



report

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Swedish Contribution to the Greenhouse Effect and Required Reductions to Meet the 550 ppmv Target

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Abstract

The Master of Science Thesis Work *Swedish Contribution to the Greenhouse Effect and Required Reductions to Meet the 550 ppmv Target* has been completed by Lina Lindell and Kristina Nilsson. The Work was conducted in collaboration with IVL, Swedish Environmental Research Institute Ltd and the Department of Earth Sciences, Uppsala University.

According to the Swedish Parliament, the Swedish international climate strategy should focus on a stabilisation of the concentration of greenhouse gases in the atmosphere. An equilibrium concentration lower than 550 ppmv CO₂-equivalents should be achieved by the end of this century. As an interim target, the yearly emissions should not exceed 4.5 tonnes CO₂-equivalents per capita by 2050.

In this study an inventory of Swedish emissions from 1834 until 2000, for the six greenhouse gases regulated by the Kyoto Protocol, is carried out. Future emission scenarios for carbon dioxide during the time period 2000-2050 are also defined. This data is used for estimating the contribution to the greenhouse effect both today and in the future. Further it is investigated if the 2050-target is sufficient for not exceeding an atmospheric concentration of 550 ppmv. The required reduction for 2100 to reach an equilibrium concentration below this level is also estimated.

The Swedish contribution to the greenhouse effect today is about 30 % larger than it should be according to the fairness factor used in this study. The Swedish emission target set for 2050 is sufficient for not exceeding 550 ppmv by that year. However, to reach a stabilisation of the concentration below this level the emissions have to be reduced to 1.0-1.5 tonnes CO₂-equivalents per capita by 2100.

Referat

Examensarbetet *Sveriges bidrag till växthuseffekten och de reduktioner som krävs för att nå 550 ppmv målet* är utfört av Lina Lindell och Kristina Nilsson. Arbetet har genomförts i samarbete med IVL, Svenska Miljöinstitutet AB och Institutionen för geovetenskaper vid Uppsala Universitet.

Sveriges riksdag har beslutat att Sverige internationellt skall verka för en stabilisering av koncentrationen av växthusgaser i atmosfären på en nivå lägre än 550 ppmv koldioxidekvivalenter. Ett delmål i arbetet för att uppnå denna stabilisering innebär att de svenska emissionerna av växthusgaser skall vara lägre än 4,5 ton koldioxidekvivalenter år 2050. Idag är emissionerna av växthusgaser mycket ojämnt fördelade mellan världens länder. Enligt de svenska klimatmålen är det önskvärt att denna fördelning jämnas ut till år 2050. Delmålet för 2050 är därför baserat på att alla människor på jorden skall ha rätt till lika stora emissioner.

I denna studie genomförs en inventering av svenska emissioner mellan 1834 och 2000 av de sex växthusgaser som regleras av Kyoto protokollet. En inventering av framtida emissionsscenarier för koldioxid från 2000 till 2050 genomförs också. Data från emissionsinventeringen används för att uppskatta både det nuvarande och framtida svenska bidraget till växthuseffekten. Uppskattningen av det svenska bidraget kan göras på olika sätt. I detta arbete utförs det genom att jämföra emissioner, ackumulerade emissioner, koncentrationer och "radiative forcing". Simuleringar utförs för att undersöka om emissionsmålet för år 2050, enligt de rådande prognoserna för befolkningstillväxt, är tillräckligt för att koncentrationen av växthusgaser i atmosfären inte ska överstiga 550 ppmv. Även de reduktioner som krävs till år 2100 för att nå en jämviktskoncentration lägre än 550 ppmv uppskattas.

Resultaten i denna studie visar att Sveriges bidrag till växthuseffekten är ungefär 30 % större än vad den rättvisefaktor som definierats i rapporten tillåter. Utförda simuleringar visar att det svenska emissionsmålet för år 2050 är tillräckligt för att koncentrationen inte ska överstiga 550 ppmv till detta år. För att nå en jämviktskoncentration lägre än denna nivå måste dock emissionerna reduceras till 1,0-1,5 ton koldioxidekvivalenter per capita till år 2100.

Preface

You are now holding the Master of Science Thesis Work of Lina Lindell and Kristina Nilsson in your hands. This thesis was carried out within the Master of Science Programme of Aquatic- and Environmental Engineering at Uppsala University, School of Engineering. The study was conducted between April and October 2002 at the Climate Department of IVL, Swedish Environmental Research Institute Ltd, Stockholm. Lina Lindell has chief responsibility for the historical emission inventory and the scenarios and Kristina Nilsson has chief responsibility for the model simulations. The model development and validation has been carried out with equal responsibility. Lars Zetterberg has been supervising the work at IVL. Senior lecturer and director of studies in Meteorology, Conny Larsson, at the Department of Earth Sciences, Uppsala University, has performed the examination. We hope that you will enjoy your reading!

Stockholm, November 2002.

Lina Lindell

Kristina Nilsson

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1 Introduction

1.1 The Greenhouse Effect

The Earth receives energy from the sun. Part of this energy is reflected back into space and part of it is absorbed by the surface i.e. land, water and atmosphere. The main constituents of the atmosphere absorb very little of both the energy received from the sun and the re-emitted planetary radiation. Nevertheless some trace gases do absorb the planetary radiation quite well. These infrared absorbing trace gases are called greenhouse gases and include water vapour, carbon dioxide, methane, nitrous oxide and ozone, to mention a few of the most important. During the process of absorbing and reemitting, some of the radiation is transformed into thermal energy that warms up the atmosphere. The greenhouse gases increase the temperature of the lower part of the atmosphere to about 33 °C above what would otherwise be the result of the incoming solar radiation. This is what we call the natural greenhouse effect and the process has been necessary for life to develop on earth.

What today is of great concern is the so-called anthropogenic greenhouse effect caused by the enhancement of the atmospheric abundance of greenhouse gases due to human activity. The amount of greenhouse gases in the atmosphere has increased considerably over the last hundred years. It is believed that the rapid rise in concentrations is causing a gradual increase in temperature. The consequences of a higher temperature are the subject of intense discussions and research. However, there are some scientifically determined relations that give us a hint of what might be forthcoming.

According to measurements the global average temperature has risen by 0.6 °C during the 20th century and during the same period the global mean ocean surface has risen by 0.1-0.2 meters. The temperature increase is probably the greatest increase that has occurred in the last 1000 years. (IPCC, 2001) The effects of a climate system in change are very uncertain and will be different in different parts of the world. The IPCC states that the global mean temperature is likely to raise 1.4-5.8 °C within the next century. The ecosystems may not be able to adjust to such rapid changes in temperature, with severe damages as a result.

Since there is great inertia in the atmospheric-oceanic system, climate change is a very slow process. Consequently, even if we would stop emitting greenhouse gases today, the concentrations would still be rising and the climate system would continue to change for many years. This means that emissions made today will have an impact on the future climate and that historical emissions do have an impact on the climate of today.

1.2 A Short Political Background

The first action on reducing emissions of greenhouse gases was taken when the Montreal Protocol was adopted in 1987. The protocol regulates substances that deplete the ozone layer and when it entered into force a phase-out of the chlorofluorocarbons, CFCs, and their substitute substances hydrochlorofluorocarbons, HCFCs, begun. These gases not only damage the ozone layer but also act as greenhouse gases.

In 1988 the United Nations Environment Programme and the World Meteorological Organisation formed the UN Intergovernmental Panel on Climate Change, IPCC. The objective of the IPCC is to evaluate the scientific evidence on climate change. Their first report, issued in 1990, formed the basis of the United Nations Framework Convention on Climate Change, UNFCCC.

At the UN Conference on Sustainable Development in Rio de Janeiro 1992 more than 150 countries, including Sweden, signed the UNFCCC that entered into force in 1994. The ultimate objective of the Convention is to work for *"the stabilisation of the greenhouse gas (GHG) concentrations at a level that would prevent dangerous anthropogenic interference with the climate system"* (IPCC, 1996). The Parties of the Convention are committed to stabilise the emissions of greenhouse gases at the 1990 level.

At the Third Session of Conference of the Parties in 1997, the Kyoto Protocol was adopted to the UNFCCC. The protocol contains legally binding commitments in addition to those of the UNFCCC. The Kyoto Protocol comprises the six greenhouse gases carbon dioxide, CO₂, nitrous oxide, N₂O, methane, CH₄, hydrofluorocarbons, HFCs, perfluorocarbons, PFCs and sulphur hexafluoride, SF₆. The industrialised countries are required to decrease their emissions of these gases by at least 5 % until 2010 compared to the 1990 emission level. The developing countries were not given quantitative restrictions. Due to uncertainties in the interpretation of the protocol it could not be ratified. Further negotiations were therefore needed to achieve an agreement. The meeting in Marrakech in 2001 was successful and since then many countries have ratified the protocol.

For the Kyoto Protocol to enter into force it is required that at least 55 Parties to the Convention ratifies the protocol. In addition it is required that the ratifying Annex I¹ Parties together accounts for at least 55 % of the carbon dioxide emissions of that group in 1990. The ratification status as of September 17th 2002 was 69 Parties. However, the Annex 1 Parties are currently only accounting for 37.1 % of the 1990 emissions.

¹ Annex 1 countries are a group of industrialised countries.

Sweden ratified the protocol in May 2002. In 2001 the U.S.A. resigned from the Kyoto Protocol completely, which is substantial as the country accounts for over 36 % of the Annex 1 emissions. Some of the other Annex 1 countries that emit the highest amounts have not yet ratified the protocol. The work for making those countries, i.e. the Russian Federation, Poland, Canada and Australia, ratify continues. (UNFCCC, 2002) At the global environment summit that took place in Johannesburg, August 2002, it was announced that Russia and most likely Canada will ratify the protocol. Also China, a non-Annex 1 country, stated that they will ratify the Protocol. (CNN, 2002)

The aim of the climate policy of the EU is to fulfil the Kyoto Protocol commitments. EU is committed to decrease the emissions by 8 % until the commitment period 2008-2012. Within EU, each member state has been given a specific emission target. Sweden has been given the right to *increase* the emissions by 4 %, which is due the substantial reduction that already has taken place in Sweden. Between 1970 and 1990 Sweden decreased the emissions of carbon dioxide by almost 50 % (Ministry of the Environment Sweden, 2000). Despite this, the Swedish Parliament has decided that Sweden shall *decrease* the emissions by 4 %.

Each industrialised country that is Party of the Convention is committed to submit National Communications, which are national inventory reports. The third National Communication of Sweden was compiled by The Swedish National Environmental Agency, Swedish EPA, and assisted by The Swedish Energy Agency, STEM. The report contains yearly emission data on the Kyoto greenhouse gases for the time period 1990 to 2000. It also includes a discussion on the emission sources, the climate policy of Sweden and future emission scenarios.

1.3 Swedish Climate Strategy

According to the Swedish Parliament the Swedish international climate strategy should focus on a stabilisation of the concentration of greenhouse gases in the atmosphere. The equilibrium concentration should be lower than 550 ppmv CO₂-equivalents. This concentration corresponds to approximately a doubling of the pre-industrial concentration of carbon dioxide in the atmosphere. Higher concentrations, or higher expected increase in temperature than 2 °C² since pre-industrial time, are probable to cause serious interference with the climate system. (Ministry of the Environment Sweden, 1995) The gases regarded in the climate strategy are the ones regulated by the Kyoto Protocol. The targets should be accomplished without compensation for uptake

² According to IPCC a concentration of 550 ppmv carbon dioxide corresponds to a rise in temperature of 3 ± 1.5 °C compared to the pre-industrial temperature (Ministry of the Environment Sweden, 2000).

by carbon sinks or flexible mechanisms like emission trading systems (Swedish EPA web-site).

In the work for reaching an atmospheric equilibrium concentration there are two interim targets decided by the Parliament:

- The emissions of greenhouse gases in Sweden should be at least 4 % lower in 2010 than the emissions in 1990.
- The yearly emissions should not exceed 4.5 tonnes CO₂-equivalents per capita by 2050. The emissions for 2050 should be followed by further reductions.

The 2050-target assumes an equalisation of the emissions between industrialised and developing countries by the middle of this century. This means that the emissions should be distributed in a fairer way. All world inhabitants should be allowed to emit the same amount of greenhouse gases by the year of 2050. Today the industrialised countries are responsible for 60 % of the total emissions despite the fact that the population is almost four times larger in the developing countries. In a historical perspective the industrialised countries accounts for about 80 % of the total accumulated emissions since the industrialisation. (Ministry of the Environment Sweden, 2000)

After 2050, the per capita emissions will have to decrease further to assure a sustainable global development of the climate, i.e. a concentration not exceeding 550 ppmv. According to the Ministry of the Environment, the stabilisation of the atmospheric concentration should be achieved by the end of this century (2000). There is no target set for 2100 but the Climate Delegation³ recommends a maximum of 3.5⁴ tonnes CO₂-equivalents per capita (Ministry of the Environment Sweden, 1995).

The present Swedish emissions are 8.3 tonnes CO₂-equivalents per capita. This implies that in order to reach the 2050-target we have to reduce our emissions by almost 50 %. The Swedish Environmental Objectives Council is a council established by the Swedish Parliament. Their task is to work with the 15 Environmental Objectives decided by the Parliament. According to this council we will not reach the 2050-target with the present-day strategies and development (2000). The emissions until 2010 are not expected to change significantly compared to the emission level of today (Table 3.2). After 2010 the

³ The Climate Delegation was a delegation at the Swedish Ministry of the Environment. The delegation was established in 1993 and the final report was issued in 1999.

⁴ The Climate Delegation suggests 0.7 tonnes C per capita (including fossil fuels only) which is equivalent to 2.6 tonnes CO₂ per capita. Assuming the same relation between total emissions and emissions of CO₂ in 2100 as in 2050, this is equivalent to 3.5 tonnes CO₂-equivalents per capita.

development depends on the phase-out of nuclear power. However, according to STEM, the emissions will increase after 2010 regardless of the time of phase-out (Section 3.3).

