypothesized that the permit prices for this period will be zero or very low. This is because Member States set a relatively lax national cap to limit the economic impact on firms in their countries.

From the results, it does seem that this hypothesis is right. In all the variants of Monte Carlo simulations I conducted, the highest permit prices were less than \$7/tC, with a large proportion of the cases producing permit prices of zero. However, it must also be emphasized that permit prices are also most likely to increase during the Kyoto period and hence, this may affect some investment decisions even if banking of permits is not allowed.

Annex

## I) National Allocation Plans of Major EU Member States

This section gives a brief outline of the important details of what a NAP consists of. The short short summaries that follow cover the major EU Member States whose NAPs were the earliest to be finalized and approved by the European Commission. The NAP of a particular Member State consists of the latest year of CO_2 emissions data from which the allocated cap is based on, the allocated cap for the ETS period, a projection of the emissions in the middle of the Kyoto Period, and finally its Kyoto target.

The NAP also gives details of the rationale for the allocated cap for the Member State, details of the trading sector, the Member State's plan to use JI/CDM and finally, policies on banking, new entrants, reserved (unallocated) allowances, and what happens to allowances upon closure of installations.
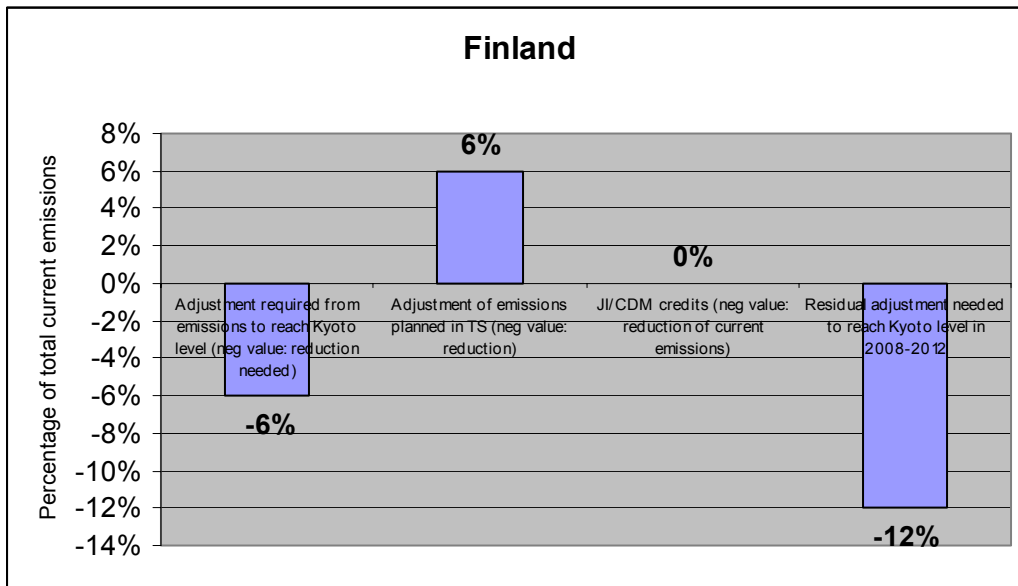
Finland

Figure A-1 shows the breakdown of emissions and projected emissions. In 2002, Finland's CO_2 emissions were about 81.7 Mt CO_2e (Column 1 of Figure A-1) and their allocated cap per annum for the EU ETS is in fact slightly higher than their 2002 emissions level. Finland's Kyoto target is about 76 Mt CO_2e, whereas its projected emissions level in 2010 is about 85 Mt CO_2e. Figure A-2 shows the breakdown of how Finland intends to achieve its target. Based on the latest emissions data in 2002 (81.7Mt), Finland has to reduce emissions by 6% (Column 1 of Figure A-2), but because it intends to increase its allocated cap by 6% (Column 2 of Figure A-2) for the second period of the ETS from 2008 - 2012, and it does not intend to use JI/CDM (Column 3 of Figure A-2) to help in the reduction efforts. Hence, the residual emissions reduction for Finland is 6% + 6% - 0% = 12% (Column 4 of Figure A-2).