1.4 The Objective of the Study

In order to reduce the anthropogenic climate impact the Swedish Parliament has made decisions regarding the future greenhouse gas emissions in Sweden (Section 1.3). The concentration of greenhouse gases in the atmosphere should be stabilised on a level lower than 550 ppmv CO₂-equivalents. Further the yearly emissions should not exceed 4.5 tonnes CO₂-equivalents per capita by 2050. In this study we will investigate the consistency of these targets and the Swedish contribution to the greenhouse effect. The analysis will be based on the following issues:

- **Historical and future Swedish emission trends**

The knowledge of the historical emissions of greenhouse gases in Sweden is limited. To obtain emission trends, an inventory of the Swedish historical emissions of the six gases regulated by the Kyoto Protocol will be carried through. We will also define scenarios for future Swedish emissions of carbon dioxide.

- **How large is the Swedish contribution to the greenhouse effect and is it fair?**

We will use the inventory of historical emissions to determine the Swedish contribution to the greenhouse effect. The contribution will be determined by comparing Swedish and global emissions, accumulated emissions, concentration increases and radiative forcing. Additionally, we will investigate what the future contribution to the concentration increase would be if we reach the 2050 emission target and follow the recommendations for 2100 given by the Climate Delegation. The results will be analysed in respect to a fairness factor (Section 5.1).

- **Is the emission target for 2050 sufficient for a stabilisation below 550 ppmv?**

A further objective is to learn more about the importance of when and how emission reductions are made. Is a per capita emission target for a certain year sufficient to assure that the atmospheric concentration does not exceed a specific level? Will there be a difference in equilibrium concentration if the reductions start today or if they are made later but at a faster rate?

- **What reductions are required after 2050 to stabilise below 550 ppmv?**

The main objective of this study is to evaluate if the emission target set for 2050 is consistent with the long-term concentration target of 550 ppmv. What further reductions are required after 2050 in order to achieve an equilibrium concentration below 550 ppmv CO₂-equivalents?

Assuming that the 2050-target involves the implementation of fairness (Section 1.3), our hypothesis is that very large emission reductions will be required until the year of 2100 to assure the fulfilment of the concentration target. We believe that initiating the reductions at an early stage, rather than making larger reductions later in time, will result in lower atmospheric concentrations. We believe that this is valid even though the same emission target is met.

The estimates of the historical emissions will mainly be made by using statistics and emission factors. To investigate the atmospheric concentrations a model using the simulation software Powersim Studio 2001 will be constructed. The model will be based on equations derived by climate models.

2 Theory

2.1 Radiative Forcing

The balance of the incoming short-wave solar radiation and the outgoing long-wave planetary radiation determines the temperature on Earth. The solar radiation absorbed by Earth, i.e. by the surface and atmosphere, is balanced at the top of the atmosphere by the outgoing planetary radiation. A change in the net radiation at the tropopause⁵ caused by either a change in solar radiation or planetary radiation is defined as *radiative forcing* and is measured in W/m^2 . For example changes in the planetary albedo or changes in the concentrations of greenhouse gases and aerosols can cause a change in planetary radiation. (IPCC, 1994) A disturbance in the balance between incoming and outgoing radiation has to be adjusted and the climatic system responds in order to re-establish the balance by altering surface temperatures. On average, a positive radiative forcing tends to warm the surface while a negative radiative forcing tends to cool it. The globally and annually averaged radiative forcing can be used to estimate the enhancement of the global mean surface temperature (Section 2.1.1).

2.1.1 Radiative Forcing of the Greenhouse Gases

A radiative forcing agent disturbs the balance between incoming and outgoing radiation at the tropopause. As described in the introduction to this section, there are a number of radiative forcing agents. In this section only the radiative forcing of the greenhouse gases treated by the Kyoto Protocol will be described.

The transparency of the atmosphere to radiation of different wavelengths is settled by the composition of gases and other constituents. Which wavelengths a gas can absorb is determined by the chemical characteristics of the gas. Most of the outgoing long-wave radiation from Earth is of wavelengths between 4-100 μm , with a maximum within the wavelength band of 7-13 μm . At the same time the atmosphere, with some exceptions, is quite transparent to radiation of wavelengths within this very wavelength band. Therefore this wavelength area is called the atmospheric window. By emitting gases, which effectively absorb infrared radiation within the atmospheric window, human activity tends to close the window. The human impact on surface temperatures by emissions of greenhouse gases can be described by using the following scheme:

⁵ The tropopause is the boundary layer between the lower part of the atmosphere, known as the troposphere, and the overlying stratosphere.

Emissions \Rightarrow Concentration Changes \Rightarrow Radiative Forcing \Rightarrow Temperature Changes

A common characteristic of the greenhouse gases included in the Kyoto Protocol is the long atmospheric lifetime, i.e. longer than one year (Appendix A). In Figure 2.1 the decay of some of the greenhouse gases is illustrated. The decay process is mathematically described by Equation 2.1.

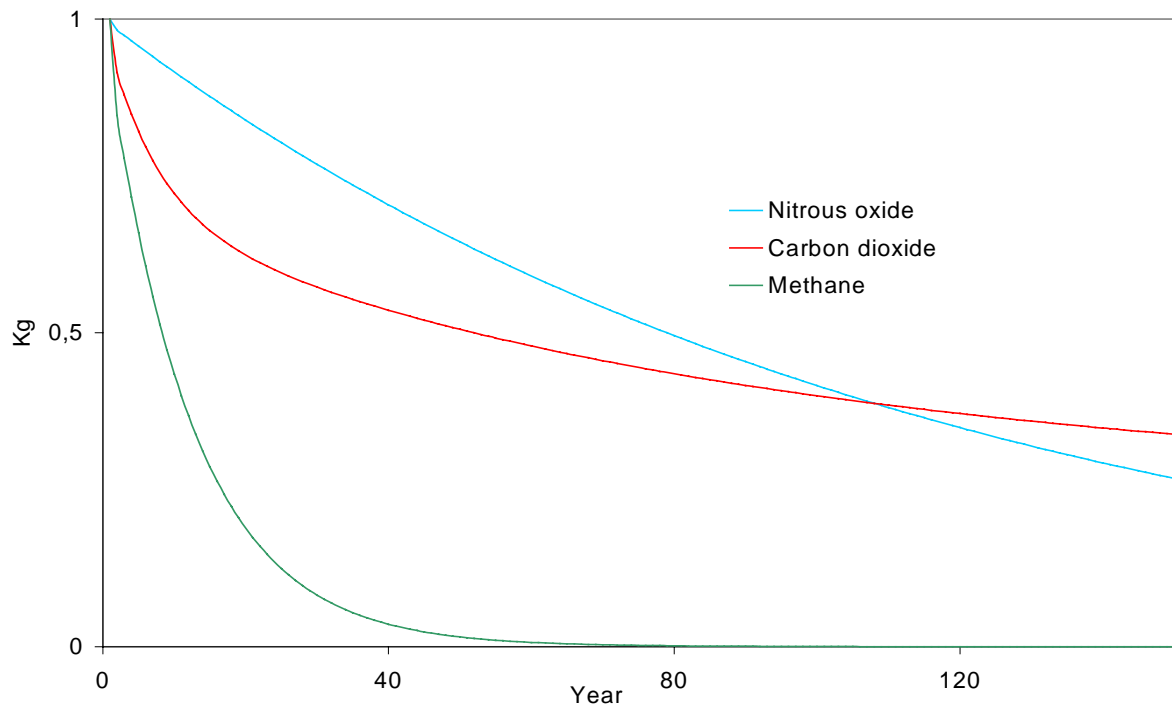


Figure 2.1 The decay process of the three greenhouse gases, carbon dioxide, methane and nitrous oxide. The graph illustrates the remaining amount of gas in the atmosphere after an instantaneous release of 1 kg of each gas.

$$m = m_0 \cdot e^{-t/\tau} \quad (2.1)$$

m = remaining mass of gas [kg]

m_0 = initial amount of gas [kg]

t = elapsed time since addition of gas [yr]

τ = atmospheric lifetime of gas [yr]

Equations for calculating the radiative forcing due to an increase in concentration have been estimated for most greenhouse gases and the equations for a selection of gases are presented in Table 2.1. As can be seen in the equations for carbon dioxide, methane and nitrous oxide, the radiative forcing of these gases is not linearly dependent on the increase of concentration of gas. According to the equations the increase of radiative forcing due to the addition of one unit of gas will be smaller when the concentration of the gas is higher. This is due to saturation effects in the absorption bands of the gases. Methane and nitrous oxide partly absorb within the same wavelength area and this overlapping is described by the function f , see Equation 2.2. For the rest of the gases there exists linear relationships between the increase in concentration and the change in radiative forcing, ΔRF .

Table 2.1 Equations for calculating radiative forcing. Source: Boucher et al., 2001, Table 6.2. See also Shine et al. 1990. For carbon dioxide the concentrations should be given in ppmv, for methane and nitrous oxide in ppbv and for the rest of the gases in pptv. The index 0 indicates pre-industrial concentrations.

Gas	Equations for Radiative Forcing, ΔRF [W/m ²]	
CO ₂	$\Delta RF = 5.35 \cdot \ln(C/C_0)$ Valid for $C < 1000$ ppmv.	C = conc. of CO ₂
CH ₄	$\Delta RF = 0.036 \cdot (\sqrt{M} - \sqrt{M_0}) - (f(M, N_0) - f(M_0, N_0))$ Valid for M and $N < 5000$ ppbv.	M = conc. of CH ₄ N = conc. of N ₂ O
N ₂ O	$\Delta RF = 0.12 \cdot (\sqrt{N} - \sqrt{N_0}) - (f(M_0, N) - f(M_0, N_0))$ Valid for M and $N < 5000$ ppbv.	$f(M, N)$ = Equation 2.2
PFCs HFCs SF ₆	$\Delta RF = \alpha \cdot (X - X_0)$	See Table A.1 for values of α .

$$f(M, N) = 0.47 \cdot \ln \left[1 + 2.01 \cdot 10^{-5} (M \cdot N)^{0.75} + 5.31 \cdot 10^{-15} \cdot M \cdot (M \cdot N)^{1.52} \right] \quad (2.2)$$

A long atmospheric lifetime implies that the gas can be considered to be well mixed throughout the atmosphere. It has been shown that for well-mixed greenhouse gases the radiative forcing for individual gases is additive (Ramaswamy et al. 2001). The total contribution from the Kyoto gases to the greenhouse effect can therefore be calculated by adding the radiative forcing from each gas (Equation 2.3).

$$\Delta RF_{tot} = \sum_{i=1}^n \Delta RF_i \quad (2.3)$$

ΔRF_i = radiative forcing of gas i

n = total number of gases

Knowledge of the total radiative forcing makes it possible to estimate the impact on climate. The change in temperature is calculated by a simple equation (2.4) describing the relationship between radiative forcing and increase in temperature.

$$\Delta T_s = \Delta RF \cdot \lambda \quad (2.4)$$

ΔT_s = change in global mean surface temperature [K]

ΔRF = annual and global average of radiative forcing $\left[\frac{W}{m^2} \right]$

λ = climate sensitivity $\left[\frac{Km^2}{W} \right]$

2.1.2 Radiative Forcing and Concentrations given in CO₂-equivalents

The aim of the Swedish climate strategy is to work for a stabilisation of the concentration of greenhouse gases below 550 ppmv CO₂-equivalents (Section 1.3). What are then CO₂-equivalents?

Since the radiative forcing of the well-mixed greenhouse gases is additive, it is possible to calculate the total radiative forcing caused by several greenhouse gases (Equation 2.3). The concentration in CO₂-equivalents is then the concentration of carbon dioxide required to give the same amount of radiative forcing. Consequently, adding the radiative forcing of all gases and then using the equation for radiative forcing of carbon dioxide given in Table 2.1, results in the corresponding concentration given in CO₂-equivalents. The calculations are described by Equation 2.5.

$$C = C_0 \cdot e^{\Delta RF_{tot}/5.35} \quad (2.5)$$

C = concentration in CO_2 – equivalents [ppmv]

C_0 = pre – industrial concentration [ppmv]

When simulating future concentrations of greenhouse gases due to different emission scenarios the concept of radiative forcing can be very useful. The effects from scenarios with different composition of gases can be compared directly by using radiative forcing. If the contribution to radiative forcing of each gas is known the corresponding CO_2 -equivalent concentration could be calculated. Hence, the resulting concentrations from scenarios describing the emissions of a number of gases could be presented in a single graph. The method of using radiative forcing to calculate CO_2 -equivalent concentrations has been used frequently in this study.

2.1.3 Global Warming Potentials and Emissions Given in CO_2 -equivalents

In order to compare the future impact of emissions of different greenhouse gases a concept called global warming potentials, GWPs, has been developed. The GWP is the time-integrated contribution to climate forcing from the instantaneous release of one kilogram of gas expressed relative to that from one kilogram of the reference gas carbon dioxide (Boucher et al., 2001). The mathematical expression is given in Equation 2.6 (Ramaswamy, 2001). The gas for which the GWP is calculated is designated by x and the reference gas by r . The GWP value is both dependent on the efficiency of the gas to absorb radiation and the atmospheric lifetime of the gas.

$$GWP(x) = \frac{\int_0^{TH} a_x \cdot [x(t)] \cdot dt}{\int_0^{TH} a_r \cdot [r(t)] \cdot dt} \quad (2.6)$$

TH = time horizon over which the calculation is considered

a_x = the radiative efficiency [$W/m^2 kg$]

$x(t)$ = the decay of abundance of the instantaneous release of one unit of gas

The emissions of a gas can be converted into CO_2 -equivalents by multiplying the emissions by the GWP of the gas. Using the concept of GWPs and CO_2 -equivalents for emissions it is possible to compare total emissions including several gases. The concept is used throughout this study and in the Swedish 2050-emission target (Section 1.3).

3 Swedish Emission Inventory

In order to investigate the national contribution to the enhanced concentration of greenhouse gases in the atmosphere, the Swedish historical emissions and future emission scenarios have been compiled. The future emission scenarios are based on projections estimated by STEM and the Swedish emission target for 2050. The historical emissions have been estimated by different methods described below. Most estimates have been based on calculations using statistics on different activities and emission factors. Activities can be production volumes, material flow or size of animal stocks. Equation 3.1 describes the general principle of an emission factor. The historical data obtained by the emission inventory was also used for calculating the Swedish historical per capita emissions.

$$\text{Emission} = \text{activity} \cdot \text{emission factor} \quad (3.1)$$

3.1 Historical Swedish Emissions

Swedish historical emissions of the six greenhouse gases regulated by the Kyoto Protocol, i.e. carbon dioxide, methane, nitrous oxide, perfluorocarbons, hydrofluorocarbons and sulphur hexafluoride, have been compiled. Because the hydrofluorocarbons, HFCs, and perfluorocarbons, PFCs, constitute families of gases, the number of gases emitted in Sweden is actually twelve. Emission data series for all gases during the time period 1990-1999 are available at the Swedish EPA web-site. The EPA emission data was revised according to the updated GWP values given by the IPCC (2001). The EPA data was used for all gases except for HFCs as updated data for HFCs is available in Kindbom et al.(2002). Neither bunker fuels, i.e. emissions from international transport by ships and aircraft, nor emissions caused by Land-use Change and Forestry, LUCF, were included in this inventory.