Figure A-1: NAP Kyoto Path for Finland
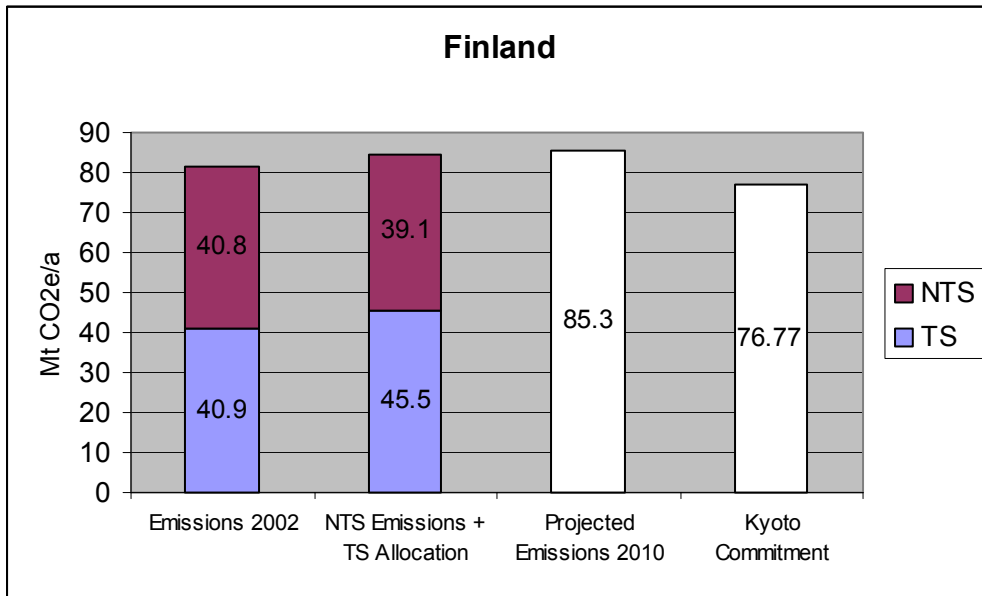
Source: Zetterberg, 2004

Figure A-2: NAP Kyoto Path for Finland

Source: Zetterberg, 2004

Rationale for Credits Allocation

The total credits allocation for Finland is about 45.5mt CO_2e/a. The basis for the allocation is a projection using the With-Measure (WAM) scenario. A strategic path (WAM-path) is calculated, which reflects the with-measure scenario, including additional national measures and use of

flexible mechanisms. The allocation for the trading sectors is the residual of the WAM-path, of which all-additional measures at a cost of max. 10 Euros/ton CO_2 in the non-trading sectors are subtracted.

Emissions Trading Sector

The trading sectors will cover 137 operators, 330 production plants and 485 installations in total. These will cover 50% of GHG emissions and 59% of all CO_2 emissions.

There is opt-in for district heating plans of capacity less than 20MW, if any of the installation of the district heating network is covered by Annex I (about 159 installations). There are no opt-out options or pooling.

Plans to use JI and CDM

There is no information in the NAP but it was to be commented on in the revisable Climate Strategy at the end of 2004. However, Finland has invested approximately 10 million Euros in the Prototype Carbon Fund of the World Bank; and signed a letter of intent on JI projects with various signatories of the Kyoto Protocol like Latvia, Lithuania, Poland, Ukraine, Hungary and Estonia. Finland has also signed a letter of intent on CDM projects with Costa Rica, El Salvador and Nicaragua.

Banking

Banking is not allowed.

New Entrants

If emissions changed due to any new legislation in the future, current installations will be treated as new entrants. New entrants will receive allowances for free from the beginning of commercial operations.

This allocation will be based on the rated thermal input, annual running time and specific emissions of the fuel used as specified for liquid/gas and solid fuel.

Reserve

A reserve of about 2% of the total allocation is set. If the reserve becomes too low, additional allowances will be purchased from the market or produced by projects linked to and recognized by EU ETS. If the reserve is too high, the allowances will be sold on the market.
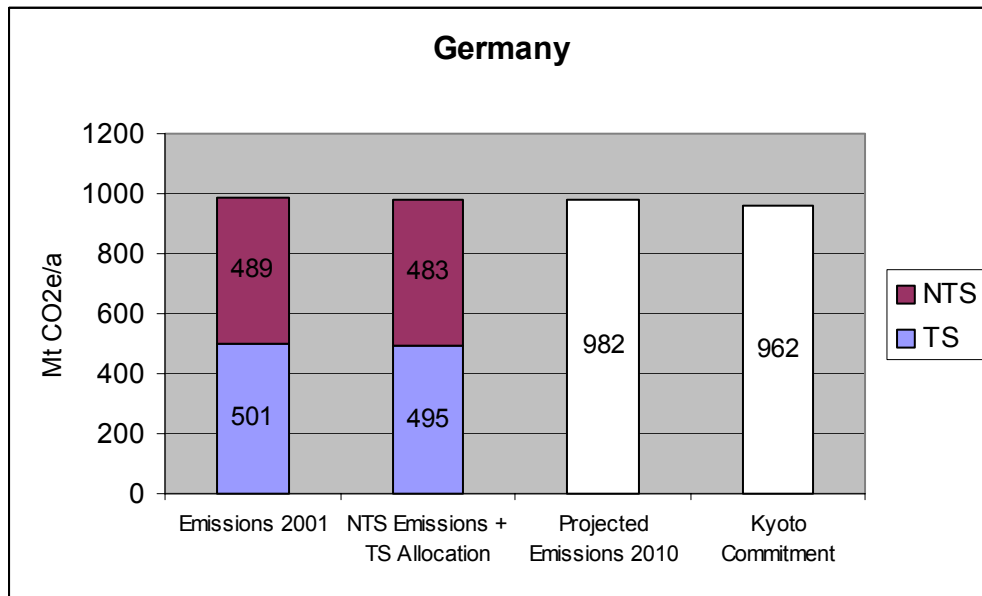
Closure of Installation

The closure of an installation is defined when the use of the installation is permanently ended. The unused allowances will be transferred to the reserve.
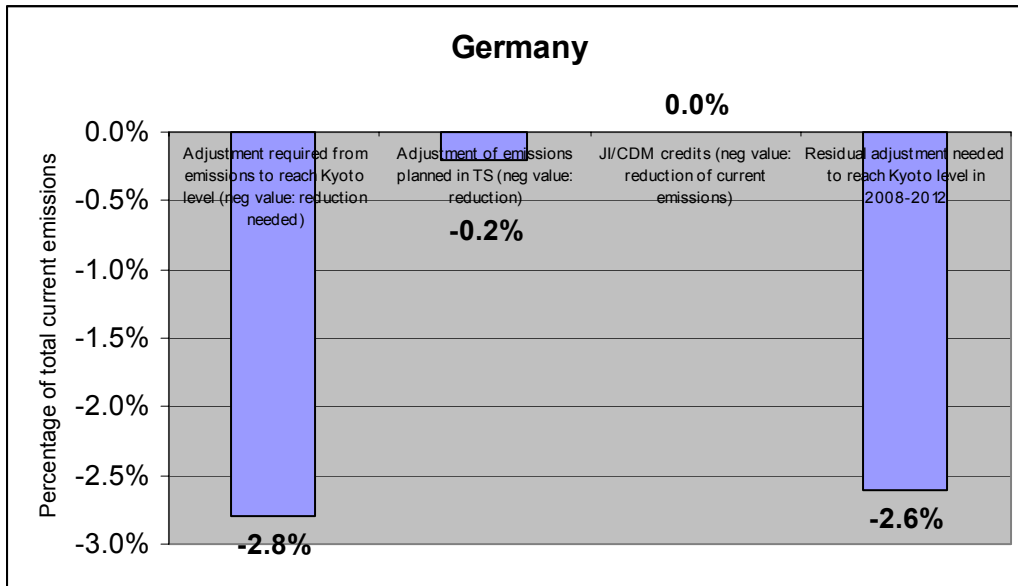
<u>Germany</u>

As can be seen from Figure A-3 and A-4, the latest emissions data and the allocated cap of the ETS for Germany are very close to the projected emissions in 2010 and its Kyoto Target. Hence, Germany is very close to achieving its target and needs to reduce emissions by only 2.6%.