Emissions for earlier years than 1990, for all gases except carbon dioxide, had to be estimated. In most cases this was performed by using historical statistics and emission factors. The year of 1834 was chosen as the start year for the emission inventory. The reason was that data on carbon dioxide, the most important gas, was not available for earlier years.

3.1.1 Carbon Dioxide, CO₂

Swedish emissions of carbon dioxide for the time period 1834-1998 is available at the Carbon Dioxide Analysis Centre, CDIAC (Marland et al., 2001). Data for the time period 1861-1990 has also been calculated by the Swedish Business Development

Agency (NUTEK, 1991). The CDIAC data has been chosen for this inventory as the Swedish EPA refers to the CDIAC data in the Third National Communication. Additionally, the CDIAC report is more recent and contains longer time series of data.

For the time period 1834-1989 emission data from CDIAC was used. This data includes emissions from fossil fuel burning and cement production and are based on historical energy statistics. For the remaining years, 1990-1999, data from the Swedish EPA was used. For this time period the EPA data shows higher yearly emissions than the CDIAC data (Ministry of the Environment Sweden, 2001. Figure 3.1). The EPA data has been chosen since it has been calculated according to the IPCC standard (IPCC, 1997).

Results from the inventory of carbon dioxide emissions

The Swedish historical emissions of carbon dioxide are presented in Figure 3.1. Global emissions of carbon dioxide are plotted in the same diagram to demonstrate differences in emission patterns. The graph of Swedish carbon dioxide emissions shows that the emissions have been reduced substantially since the 1970s. No such trend can be seen for the global emissions, which on the contrary are increasing. The oil crisis in the 1970s and the implementation of nuclear power are reasons for the trend-break in the Swedish emissions. The two larger emission-dips in the Swedish graph represent World War I and II.

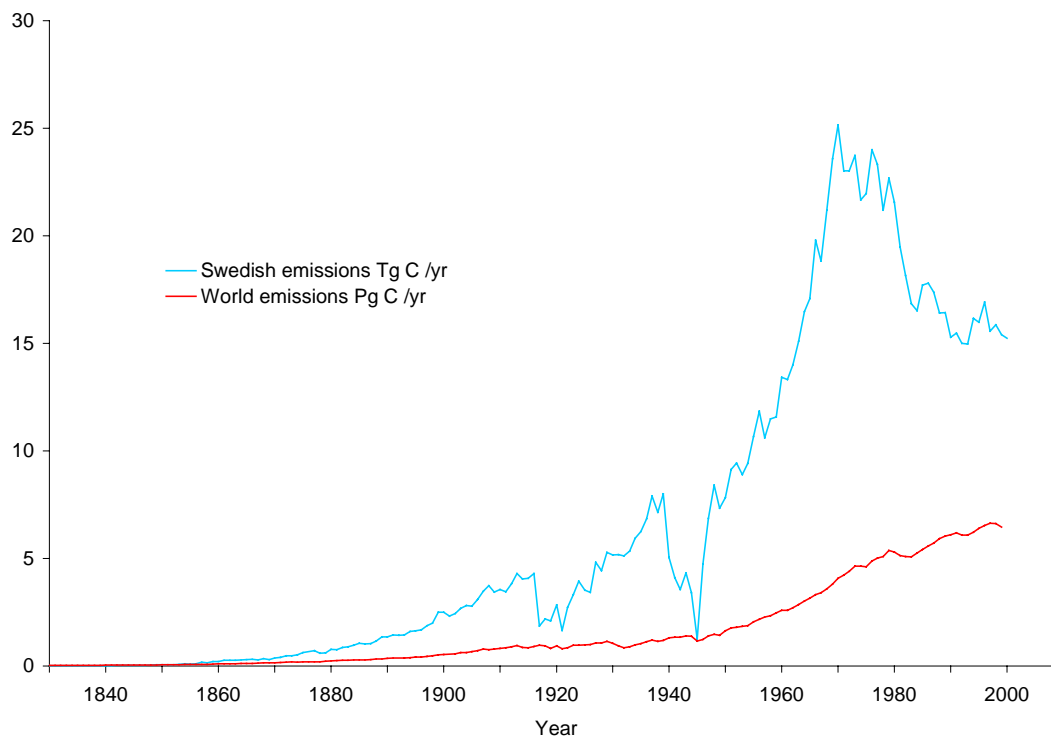


Figure 3.1 Historical Swedish and global carbon dioxide emissions.

3.1.2 Methane, CH₄

The main sources of Swedish methane emissions are agricultural processes and landfills but the industry and the energy sectors also contribute. The knowledge of the development of emissions during the 20th century is highly uncertain. (Ministry of the Environment Sweden, 2001)

Some sources of methane emissions, that are of importance globally, can be neglected when determining the Swedish emissions. There is for example no rice production in Sweden and the production of coal is negligible compared to the global (Kjellström, 1998) (STOSEB, 2002). Further, no gas flaring occurs and natural gas has only been used as an energy source since 1985 and only in relatively small amounts (STEM, 1999). The sources that are of importance both globally and in Sweden are agricultural processes, landfills, the energy and industry sectors.

Agricultural processes

Livestock contribute to methane emissions by enteric fermentation and manure. Cattle are the animal group that contributes most to the methane emissions. Other groups cause relatively small emissions and have therefore been neglected. According to Staaf (2002) one can assume that the emissions from cattle have been more or less constant during the 20th century. The emission per animal is greater today than 100 years ago, due to larger milk production per cow and year, but at the same time the number of animals has decreased significantly. In this study it has been assumed that the cattle and their forage were not significantly modified during the 19th century. The emission factor of methane per cattle has therefore been assumed to be constant throughout the 19th century. The emission factor was used for calculating the emissions of methane from cattle in the year of 1834. Since the number of cattle approximately has increased linearly between 1834 and 1900, linear interpolation has been used to calculate the emissions for this time period (Statistics Sweden, 1959).

Landfills

For the time period of 1860-1994 calculated values for global methane emissions can be found at CDIAC (Kaufmann & Stern, 1998). The global data on emissions from landfills has been used to estimate the Swedish emissions from this source. The global data is based on the assumption that emissions are proportional to economic growth. The global data includes emissions from anaerobic decomposition of garbage before landfills were introduced. The Swedish share of the global emissions from landfills has been calculated for the year 1990. In this study it was assumed that the Swedish fraction of the global emissions from landfills was constant during 1860-1990. The yearly global emissions have therefore been multiplied by this share to obtain yearly Swedish emissions. To obtain data for the time period 1834-1860 data has been extrapolated assuming zero pre-industrial emissions.

The energy and industry sectors

The emissions from the energy and industry sectors 1834-1989 have been calculated by assuming an exponential increase. This assumption was made since statistics show that the energy production in Sweden has increased exponentially (Kander, 1999). The emissions from industry have been included in the assumed exponential increase. An exponential function ($y = e^{ct}-1$) was fitted between the years 1750-1990. The emissions in 1990 were obtained from the Swedish EPA and the emissions in 1750 were assumed to be zero. The reason for not estimating emission data by using statistics on energy production and emission factors was the limited time allocated to accomplish the emission inventory.

Results from the inventory of methane emissions

The Swedish historical emissions of methane are given in Figure 3.2. Global emissions of nitrous oxide are plotted in the same diagram to demonstrate differences in emission patterns. The global and Swedish emissions of methane have increased similarly until the 1950s (Figure 3.2). Thereafter the global emissions have increased at a faster rate. After the year 1990 the Swedish emissions have decreased. This is due to decreasing emissions from all sources of methane emissions considered in this inventory, see Appendix B.

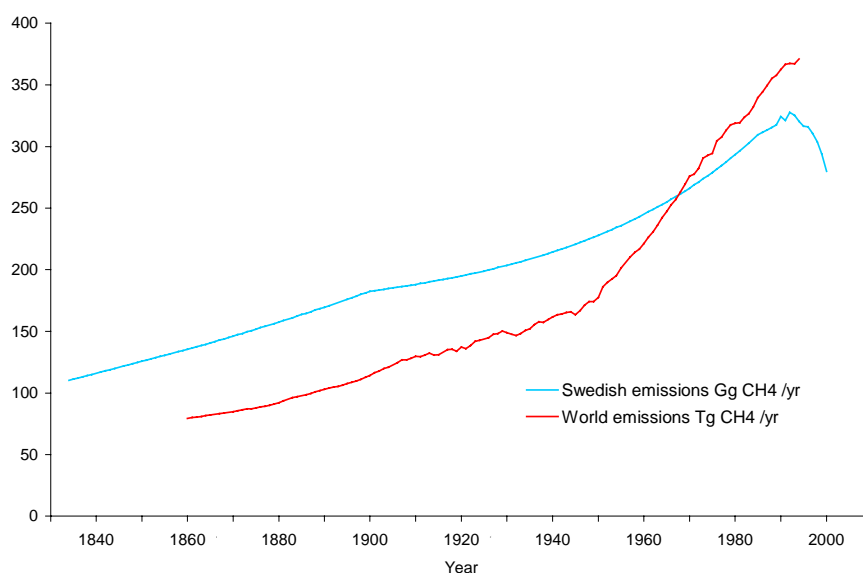


Figure 3.2 Historical Swedish and global methane emissions.

3.1.3 Nitrous Oxide, N₂O

The Swedish emissions of nitrous oxide during the 20th century are poorly known. The main source of emissions is agriculture but the energy and industry sectors also contribute. (Ministry of the Environment Sweden, 2001) There are various agricultural sources of nitrous oxide. In this study, emissions from nitrous oxide have been calculated considering emissions from animal waste, commercial fertilisers, manure management, grazing, miscellaneous agricultural sources, production of nitric acid and the energy sector.

Animal waste

Historical statistics, from 1927 and onwards, on the total amount of nitrogen in domestic animal waste is available at SCB. About 30 % of the nitrogen in manure forms ammonia and was therefore subtracted from the statistics before calculating the emissions (Swedish EPA, 2001). The emissions were calculated by multiplying the remaining amount of nitrogen by an emission factor. The emission factor is estimated by the Swedish EPA (2001) to 0.8 %. Since there are no statistics on nitrogen amount in animal waste available for years earlier than 1927, the emissions for those years had to be estimated in a different way (Statistics Sweden, 1995). The nitrogen amount and the number of horses, cattle, sheep and pigs in 1927 were used for calculating emission factors for each animal group. The yearly emissions 1834-1927 were calculated assuming constant emission factors over time for the different animal groups. The emissions were estimated by multiplying each emission factor with the number of animals in each group (Statistics Sweden, 1959). For some years interpolation has been used to estimate the number of animals. The total emissions for this time period were calculated by adding the contributions from the different animal groups.

Commercial fertilizers

Yearly statistics on the total amount of nitrogen in commercial fertilisers were used for calculating the emissions. The statistics were multiplied by an emission factor of 2.5 %, estimated by the Swedish EPA (2001). According to statistics, emissions from commercial fertilisers were negligible before 1901 (Statistics Sweden, 1995).

Manure management

The estimate of emissions from manure management in this study was based on the emissions of manure. The relationship between emissions from manure management and manure has been assumed to be constant during the 19th century. The emissions from manure management were 80 % of the total emissions from manure in 1900 (Staafl, 2002). For the 20th century estimates made for certain years⁶ by the Swedish

⁶ Those years are 1900, 1950 and 1990.

EPA have been used (Staaf, 2002). To get yearly estimates linear interpolation has been used.

Grazing

The estimate of emissions from grazing has been based on emissions from animal manure (Statistics Sweden, 1959). Emissions from manure caused by horses, cattle and sheep have been considered, as these constitute the grazing animal group. The emissions from manure have been multiplied with the relationship between emissions from manure and grazing that prevailed in 1927. This relationship has been assumed constant during the 19th century. For the 20th century estimates made for certain years⁶ by the Swedish EPA have been used (Staaf, 2002). To get yearly estimates linear interpolation has been used.

Miscellaneous agricultural sources

The Swedish EPA has made estimates of emissions from miscellaneous agricultural sources i.e. harvest residues, nitrogen-fixating crops, cultivation of organic and mineral soils and indirect emissions to air. The amount of emissions from most of these sources is closely related to arable land area. Estimates of these emissions have been made for specific years⁶ during the 20th century (Staaf, 2002). To get yearly estimates linear interpolation has been used. The relationship between emissions and arable land area has been assumed to be constant over time. Arable land in 1900 was about 3.6 million hectares and the figure for 1834 was about 1.6 million hectares. Estimates on the emissions in 1900 and the area of arable land in 1900 and in 1834 made it possible to estimate the emissions in 1834. Interpolation has been used to estimate the emissions for the time period 1834-1900, as the increase in arable land area approximately has been linear. (Statistics Sweden, 1990)

Production of nitric acid

Production of nitric acid is the main industrial emission source of nitrous oxide. Emissions have been calculated by multiplying statistics on production of nitric acid by emission factors (Statistics Sweden, 1911-1989). The first year of production of nitric acid in Sweden was 1911. For the time period 1911-1955 it has been assumed that the same emission factor as for 1956-1981 can be used. Based on Karlsson (2002) this emission factor is 4.5 kg N₂O per tonne acid. The emission factor of 6.0 kg N₂O per produced tonne acid used for the time period 1982-2001 is also based on Karlsson (2002).

The energy sector

The emissions from the energy and industry sectors 1834-1989 have been calculated by assuming an exponential increase. This assumption was made since statistics show that the energy production in Sweden has increased exponentially during this time period (Kander, 1999). An exponential function ($y = e^{ct} - 1$) was fitted between the years 1750-

1990. The data on emissions in 1990 were obtained from the Swedish EPA and the emissions in 1750 were estimated to be zero. The reason for not estimating emission data by using statistics on energy production and emission factors was the limited time allocated to accomplish the emission inventory.