Figure A-3: NAP Kyoto Path for Germany

Source: Zetterberg, 2004

Figure A-4: NAP Kyoto Path for Germany

Germany

Chart showing "Percentage of total current emissions" on the y-axis ranging from -3.0% to 0.0%.

- Adjustment required from emissions to reach Kyoto level (neg value: reduction needed): **-2.8%**
- Adjustment of emissions planned in TS (neg value: reduction): **-0.2%**
- JI/CDM credits (neg value: reduction of current emissions): **0.0%**
- Residual adjustment needed to reach Kyoto level in 2008-2012: **-2.6%**

Source: Zetterberg, 2004

Rationale for Credits Allocation

The total credits allocation for Germany is about 495mt CO_2e/a. The credits allocation was set politically and is less stringent than the existing voluntary agreement would have implied.

Emissions Trading Sector

The trading sectors cover about 2320 installations. An "installation" refers to the installations covered by 1 permit, not necessarily individual technical institutions. Steam crackers and melting furnaces are not covered. The accumulation rule was interpreted according to national implementation of IPPC, i.e. the following criteria have to be fulfilled at the same time: same operator, same site, same subheading and the installations must be technically linked. Covered installations will include about 50% of total GHG emissions and 58% of CO_2 emissions.

There are no opt-in or opt-out provisions. Pooling is possible.

Plans to use JI and CDM

There were no plans for contribution from JI and CDM projects.

Banking

Banking is not allowed.

New Entrants

New entrants are defined as new installations or if existing installations expand their capacity. There will be free allocation to new entrants from reserve for 14 years based on the projected output. Also, the allowances can be transferred to a new replacement installation of the same operator (in Germany) for 4 years.

Reserve

The reserve consists of 0.6% of total allowances. Allowances from the reserves will be allocated to new entrants on a first-come, first-served basis.

Closure of Installation

Allocation will be terminated the year after closure and the unused allowances will go back to the reserve.
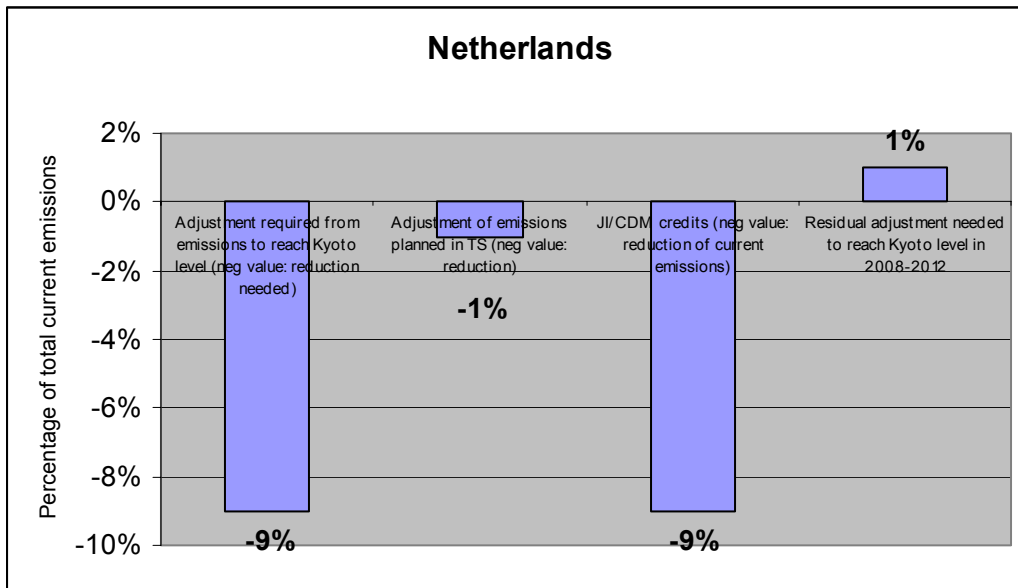
Netherlands

As seen in Figures A-5 and A-6, although the Netherlands needs to reduce emissions from 2000 by 9% to meet its Kyoto target, because it intends to use JI/CDM mechanisms (9%) and also intends to reduce their allocated trading cap (1%), Netherlands will have a 1% buffer to meet its Kyoto target.

Figure A-5: NAP Emissions Data for Netherlands
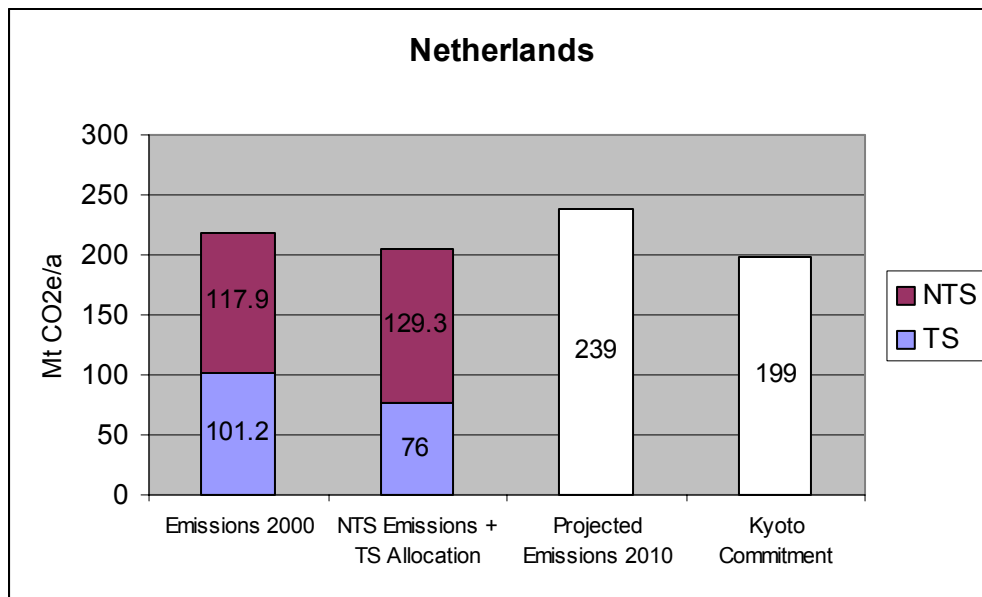
Source: Zetterberg, 2004

Figure A-6: NAP Kyoto Path for Netherlands

Netherlands

Source: Zetterberg, 2004

Rationale for Credits Allocation

The total credits allocation for the Netherlands is about 76mt CO_2e/a. The allocation is based on existing policies, including voluntary agreements of energy-intensive industries, including the energy and electricity sectors. The total allocation was derived from total CO_2 cap 2005-2007 on energy/industry companies of 115 Mt CO_2e/a.

Emissions Trading Sector

The trading sectors will cover about 333 installations. A fairly wide interpretation based on implementation of IPPC directive was used. An "installation" refers to the installations covered by 1 permit, not necessarily individual technical institutions. These cover 44% of total GHG emissions and 54% of CO_2 emissions.

The Dutch government has proposed to the European Commission to opt-out 74 small installations with emissions less than 25,000 tons of CO_2 from the EU ETS.

Plans to use JI and CDM

Netherlands has plans to use JI and CDM to fulfill its commitments. There are no plans for government purchase of credits for 2005-2007 but about 100 Mt is planned in 2008-2012. About 740 million Euros have been set aside for the purchase of the 100 Mt CO_2 (of which 77 tons have been bought through public contracts to individual companies).

Banking

Banking is not allowed.

New Entrants

New entrants are defined as installations that are expanding production capacity or starting operations in 2003-2008. The allocation of allowances from the reserve will be free and it is based on 'realistically planned' annual CO_2 emissions.

Reserve

The reserve consists of 4.1% of total allowances. If the reserve is too low, it will be allocated on a first-come, first-serve basis. If it is too high, it will be allocated proportionally for free to all existing installations under the ETS.