Results from the inventory of nitrous oxide emissions

The Swedish historical emissions of nitrous oxide are given in Figure 3.3. Global emissions of nitrous dioxide are plotted in the same figure to demonstrate differences in emission patterns. The global and Swedish emissions of nitrous oxide have increased similarly. The Swedish emissions have been increasing until the 1980s when the emissions started to level out. At this time the increasing trend of the use of commercial fertilisers and the production of nitric acid started to level out (Appendix B).

According to the Swedish EPA (1995) the national emissions of nitrous oxide have increased by about 50 % during the time period of 1900-1990. In this inventory the resulting increase is 52 %, which is very close to the EPA estimate.

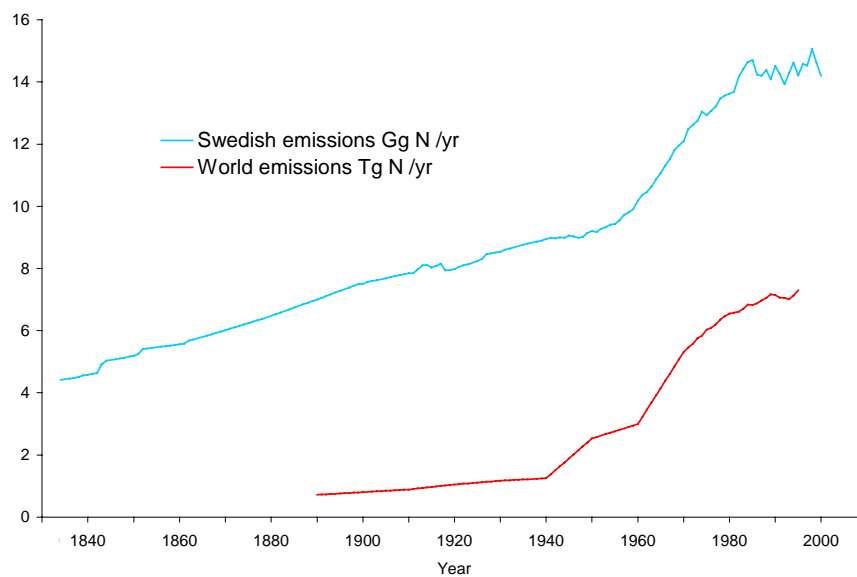


Figure 3.3 Historical Swedish and global nitrous oxide emissions.

3.1.4 Fluorocarbons, PFCs & HFCs and Sulfur Hexafluoride, SF₆

Perfluorocarbons, PFCs

PFCs, perfluorocarbons, are human-made gases. The main source of emissions of PFCs is production of *primary* aluminium (Kindbom et al., 2001). The only producer of primary aluminium in Sweden today is KUBAL AB. Emissions only occur during the "anode effect" which is an unwanted effect during the process of producing primary aluminium. The production causes emissions that are composed to 90 % of CF₄ and to 10 % of C₂F₆. According to Handå (2002), this relationship can be assumed constant over time.

The emissions of PFCs depend both on the number of anode effect (AE) minutes per day and the process type. There are two main types of aluminium smelting technologies, where the principal difference is the anode type used. The *Söderberg* method gives rise to larger emissions of PFCs than the *Pre-baked* method. Aluminium production was initiated in 1934 in Sweden. In a historical perspective, basically only the Söderberg method has been used. In 1987 the Pre-baked method was introduced and has since then accounted for 25 % of the yearly production. The emission factors of PFCs have been calculated with the experimentally derived Equation 3.2, recommended by the European Aluminium Organisation.

$$EF \text{ (kg of PFC /tonne aluminium)} = \text{slope} \cdot \text{AE minutes per cellday} \quad (3.2)$$

The slope for Söderberg is 0.08 and the slope for Pre-baked is 0.12. Measurements of the number of AE minutes per oven and day at KUBAL AB have been made for the time period 1995-1999. According to these measurements the number of AE minutes per day was on an average 0.456 for the Pre-baked method and 7.940 for Söderberg. (Handå, 2002). The same values on daily AE minutes have also been applied for the time period 1986-1994. According to Handå (2002), the daily number of AE minutes was about twice as many in the 1970s as in 1987. Linear interpolation has been used to estimate the decrease in AE minutes between 1971 and 1986. For earlier years the number of AE minutes has been estimated by the 1970-year value. To obtain the actual emissions the emission factor, EF, has been multiplied by historical statistics on produced primary aluminium (Pettersson, 2002).

Hydrofluorocarbons, HFCs

HFCs, incompletely halogenated fluorocarbons, are for example used for refrigeration and for producing plastics. The gases are invented by man and are used for substituting the CFCs that are being phased out. HFCs were not produced for commercial use until 1990 (Ministry of the Environment Sweden, 2001). Emission data from the Swedish EPA has been used for these gases. The six HFC compounds that are emitted in Sweden can be found in Appendix A.

Sulfur hexafluoride, SF₆

In 1990 about 97 % of the emissions of sulphur hexafluoride, SF₆, were caused by leakage from insulation of heavy electric equipment (Kindbom et al., 2001). Other sources of SF₆ emissions have been neglected in this study. The technology for using SF₆ as insulation in electric equipment was introduced in the 1960s (Nätrådets Drift- och Underhållskommitté, 1996). The emissions of this gas during the 1990s were very small, they accounted for less than 0.2 % of the total emissions of Kyoto greenhouse gases given in CO₂-equivalents. Before 1990 the contribution of SF₆ to the total emissions can be assumed to have been even smaller. Since the emissions of SF₆ are diffuse, it is very difficult to estimate them. A deeper analysis of the emissions was beyond the scope of this study. To give an idea of the emission trend, linear interpolation between zero emissions in 1960 to the value given by the Swedish EPA in 1990 was used.

Results from the inventory of PFCs, HFCs and SF₆ emissions

The Swedish historical emissions of PFCs, HFCs and SF₆ are given in Figure 3.4. The emissions are given in CO₂-equivalents and each family of gases is represented by a single graph. The emissions of HFCs have increased rapidly since the introduction in the beginning of the 1990s. This is because this family of gases is used as a substitute for CFCs, which are being phased-out. The emissions of PFCs increased until the 1970s due to increasing production of primary aluminium, after this the technology improved and the emissions decreased. The increase of emissions in 1989-1990 is due to differences in used emission factors. In this study the estimated emission factor of 1986-1989 is an average of the measured emission factors of 1995-2000. The Swedish EPA has estimated higher emission factors for the early 1990s and thus the appearing increase of emissions in 1989-1990. The emissions of SF₆ have increased since the introduction of the gas in the 1960s. The emission development of this gas during 1960-1990 has not been analysed, only estimated by linear interpolation.

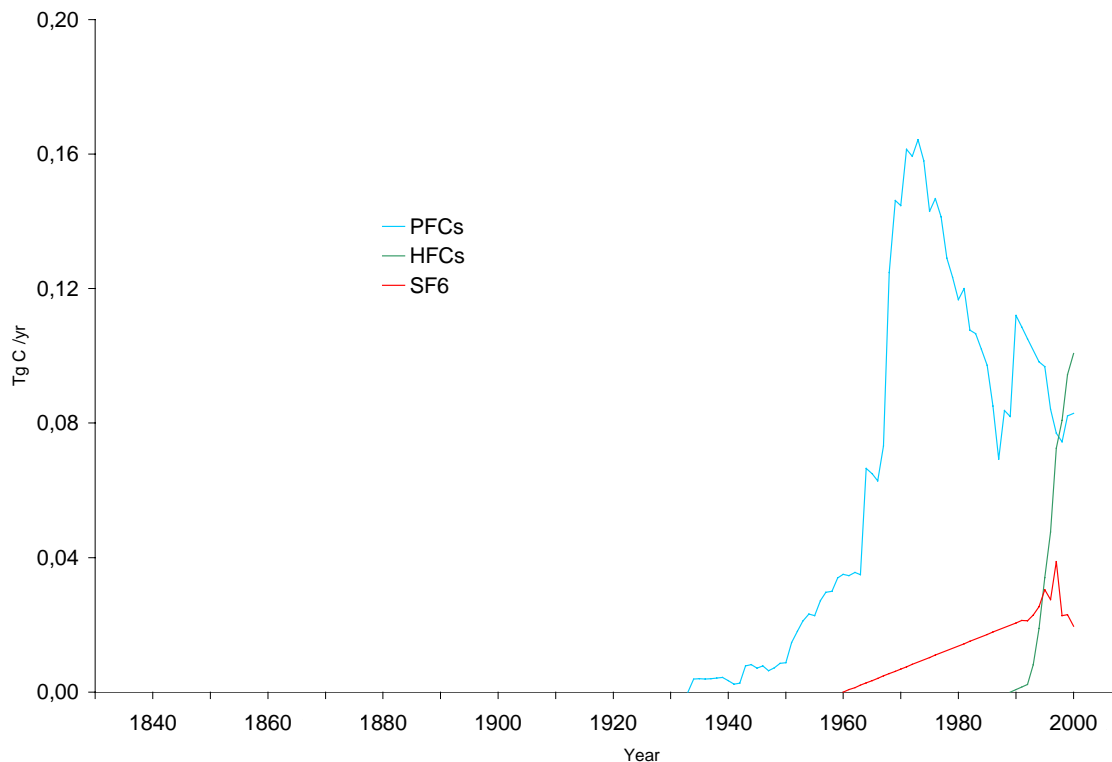


Figure 3.4 Swedish emissions of PFCs, HFCs and SF₆ given in CO₂-equivalents.

3.1.5 Total Historical Swedish Emissions

The estimated Swedish historical emissions of the six greenhouse gases regulated by the Kyoto Protocol are presented graphically in Figure 3.5. To give an idea of the amount of emissions of the different gases relative to each other, all gases are plotted in the same diagram. Emissions are given in CO₂-equivalents.

As can be seen in Figure 3.5, carbon dioxide is dominating the Swedish emissions. Methane and nitrous oxide together represent about 20 % of the Swedish emissions. The two gases are of approximately the same magnitude when given in CO₂-equivalents. The remaining gases contribute marginally to the emissions. According to the Swedish EPA, the relative contribution of these gases is expected to increase in the future.

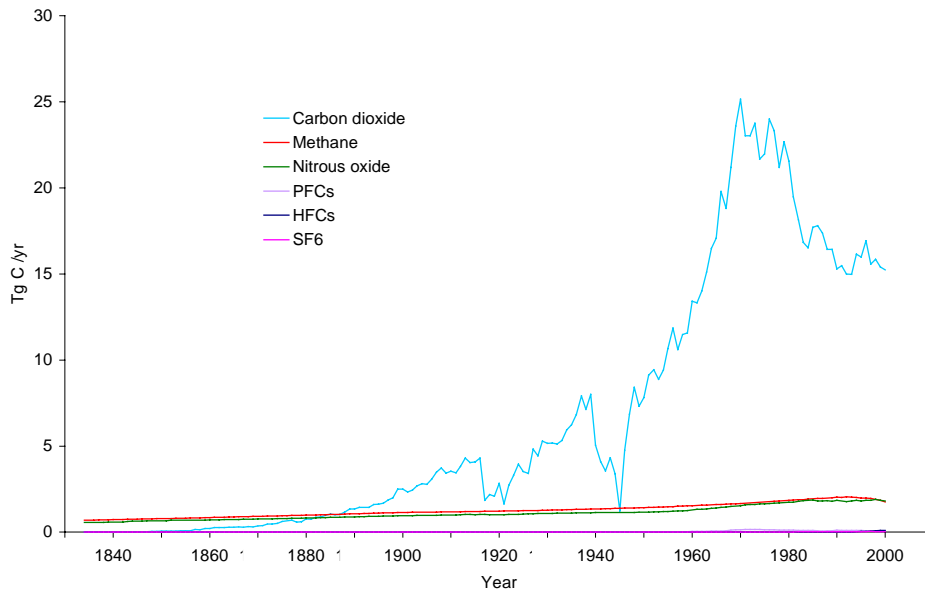


Figure 3.5 Swedish emissions of the Kyoto greenhouse gases given in CO₂-equivalents.

3.2 Historical Per Capita Emissions

To give an idea of historical emission trends the per capita emissions in CO₂-equivalents for the time period 1834-2000 have been calculated. Emissions of the six Kyoto gases estimated in Section 3.1 have been used. The historical demographic data used was obtained from SCB (2001).

The Swedish historical per capita emissions of the Kyoto gases, given in CO₂-equivalents, are presented in Figure 3.6. The equivalents have been calculated using GWP(100) (Section 2.1.3). The same trends can be observed as in the graph of carbon dioxide emissions (Figure 3.1). Per capita emissions for a selection of years can be found in Table 3.1 together with the total emissions given in CO₂-equivalents.

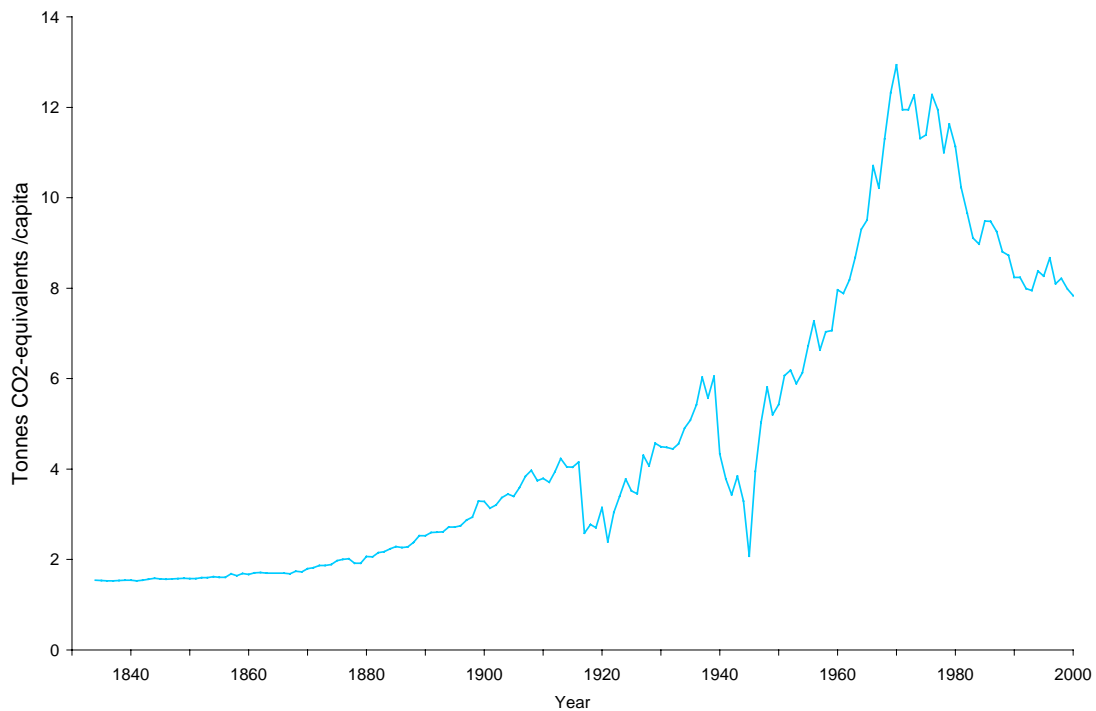


Figure 3.6 Swedish historical per capita emissions 1834-2000. The gases included are the six Kyoto gases and they are all given in CO₂-equivalents.