Closure of Installation

Installations that stop their operations during 2005-2007 will be allowed to keep their allowances.
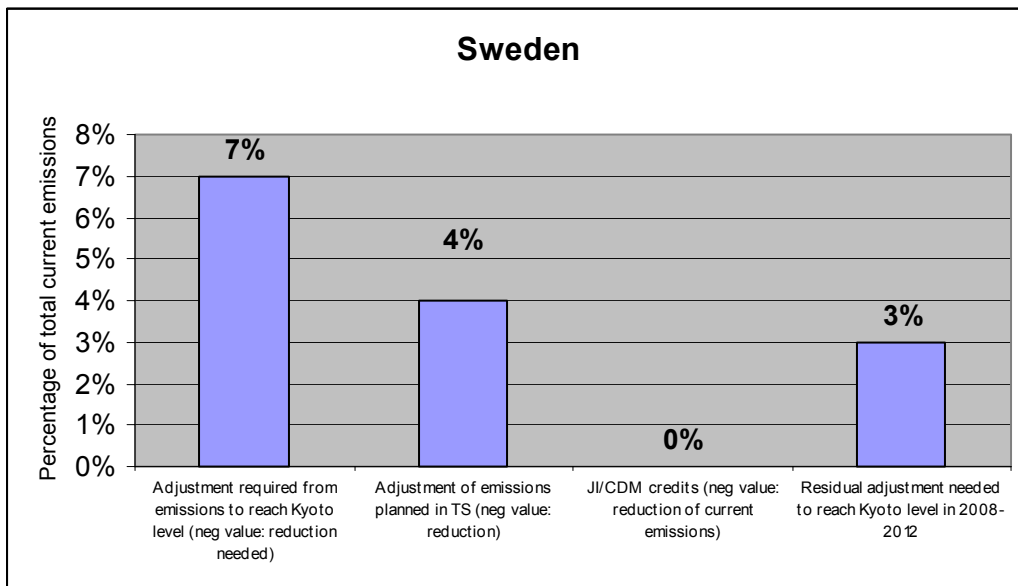
Sweden

As can be seen from Figures A-7 and A-8, Sweden's emissions are currently below its Kyoto Target and it is on course to meet its Kyoto target, with a 3% buffer, even though they intend to increase their allocated cap of the ETS by 4%.

Figure A-7: NAP Kyoto Path for Sweden
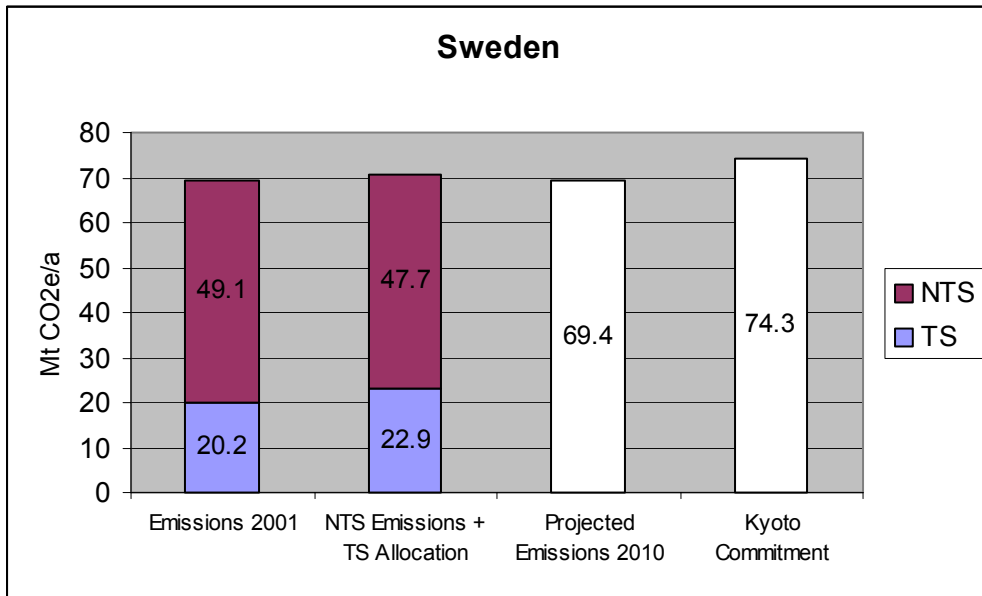
Source: Zetterberg, 2004

Figure A-8: NAP Kyoto Path for Sweden

Source: Zetterberg, 2004

Rationale for Credits Allocation

The total credits allocation for Sweden is about 22.9mt CO_2e/a. The allocation was determined by what is feasible for a strict implementation of the criteria in Appendix III of the Directive.

Emissions Trading Sector

The trading sectors will cover about 500 installations. These cover about 28% of total GHG emissions and 30% of CO_2 emissions.

Installations producing power or heat less than 20MW can opt-in if they are part of a district heating system that is larger than 20MW.

Plans to use JI and CDM

JI and CDM will not be used to fulfill requirements of the Kyoto Protocol, although Sweden has been involved in pilot projects of JI and CDM since 1993. Sweden has a CDM program and contracts are being negotiated with Russia, Estonia, Lithuania and Romania.

Banking

There was no decision made.

New Entrants

There will be free allocation for all new entrants based on either expansion of capacity or starting operations.

Reserve

The reserve consists of 3.5% of total allowances. The allowances will be allocated on a first-come, first-served basis. No decision has been made on what to do with leftover allowances.
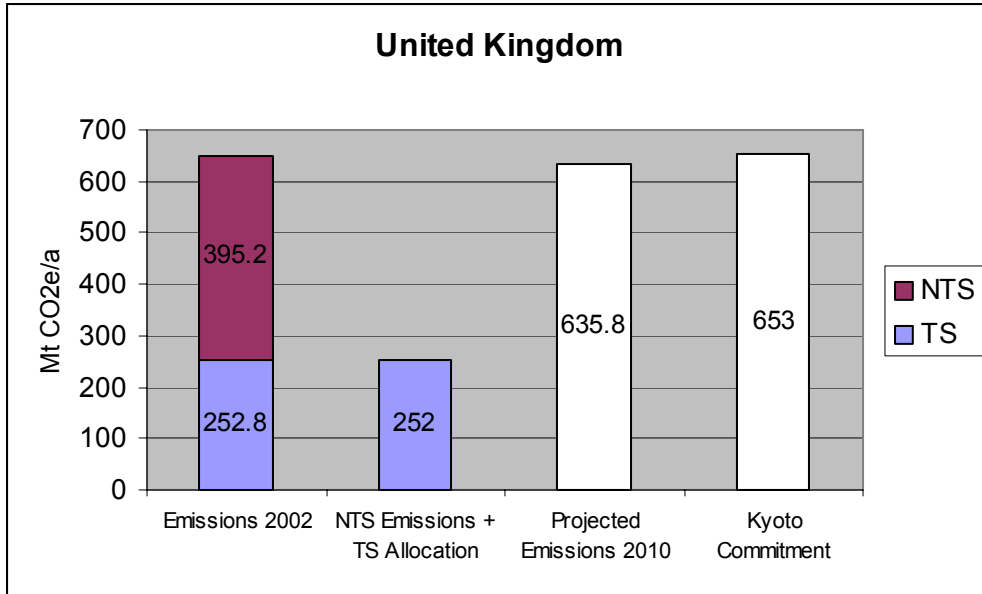
Closure of Installation