Table 3.1 Total emissions and emissions per capita given in CO₂-equivalents for a selection of years.

Year	1840	1900	1930	1970	1990	2000
Emissions [Gg CO ₂ -equivalents]	4840	16867	27597	104542	70766	69636
Emissions [Tonnes CO ₂ -equivalents per capita]	1.5	3.3	4.5	12.9	8.2	7.8

3.3 Swedish Emission Scenarios of Carbon Dioxide

To be able to simulate the Swedish future contribution to the greenhouse gas concentration in the atmosphere, one needs scenarios of Swedish future emissions. The Swedish Energy Agency, STEM, has made three different projections that have been

used in this study. STEM has estimated one value for emissions of carbon dioxide for 2010 and two different values for 2020 (Table 3.2). The projections are business as usual scenarios i.e. the analyses are based on the present energy and environmental policies. The development between 2010 and 2020 depends on the phase out of nuclear power. Projection 2020_1 assumes that the present nuclear power plants will be used as long as it is profitable. Projection 2020_2 assumes a phase-out after 40 years of operation. However, both projections assume that all nuclear power will be replaced no later than 2025. (STEM, 2001)

Table 3.2 Projections for future carbon dioxide emissions are given in Gg /yr. Source: Swedish Energy Agency, 2002.

Year	1999	2010	2020	2020
Projection		2010	2020_1	2020_2
Emissions	56 347	57 742	60 145	65 908

In this study five different scenarios were used, see Figure 3.7. All scenarios, except scenario E, reach the Swedish 2050-emission target. Since the emission scenarios only consider carbon dioxide the corresponding value of the 2050-target, 3.4 tonnes carbon dioxide per capita has been used (Ministry of the Environment Sweden, 2000). Scenario A is a best case scenario where actions are taken today to reduce emissions, while scenario E can be regarded as a worst case scenario where the 2050-emission target is not reached. However, this is not at all an unrealistic scenario as according to STEM the electricity production beyond 2020-2025 is likely to be based on fossil fuels. Consequently both STEM projections for 2020 will be followed by substantially higher emissions.

Scenario A: The emissions increase according to the 2010 projection until 2002, thereafter the emissions decrease linearly to the emission target 2050.

Scenario B: The emissions increase to the 2010 projection, thereafter the emissions decrease linearly to the emission target 2050.

Scenario C: The emissions increase to the 2020_1 projection, thereafter the emissions decrease linearly to the emission target 2050.

Scenario D: The emissions increase to the 2020_2 projection, thereafter the emissions decrease linearly to the emission target 2050.

Scenario E: The emissions increase to the 2020_2 projection, thereafter the emissions are held at a constant level. Thus, this scenario does not reach the 2050-emission target.

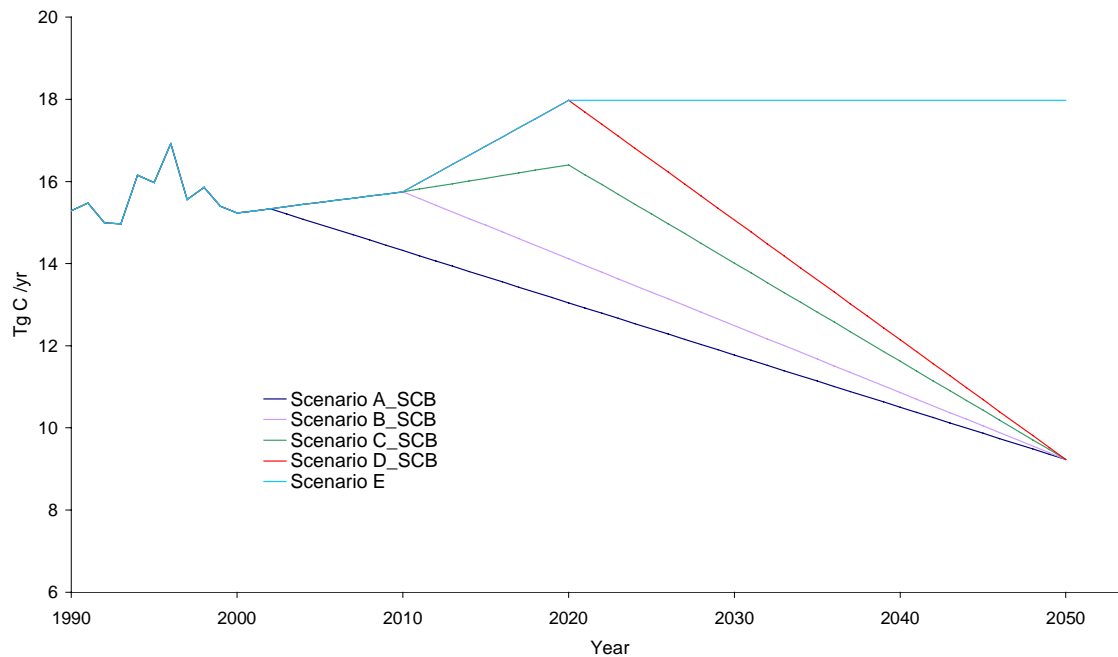


Figure 3.7 The five scenarios for future emissions of carbon dioxide assuming the population to grow according to the SCB projection.

Since the target is given in CO₂-equivalents per capita, the future population of Sweden had to be estimated to be able to calculate the emissions in 2050. As the projections for population growth vary significantly, two different projections have been chosen. SCB, Statistics Sweden, (2001) estimates that the Swedish population will grow to 9.956 million by 2050 and the UN medium projection (2001) to 7.777 million by the same year. SCB assumes both the fertility and the net immigration in Sweden to increase whereas UN bases the future estimates on the historic development and trends. Over the past years the fertility in Sweden has been decreasing, hence the estimate of a population-decrease.

Scenario E does not reach the 2050-target and is thus independent of the development of the population. Accordingly, there are altogether nine different scenarios. The per capita emission target is given in CO₂-equivalents. To calculate the emissions for each gas in 2050 the same relative composition of gases that prevailed in 2000 has been used.

4 Model Development

The model used in this study was built by using Powersim Studio 2001, which is a software tool for simulation models. The model calculates the atmospheric concentrations and the radiative forcing due to emissions of the greenhouse gases comprised by the Kyoto Protocol. Sweden emits twelve different Kyoto gases (Section 3.1) and for this model carbon dioxide was divided into three components treated separately. Therefore the main model was built for a total of 14 gases. To change the total amount of gases in the model is easy. In Appendix C the complete diagram of the model is given along with the specific equations.

One of the most important model parameters is the atmospheric lifetime of each gas, which determines the rate of removal of added gas. For all gases, except carbon dioxide, the atmospheric lifetimes can be found in Appendix A. Since the decay of carbon dioxide does not follow a simple exponential relation it is difficult to determine the atmospheric lifetime (Section 2.1.1). There are many parameterisations of the atmospheric lifetime of carbon dioxide (IPCC, 2001) and for this model an ocean-atmosphere box diffusion model (Albritton et al. 1995) has been used. The parameterisation in that model is made by dividing the gas into three components with different atmospheric lifetimes. One fraction of the added gas disappears relatively fast by biospheric uptake while the rest, which is removed by uptake to the ocean surface water and transfer to deep ocean water, remains for a very long time. The fractions and lifetimes are 6.993 years, 71.109 years and 815.727 years respectively. The corresponding mass fractions are 0.30036, 0.34278 and 0.35686. A comparison between simulated concentrations and measured atmospheric concentrations confirmed that the chosen parameterisation of the atmospheric lifetime of carbon dioxide describes the decay well (Appendix E).

All twelve gases treated by the model have long atmospheric lifetimes, i.e. longer than one year, which imply that they all can be assumed to be well mixed throughout the atmosphere. The concept of “well mixed” eliminates the need for the model to include spatial variation. The removal of each gas is governed by Equation 2.1 given in Section 2.1.1. The atmospheric concentration increase of each gas, ΔC , is calculated using Equation 4.1.

$$\Delta C = \left(\frac{m_{gas}(t)}{M_{gas}} \right) - \left(\frac{m_{atm}}{M_{air}} \right) \quad \begin{aligned} m_{gas}(t) &= \text{remaining amount of gas after } t \text{ years [g]} \\ M_{gas} &= \text{molar mass of the gas [g / mole]} \\ m_{atm} &= \text{total atmospheric mass [g]} \\ \overline{M}_{air} &= \text{mean molar mass of air [g / mole]} \end{aligned} \quad (4.1)$$

The model is based on the assumption that the atmospheric concentrations of the modelled gases were at equilibrium before the industrial revolution (Siegenthaler & Oeschger, 1987). For this reason the initial amount of gas, m_0 , (Equation 2.1) is zero when starting the simulations in 1750. If the simulations start at a later time, m_0 is the amount of added gas since 1750 that still remains in the atmosphere. The pre-industrial atmospheric concentrations given in Appendix A are used as background concentrations.

Another important model parameter is the radiative properties of the gases. The radiative properties are expressed as functions giving the radiative forcing due to changes in concentrations, see Table 2.1. The radiative forcing of each gas is then summed according to Equation 2.3 and the total concentration given in CO₂-equivalents is calculated using Equation 2.5.

The input information to the model is time-series of emission data for each gas given in kilo tonnes of gas. The model imports this information from MS Excel Worksheet files. After executing the model with scenarios running from 2000 until 2050 it was obvious that the model had to be run for a longer time period in order to reach an equilibrium concentration. It was therefore necessary to extend the simulation period and hence the input data series. All simulations on future scenarios were run until 2300.

In Powersim Studio 2001 the user has the possibility to choose the integration method to be used in each simulation run. In this study all simulations were performed using a Runge-Kutta integration method and a time step of one year. The reasons for these choices are given in Appendix D.

5 Calculations and Simulations

5.1 The Swedish Contribution to the Greenhouse Effect

The Swedish contribution to the greenhouse effect has been estimated based on emissions, accumulated emissions, concentration increases and radiative forcing respectively. To get an indication of fairness the results were compared to a fairness factor, which is defined as the ratio between the global and Swedish population. The fairness factor is presented in Equation 5.1, where t represents one year and n is the total number of years. Since radiative forcing and concentrations are the results of accumulated emissions, the comparison has been made by using “accumulated populations”. The accumulated population has been calculated by adding the yearly population data from 1750 until today, both for Sweden (SCB, 2001) and the world (UN, 2001).

$$\text{Fairness factor} = \frac{\sum_{t=1}^n \text{Swedish population}(t)}{\sum_{t=1}^n \text{Global population}(t)} \quad (5.1)$$

The degree of fairness, DF, is the ratio between the Swedish contribution and the fairness factor. The Swedish contribution is given as a percentage of the total global emissions, concentration increase or radiative forcing. The following relations describe the degree of fairness:

$DF > 1$	<i>Contribution larger than the global average</i>
$DF = 1$	<i>Fair contribution</i>
$DF < 1$	<i>Contribution smaller than the global average</i>

5.1.1 The Swedish Contribution Based on Emissions

The Swedish accumulated emissions of carbon dioxide, methane and nitrous oxide were calculated and compared to the global emissions of these gases. The time period considered varies between the gases due to availability of global emission data. A comparison between the Swedish and global emissions for the last year in each time period was made as well. All results were compared to a fairness factor.

National accumulated emissions of the individual gases can be found in Table 5.1. The table contains information on how large the emissions are relative to the accumulated global emissions for the same time period. Values comparing only the emissions made in the last year of each time period can also be found in the table. When comparing emissions for only one year the values should be compared to the fairness factor for those specific years.

Both when comparing the accumulated emissions and the emissions for only the last year in each time period the methane emissions are the only emissions that do not exceed the fair level. A probable reason for this is that Sweden lacks many of the sources of methane emissions (Section 3.1.2).

Table 5.1 Swedish accumulated emissions of greenhouse gases. The fairness factor is designated by F. DF is the degree of fairness i.e. the closeness to the fair level. 1 is fair, <1 higher than the global average and >1 lower than the global average.

Gas	Time period	Accumulated emissions	Share of accumulated global emissions F=0.24 %	Share of global emissions in the last year of the time period F=0.15-0.16 % ⁷
CO ₂	1750-1999	1.1 Pg C	0.40 % (DF=1.7)	0.24 % (DF=1.6)
CH ₄	1900-1994	22.4 Tg CH ₄	0.11 % (DF=0.5)	0.09 % (DF=0.6)
N ₂ O	1900-1995	0.98 Tg N	0.33 % (DF=1.4)	0.19 % (DF=1.2)

Table 5.1 shows that the emissions of all three gases have decreased in recent years relative to the global emissions. There is no significant difference in degree of fairness for carbon dioxide whether considering the historical emissions or not. For the other two gases the degree of fairness is closer to one if considering only the emissions of today. Since the degree of fairness is above one for nitrous oxide this is a positive trend but for methane the conditions are reversed. However, the methane emissions are still the only emissions that are below the fair level.