There was no decision made.
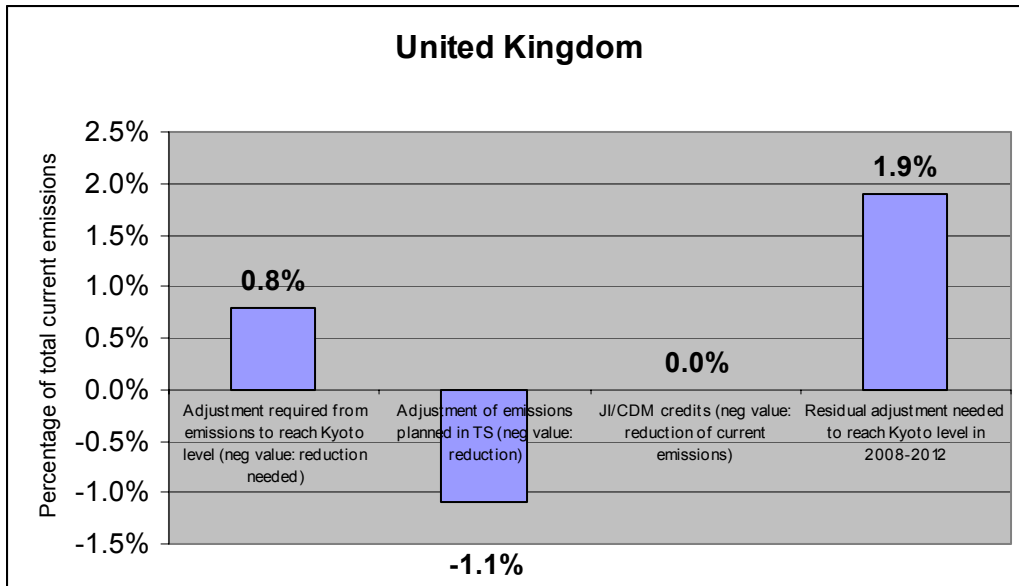
<u>United Kingdom</u>

From Figures A-9 and A-10, the UK's situation is also similar to Sweden where its current emissions level is below its Kyoto target and hence, it is on course to meet the target with about a 2% buffer.

Figure A-9: NAP Kyoto Path for United Kingdom

Source: Zetterberg, 2004

Figure A-10: NAP Kyoto Path for United Kingdom

Source: Zetterberg, 2004

Rationale for Credits Allocation

The total credits allocations for the UK is about 252mt CO_2e/a. The rational of the allocation is based upon the Department of Trade/Industry's projections of sector emissions for 2005 and 2010, including the effects of the UK climate change program (CCP), which includes the effects of Climate Change Agreements.

Emissions Trading Sector

The trading sectors will cover 1500 installations. These cover about 38% of total GHG emissions and 46% of CO_2 emissions.

There is no opt-in. Signatories of Climate Change Agreements and participants of the UK Emissions Trading Scheme may apply to opt-out of the Scheme for the first phase. Pooling is allowed but only limited to operators of combustion installations with a rated thermal input of less than 50MW.

Plans to use JI and CDM

UK is expected to meet the Kyoto Protocol target and hence, it has no plans to use JI and CDM.

Banking

Banking is not allowed.

New Entrants

New entrants are installations that start operations after 31st Dec 2003, with some exceptions. The allowances will be allocated free, and on a first-come, first-served basis. Allocation will be partial for installations that start operations during the course of a year. Allocation is based on a standardized benchmark.

Reserve

The reserve consists of 7.7% of total allocation. Any surplus allowances at the end of each year will be auctioned off.

Closure of Installation

Allocation will stop the year following closure. Any unused allowances will be transferred back to the reserve.

II) PDF of LPG

Logistic Distribution

This is a continuous distribution with mean μ and scale parameter β where $\beta > 0$ and its probability density function, $P(x)$ and cumulative density function, $D(x)$ are:

$$P(x) = \frac{e^{-(x-\mu)/\beta}}{\beta\,[1 + e^{-(x-\mu)/\beta}]^2}$$

$$D(x) = \frac{1}{1 + e^{-(x-\mu)/\beta}}$$

Extreme Value Distribution

This distribution is sometimes also called the Fisher-Tippett distribution or log-Weibull distribution and it is the distribution of the extreme order statistic $X^{(1)}$ or the maximum for a distribution of N elements. It has a location parameter α and scale parameter β.

$$P(x) = \frac{e^{(\alpha-x)/\beta - e^{(\alpha-x)/\beta}}}{\beta}$$

$$D(x) = e^{-e^{(\alpha-x)/\beta}}$$

Normal Distribution

This is a statistic distribution in a variate X with mean μ and variance σ^2.

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}}e^{-(x-\mu)^2/(2\sigma^2)}$$

$$D(x) = \int_{-\infty}^{x} P(x')dx'$$

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