5.1.2 The Swedish Contribution Based on Concentrations

In order to calculate the Swedish contribution to the atmospheric increase in concentrations of greenhouse gases, a simulation from 1750 until 2000 with Swedish emissions of carbon dioxide, methane and nitrous oxide was performed. Since the

⁷ F is 0.16 % for 1994 and 1995. F is 0.15 % for 1999.

emission inventory (Section 3) only contains data from 1834 and onwards, the data series had to be extrapolated to 1750. Carbon dioxide and methane were extrapolated assuming zero emissions in 1750. This assumption will not have great impact on the result since the emissions before 1834 were very small. Moreover, the lifetime for methane is very short (Appendix A). The global emissions of nitrous oxide were approximately constant during the time period 1750-1834 (Van Aardenne et al., 2001). The Swedish emission trend was assumed to be similar to the global, hence the Swedish yearly emissions of nitrous oxide were assumed to be constant during this time period. The Swedish contribution to the concentration increase was compared to the global concentration increase.

The Swedish contribution to the increase in the concentration of the gases carbon dioxide, methane and nitrous oxide by the year 2000 is shown in Table 5.2. As in the case of comparing emissions, methane is the only gas with a contribution below the fair level. The percentage of the increase in concentration of carbon dioxide is less than the accumulated emission percentage (Table 5.1). This is the result of the emission reductions accomplished in more recent years (Figure 3.1). Notice that for methane and nitrous oxide, the comparison between concentrations considers the whole time period since the industrial revolution. For comparisons between emissions of these gases the time periods considered are shorter. For methane, the difference in length of time period should not be of great importance when comparing the share of emissions and share of concentrations since its atmospheric lifetime is short. The difference in Swedish contribution between the comparison of emissions and concentrations for methane is within the range of uncertainty of the simulation model. For nitrous oxide no such comparison can be made since the atmospheric lifetime of the gas is long. The emissions of nitrous oxide from 1750 to 1900 included in the concentration calculations can not be neglected as a considerable amount of these emissions still remain in the atmosphere.

5.1.3 The Swedish Contribution Based on Radiative Forcing

It is not easy to determine the Swedish contribution to radiative forcing. The problem is to determine the initial concentrations in the equations given in Table 2.1. Using for example an initial concentration of carbon dioxide of 550 ppmv results in an under-estimate of the Swedish contribution, while using the pre-industrial concentration of 270 ppmv results in an over-estimate. Calculating the radiative forcing using the Swedish concentration increase only would thus over-estimate the Swedish contribution. The reason for an over-estimate is that the global concentration has been increasing not only due to Swedish emissions but also due to emissions from other countries. The increase of radiative forcing due to the addition of one unit of gas becomes smaller as the concentration of the gas in the atmosphere increases (Section 2.1.1). In this study the Swedish contribution to the radiative forcing of each gas is defined by Equation 5.2.

Radiative forcing has been calculated assuming that the relative contribution to radiative forcing is the same as the relative contribution to the concentration increase. The assumption is justified since the global radiative forcing is caused by all gas molecules in the atmosphere. Adding the radiative forcing caused by carbon dioxide, methane and nitrous oxide results in the total Swedish contribution to the greenhouse effect caused by the mentioned gases. This was compared to the total global radiative forcing caused by these gases and the fairness factor.

$$\Delta RF_{Sweden} \equiv \frac{\Delta C_{Sweden}}{\Delta C_{World}} \cdot \Delta RF_{World} \quad (5.2)$$

ΔRF_{Sweden} = the Swedish contribution to radiative forcing

ΔRF_{World} = the global increase in radiative forcing

ΔC_{Sweden} = the Swedish contribution to the concentration increase

ΔC_{World} = the global increase in concentration

Calculated values of global radiative forcing can be found in Table 5.2. The global values have been used for calculating the total Swedish contribution to the greenhouse effect for the three gases in question. The Swedish share of the total radiative forcing was defined by the ratio between the total Swedish radiative forcing and the total global radiative forcing. The ratio is 0.32 % and can be compared with the fairness factor for the same time period which is 0.24 %. The degree of fairness is thus 1.33, which implies that the Swedish contribution is about 33 % larger than the global average.

Table 5.2 This table shows the simulated Swedish contribution to the increase of concentration of greenhouse gases by the year of 2000 and calculated values for radiative forcing. DF is the degree of fairness i.e. the closeness to the fair level. 1 is fair, <1 higher than the global average and >1 lower than the global average.

Gas	Swedish contribution to conc. increase	Share of global conc. increase F = 0.24 %	RF(World) [W/m ²]	RF(Sweden) [W/m ²]
CO ₂	0.31 ppmv	0.34 % (DF=1.42)	1.50	0.00570
CH ₄	1.32 ppbv	0.13 % (DF=0.54)	0.49	0.00061
N ₂ O	0.19 ppbv	0.40 % (DF=1.67)	0.14	0.00041
Total			2.13	0.00672

5.1.4 The Swedish Future Contribution

The Swedish future contribution to the greenhouse effect was simulated using the emission scenarios presented in Section 3.3. Two different sets of simulations, including carbon dioxide emissions only, were performed. In both sets of simulations the Swedish emission target set for 2050 was met. In one of the simulation sets the emissions were reduced to the level recommended by the Climate Delegation, 2.6 tonnes CO₂ per capita in 2100 (Section 1.3). In the other simulation set the emissions were reduced to a low level of 0.77 tonnes CO₂ per capita, which corresponds to 1.0 tonnes CO₂-equivalents per capita. This level was chosen since simulations performed in this study indicate that it is the required level for reaching an equilibrium concentration of 550 ppmv CO₂-equivalents (Section 5.3.1). Scenario 5 is independent of any emission target in 2100 as the yearly emissions are held at a constant level after 2050. The Swedish contribution to the concentration of carbon dioxide in the years 2050, 2100 and 2300 were compared to a global concentration of 500 ppmv. This concentration is equivalent to the 550 ppmv target when carbon dioxide is the only gas included. (Ministry of the Environment, 2000). The results were compared to concentrations representing a fair level. These fair contributions are based on the fairness factor (Section 5.1).

The simulations of the Swedish future contribution were performed with carbon dioxide emissions only. However, it would be possible to include all gases. This has not been done since it would be difficult to compare the results to the global concentrations. It would not be feasible to transform the Swedish concentrations into CO₂-equivalents since the transformation uses the concept of radiative forcing and it is problematic to calculate radiative forcing for Swedish concentrations only (Section 2.1.1 & Section 5.1.3).

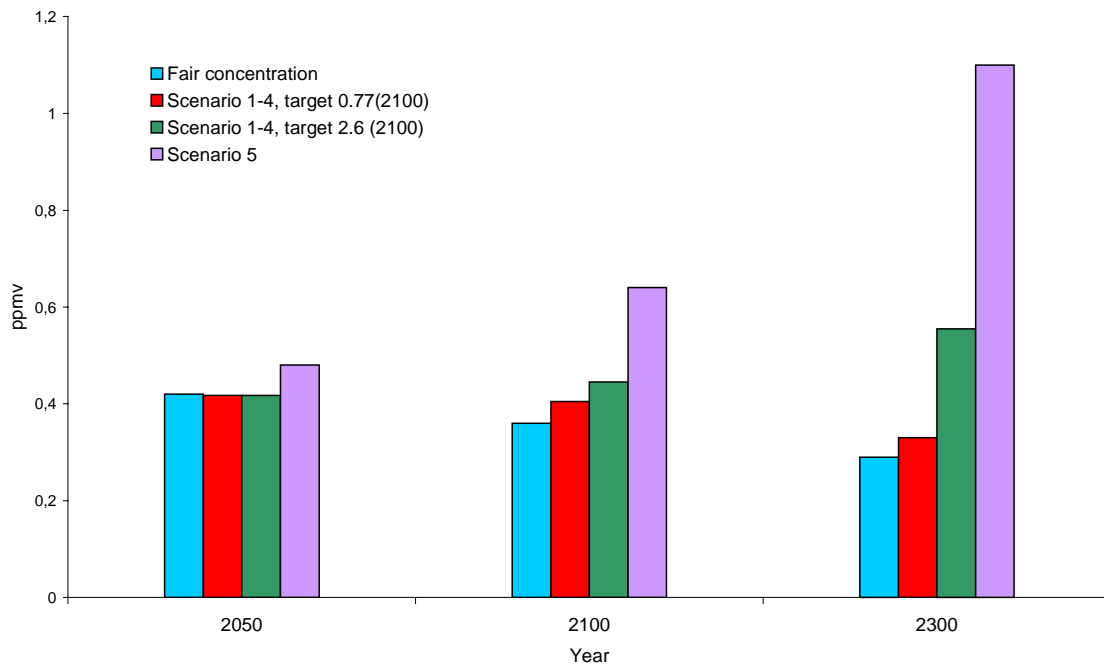


Figure 5.1 Swedish future concentrations according to an average of the four SCB scenarios for both a target of 2.6 tonnes CO₂ and 0.77 tonnes CO₂ in the year of 2100 and also according to scenario 5. A global concentration of 500 ppmv CO₂ by 2050 has been assumed for all years. Fair concentrations for the years in question have been calculated by multiplying the assumed global concentration increase by the fairness factor.

The future contribution to the atmospheric concentration of carbon dioxide, due to Swedish emissions, is shown in Figure 5.1. The results from the UN and SCB population scenarios are very similar and therefore only the results from the SCB scenarios are shown in the figure. The results for the scenarios 1-4 are also very similar, which probably is due to similar total emission amounts. An average of the four scenarios is shown in the figure. Detailed results for both SCB and UN scenarios can be found in Appendix F. The global concentration has been assumed to be 500 ppmv for all years considered. Fair concentrations for the years in question have been calculated by multiplying the assumed global concentration increase by the fairness factor (Section 5.1). The fairness factors for the different years can be found in Appendix F. The fair concentration decreases with time as it is based on the fairness factor. The fairness factor decreases with time as the Swedish share of the global accumulated population decreases with time.

The results show that the Swedish contribution is fair by 2050 since it is compared to a global concentration of 500 ppmv, which is higher than it probably would be by this year. According to simulations with corresponding emission scenarios the global concentration in 2050 is lower than 500 ppmv CO₂ (Section 5.3.1). By 2100 and 2300 both target levels set for 2100 result in contributions larger than the global average. Thus, the recommended 2.6 tonnes CO₂ per capita is not sufficient (Section 1.3). It could be expected that fair emissions of 0.77 tonnes CO₂ per capita between 2100 and 2300 should lead to fair concentrations. However, the resulting concentrations are higher than the fair level. The reason for this is that the Swedish emissions historically have been larger than the global average. In fact, since the historical emissions are considered, the Swedish emissions would have to be lower than the global average for a long time period for Sweden to reach the fair level. Scenario 5 causes concentrations that are well above the fair level for all years considered.

5.2 Importance of Pathway for Emission Reductions

The 2050-target for Swedish emissions does not consider when and at what rate emission reductions should be made. To investigate the consequences of this and in order to illustrate how the equilibrium concentration responds to different emission scenarios, two simulation sets have been performed. Both simulation sets reach the same emission target by 2050. In one of the simulation sets pathways with different accumulated emissions were studied, while the accumulated emissions were equal in the other simulation set. In both simulation sets global emissions were used as input data to the model. The simulations included the three greenhouse gases that account for the largest emissions, i.e. carbon dioxide, methane and nitrous oxide. The relative ratio between the global emissions of gases in 2000 was assumed to be constant over time.

5.2.1 Same Target - Different Total Emission Amounts

Simulations have been performed with emission pathways meeting a low emission target⁸ set for 2050. How much does the concentration differ if the reductions are distributed differently in time and the total emitted amounts are not equal? Three representative pathways, described in Figure 5.2, were considered.

The results from the simulations are shown in Figure 5.3. Both the maximum and the long-term concentration are higher when the total emitted amount is higher. The concentration peak resulting from emissions following pathway A is due to the sudden emission reductions in 2050. The difference between the maximum concentration and the long-term concentration is larger for pathway A than for the Default pathway. The

⁸ Notice that the target level is different from the actual 2050-target.

results show that the choice of pathway of reaching a specific target and the total accumulated emissions will affect the concentration significantly. Differences in total accumulated emissions before 2050 results in an offset in concentration that remains for hundreds of years.

5.2.2 Same Target – Equal Total Emission Amount

Is there a difference in resulting concentration if we do meet the emission target set for 2050 and emit the same amount of gas but distribute the emission reductions differently in time? Three representative pathways were considered, see Figure 5.4.

The results from the simulations are shown in Figure 5.5. If the amounts of accumulated emissions are equal the pathway of reductions is less important than if the amounts are not equal. The concentrations differ at first due to different emitted amounts but converge to approximately the same value. The different pathways result in small differences in long-term concentrations and the differences decrease over time. The maximum concentrations in the beginning of the simulation are not equal since the total emitted amount differs at this point.

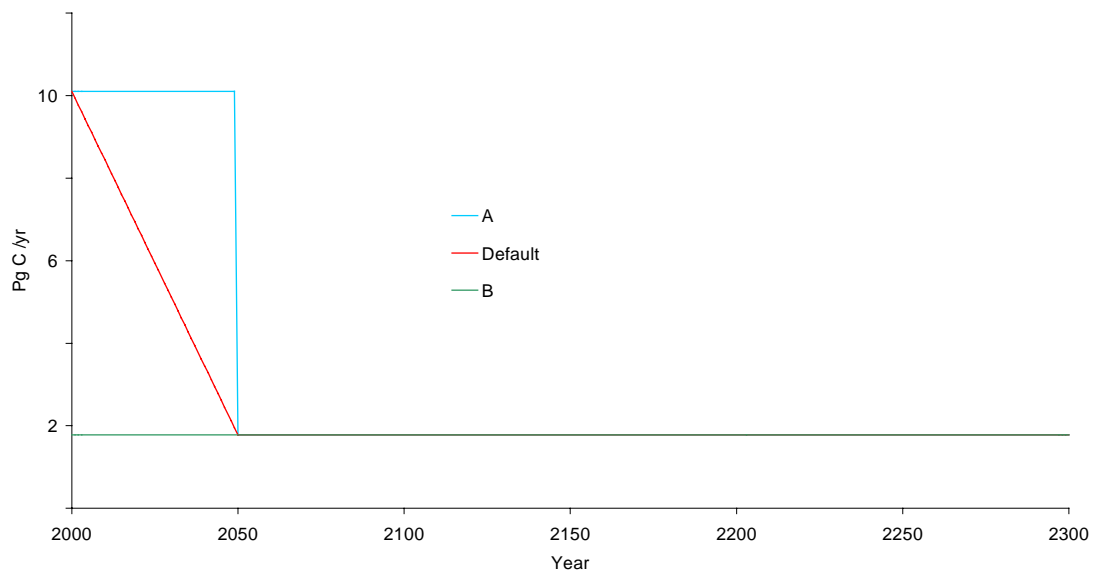


Figure 5.2 Emissions for the simulation set with different amounts of emitted gas but the same target in 2050. **A:** Constant emissions starting on the level of today until 2050 when a low emission target is reached instantaneously. **Default:** Linear reductions from the level of today with the low target level met in 2050. **B:** Immediate reductions from the level of today to the target level.

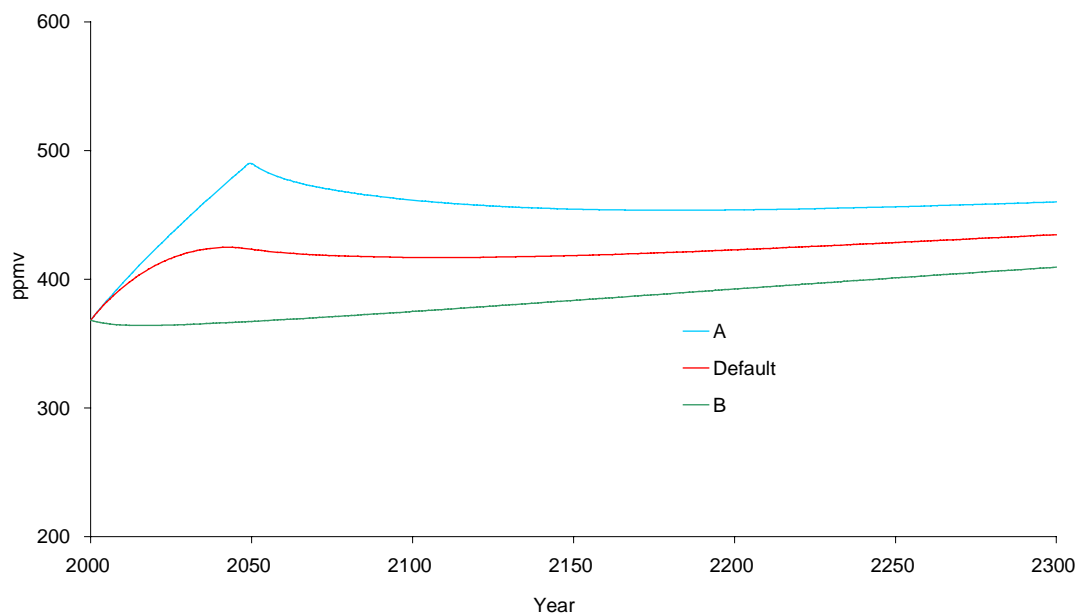


Figure 5.3 Concentrations caused by different emission reduction rates and different total emitted amounts. The gas simulated is carbon dioxide.

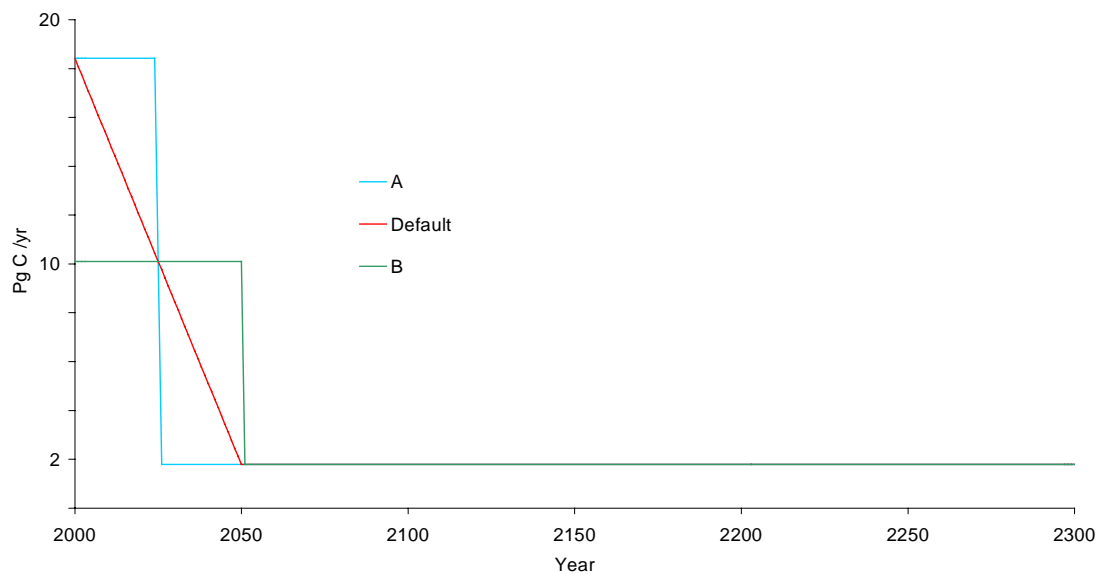


Figure 5.4 Emissions for simulations with equal amounts of emitted gas but emissions distributed differently in time. Today the global emissions are ~ 10 Pg C/yr. **A:** Emissions starting on a high level and are kept constant until 2025 when an immediate reduction to the low target level is carried out. **Default:** Emissions starting on the same high level as in A, with linear reductions until 2050 when the low target level is reached. **B:** Emissions are held constant at the level of today until 2050 when the low target level is met.

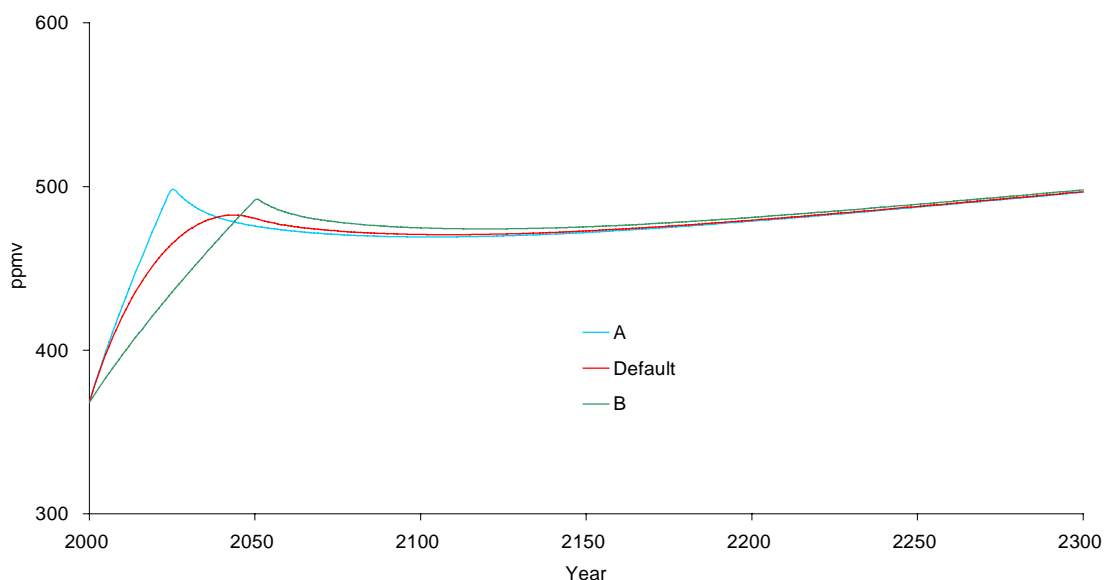


Figure 5.5 Concentrations caused by emission scenarios with different emission reduction rates but equal total emitted amounts. The gas simulated is carbon dioxide.

5.3 Consistency of the Swedish Targets

Two simulation sets with the purpose of further investigating the consistency of the Swedish long-term targets for limited climate impact were performed. In one of the simulation sets both 2050-targets and 2100-targets were set and in the other only emission targets for 2100 were set. The simulations included the three greenhouse gases that account for the largest emissions; carbon dioxide, methane and nitrous oxide. The relative ratio⁹ between the global emissions of gases in 2000 was assumed to be constant over time.

5.3.1 Simulations Meeting 2050- and 2100-targets

Simulations were performed starting at the global emission level of today reaching the Swedish emission target set for 2050. The global emissions in 2050 were calculated by multiplying the per capita emission target by the global population estimated by UN¹⁰ (2002). As recommended by the Ministry of the Environment Sweden (2000) the emissions were thereafter reduced further to reach a constant, preferably sustainable, level by the year of 2100 (Figure 5.6). Different emission targets for 2050 and different final emission levels were tested. Four simulations meeting the 2050-target followed by further reductions were performed. One of these meet the level recommended for 2100 by the Climate Delegation, while the remaining three have even lower emission levels by that year. In the fifth simulation the 2050-emission level was lower than the Swedish target.

Figure 5.7 shows the results from the simulations. All simulations with an emission target of 4.5 tonnes CO₂-equivalents per capita in 2050 exceed the target level. The only scenario that is below the target level during the whole simulation period is the scenario with the emission targets, 4.0 tonnes CO₂-equivalents per capita in 2050 and 1.0 tonnes CO₂-equivalents per capita in 2100. The emission pathway meeting the Swedish 2050-target and the recommended level for 2100 result in a concentration exceeding 550 ppmv before the turn of this century. This is valid assuming the global population to stabilise at 9.3 milliards by 2050. If the population development deviates from this, the figures would have to be adjusted by the same magnitude.

⁹ In 2000 the global emissions of greenhouse gases were 70 % carbon dioxide, 21 % methane and 9 % nitrous oxide.

¹⁰ UN medium Scenario for future population development was used.

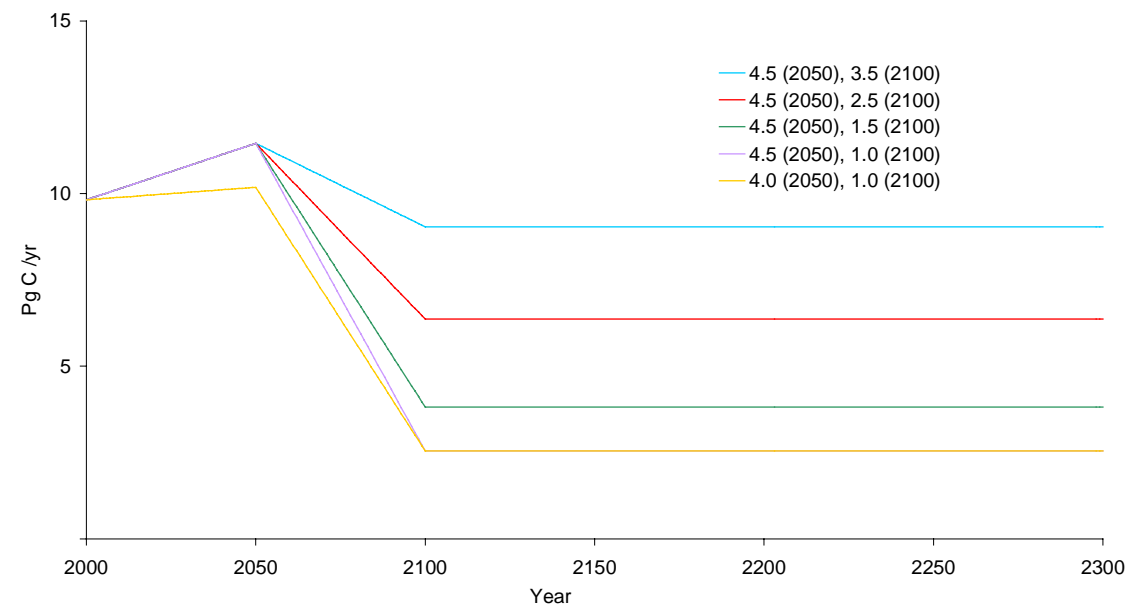


Figure 5.6 Emission pathways with different emission targets for 2050 and 2100. The blue line represents the global emissions according to the Swedish 2050-target and the recommended level for 2100. The emissions are given in CO₂-equivalents.

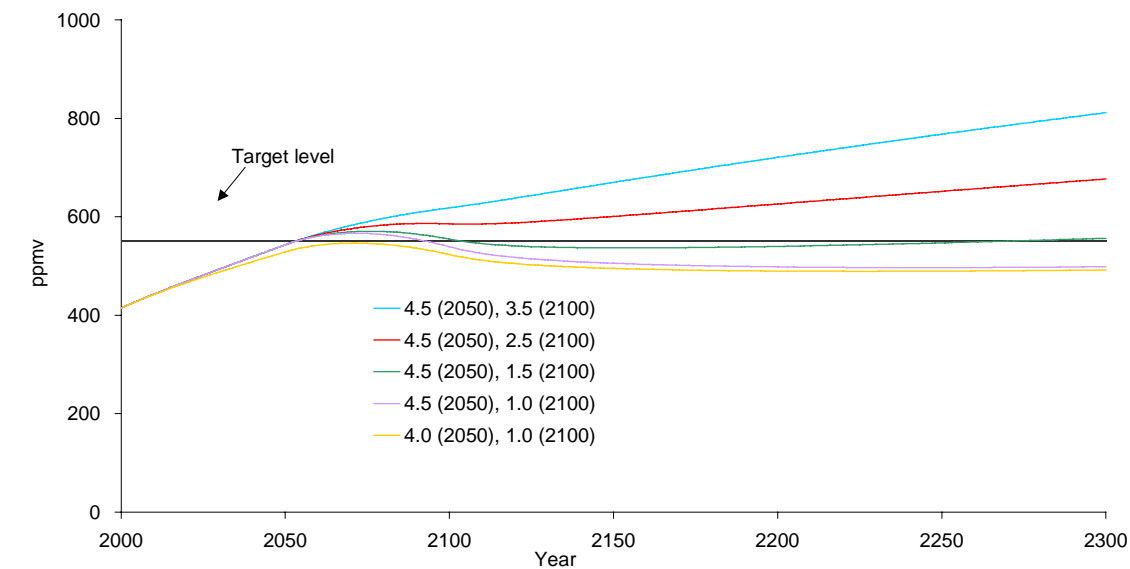


Figure 5.7. Resulting concentrations from simulations with different emission targets in 2050 and 2100. The 550 ppmv target-level is shown. Concentrations are given in CO₂-equivalents.

5.3.2 Simulations Meeting 2100-targets Only

A series of model simulations was performed where the emissions start at the level of today and decrease linearly to different per capita emissions in 2100. Thus, no specific target for 2050 is set. The emission projections are presented in Figure 5.8.

The emission pathways with only a specific target for 2100 result in lower concentrations than the simulations in Section 5.3.1 even when the same target is reached by 2100 (Figure 5.9). This is because the emission pathways without a specific target for 2050 result in lower total emissions. If the emissions are reduced to 2.5 tonnes CO₂-equivalents by 2100 the concentration does not rise above 550 ppmv until shortly after 2100. To reach an equilibrium concentration below 550 ppmv the emissions probably have to be reduced to approximately 1.0-1.5 tonnes CO₂-equivalents per capita.

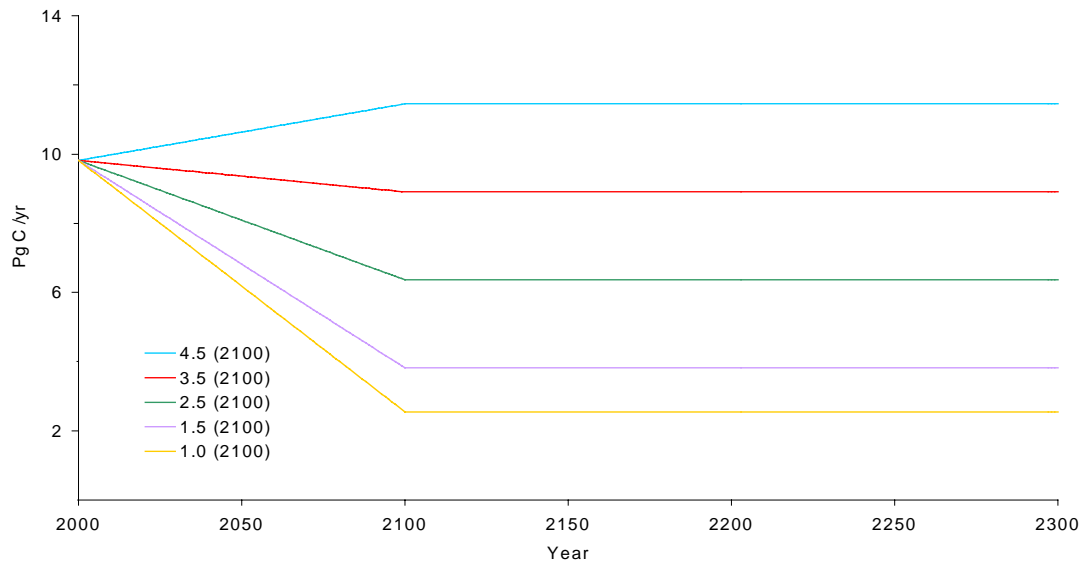


Figure 5.8 Global emissions with reductions to different levels by 2100. No specific targets for 2050 are regarded. The emissions are given in CO₂-equivalents.

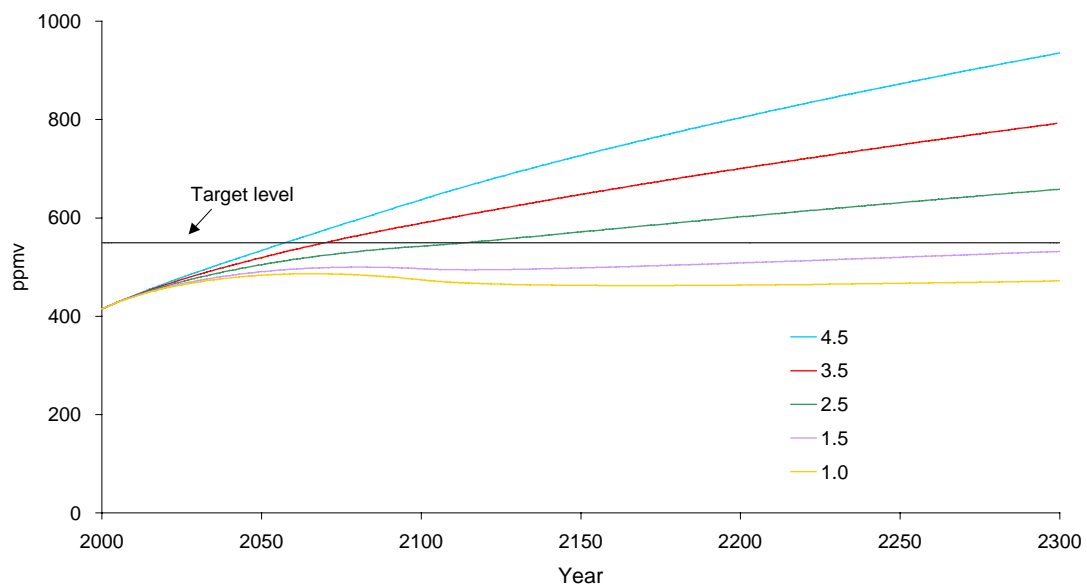


Figure 5.9 Resulting concentrations from the simulations without a specific emission target for 2050. All concentrations are given in CO₂-equivalents.

6 Uncertainties

6.1 The Emission Inventory

It is difficult to estimate all the uncertainties of the emission inventory. The emissions have been estimated using a number of different methods and in most cases several sources have been used for estimating the emissions of each gas. It was not possible to accomplish a complete analysis of uncertainties due to the limited time allocated to this part of the study. For all gases we have used the data given by the Swedish EPA for the years 1990-2000. Interpolation has been used for some sources of the gases methane, nitrous oxide and sulphur hexafluoride to meet the EPA value of 1990. Any uncertainty in the 1990 value will be reflected on earlier years. Since the estimates are based only on larger emission sources, there are also uncertainties caused by the neglecting of smaller sources. The uncertainties of the estimated emissions are larger for earlier years due to increasing uncertainties of statistics and emission factors. The estimates for the 19th century are very uncertain. All results in the inventory of historical emissions, for years earlier than 1990, are uncertain and are to be regarded as probable trends. For uncertainties of both historical and future emissions not directly estimated in this study, please refer to the appropriate reference.

6.2 The Model

The uncertainty of calculated gas concentrations mainly depends on the uncertainty of atmospheric lifetimes. According to Fuglestvedt et al. (2001) the uncertainties of the atmospheric lifetimes are within the range of 10-30 %. The uncertainties of the radiative forcing depend on the uncertainty of both the change in concentrations and background concentrations. An estimate of the uncertainty of the radiative forcing caused by well-mixed greenhouse gases until today is 10 % (Ramaswamy, 2001. Table 6.11). The radiative forcing given in Ramaswamy is calculated using the same equations as in this study, hence the estimate can be applied also on simulations with resulting concentrations close to the present atmospheric concentrations. The validation and comparison with IPCC simulations give an estimate of the total uncertainty of the model (Appendix E).

In this model the atmospheric lifetimes are constants and processes that change the lifetimes are therefore not considered. There are, for example, mechanisms that might alter the uptake of carbon dioxide both to the oceans and to the biosphere and hence change the atmospheric lifetime. Since carbon dioxide is the gas that contributes most to the greenhouse effect and approximately 35 % of the emitted carbon dioxide have an

atmospheric lifetime of 815 years, such changes could have dramatic impact on the atmospheric concentration.

6.3 Impact of Population Development on Results

A source of uncertainty is the assumptions made concerning the Swedish and the global populations. In this study it has been assumed that the global population follow the development according to the UN medium scenario until 2050. Thereafter it has been assumed that the global population stabilises at the 2050-level. If the population development would be different, the per capita emissions concluded to be sufficient in this study would have to be adjusted by the same magnitude. The total global emissions would still be valid and would only have to be divided by the actual population to get revised per capita emissions.

When investigating the Swedish future contribution to the greenhouse effect two different population developments for Sweden until 2050 have been assumed. The UN medium projection and the SCB projection were chosen. As for the global population it has been assumed that the Swedish population thereafter stabilises at the 2050-level. Since the fairness factor is calculated as the ratio between the Swedish and the global population any deviations from the assumptions would affect the results.

7 Discussion

The emissions of greenhouse gases are distributed unevenly between the countries of the world. The industrialised countries are responsible for 80 % of the total accumulated emissions. The Ministry of the Environment Sweden suggests that the differences should be equalled out so that the per capita emissions will be the same in all countries by 2050. We have based our measure of fairness on globally equal per capita emissions given in CO₂-equivalents throughout the study. Of course this definition of fairness could be questioned. Countries have different requirements on energy due to for example different climate and industry. The industrial base of a country is to a large extent determined by the existing natural resources, which vary between countries. Consequently the per capita concept might not be the most effective and fair way to distribute the emissions. A better method would possibly be to determine the per capita emissions for different regions by considering a larger number of parameters. Additionally, a fairer distribution of the emissions might result in more countries being interested in ratifying agreements on reductions.

What is the most appropriate measure for assessing the Swedish contribution to the greenhouse effect? The contribution could be calculated by using emissions, accumulated emissions, concentrations or radiative forcing. The investigation of the Swedish contribution to the greenhouse effect based on emissions could include only the emissions of today or the historical emissions as well. The result presented in Table 5.1 show that for carbon dioxide, there is no significant difference in degree of fairness whether considering the historical emissions or not. For the other two gases the degree of fairness is closer to one if considering only the emissions of today. However, the atmospheric concentration of gases is affected by when emissions are made. It is thus more relevant to compare concentrations than emissions when investigating the Swedish contribution to the greenhouse effect. To determine whether the Swedish contribution is fair or not by using the fairness factor of this study is not optimal. According to the fairness factor the Swedish emissions have to be lower than the global average in order to achieve a fair Swedish contribution in the future. The reason is that the Swedish emissions have been higher than the global average for hundreds of years. We believe that radiative forcing is the best measure to describe the total contribution to the greenhouse effect from several gases. If calculating the total contribution by adding the historical emissions and using the concept of CO₂-equivalents, the decay process of the gases is left out. The relatively low methane emissions compensate for part of the relatively high contribution from carbon dioxide and nitrous oxide. However, the compensation is not large enough to make the Swedish contribution fair.

When simulating the Swedish future contribution to the concentration increase we have assumed the global concentration to equilibrate at 500 ppmv carbon dioxide by the year of 2050. The equilibrium concentration might be higher, which would make the relative Swedish contribution to the global concentration increase smaller and hence fairer. However, to compare with a concentration different to the target level is not relevant since we are investigating the compatibility between the targets.

We have concluded that it is likely that the Swedish 2050-emission target of 4.5 tonnes CO₂-equivalents per capita will result in concentrations close to 550 ppmv. We therefore believe that in accordance with the cautionary principle the emissions should be reduced below 4.0 tonnes CO₂-equivalents per capita by 2050. Allowing the concentration to rise above 550 ppmv even for a short time period may have dramatically effects on the climate system. Threshold effects could cause unfavourable damages on ecosystems. In order to stabilise the atmospheric concentration below 550 ppmv it is of great importance that the emissions will be reduced further after 2050.

The pathway of reaching an emission target is of importance. Delaying the emission reductions will probably result in larger total emission amounts, which will affect the concentration development. Therefore the formulation of an emission target set for a certain year might be insufficient. In Figure 5.3 it can be seen that late reductions cause higher equilibrium concentrations. The target could be more efficient if it included a limitation on maximum accumulated emissions as well as a limitation on yearly emissions.

If we compare the required emission level for 2100 with the historical per capita emissions we can see that the emissions have not been below 1.5 tonnes CO₂-equivalents per capita since sometime before 1830. To reduce the emissions to such levels would request tremendous efforts on development of technology and adjustment of lifestyles. It also has to be taken in to account that the larger reductions already made, the larger efforts are required for further reductions. However, the required reduction rate to reach the Swedish 2050 emission target is about three times slower than the rate of the reduction made since the 1970s. Thus the reduction does not seem to be impossible.

In some of the simulations the concentration seems to stabilise when emissions are kept constant but rises further after a certain time without the emissions being changed. For this reason it is important to simulate for longer time periods. This effect is obvious in the B1 simulation in Appendix E.

In neither of the simulations all greenhouse gases are included and some of them probably have considerable impact on the radiative forcing. Three of the Kyoto gases (PFCs, HFCs and SF₆) are excluded in the simulations as their contribution until today

is marginal. In the future it is likely that these gases will represent a larger share of the total emissions and therefore will be of greater importance. Simulating with all Kyoto gases could give a different result and the emissions might have to be reduced even further to meet the long-term concentration target.

There are greenhouse gases not included in the Kyoto Protocol that affects the climate. The ozone depleting greenhouse gases CFCs and HCFCs are regulated by the Montreal Protocol and are under the process of being phased out globally; however they still contribute to the greenhouse effect. This contribution will continue for a substantial time period. Ozone is another important greenhouse gas with two different effects on radiative forcing. Roughly, the depletion of stratospheric ozone results in a negative radiative forcing while the increase in concentration of tropospheric ozone results in a positive radiative forcing. It would not have been possible to consider ozone in our simple model since the atmospheric lifetime is short and the gas therefore is unevenly distributed in the atmosphere. International bunkers are not included in the national emission reports and are today responsible for about 5 % of the global emissions. Land use change and forestry, LUCF, could be either a source or a sink of carbon dioxide. Neither of these sources is included in the emission targets of the Kyoto Protocol nor in the Swedish emission target. Therefore they were not considered in our simulations. However, all these sources have consequences on the greenhouse effect and should be regarded when determining per capita emission targets.

8 Conclusions

According to the emission inventory including the greenhouse gases regulated by the Kyoto Protocol, carbon dioxide is the dominating gas. Methane and nitrous oxide together represent about 20 % of the Swedish emissions. The two gases are of approximately the same magnitude when given in CO₂-equivalents. The remaining gases contribute marginally to the emissions.

The Swedish emissions of carbon dioxide and nitrous oxide are above the fair level whereas the methane emissions are below the global average. The same result is valid for the Swedish contribution to the concentration increase. The total Swedish contribution to the greenhouse effect, including carbon dioxide, methane and nitrous oxide, is about 30 % above the fair level. However, we believe that the concept of equal per capita emissions is insufficient to describe the concept of fairness. More complex parameters are required to describe this concept.

Given a specific yearly emission target, in this case for the year 2050, the choice of pathway will be of importance. Emission reductions performed at an early stage, thus leading to smaller amounts of accumulated emissions, will result in a lower equilibrium concentration. If the total emitted amounts are equal, earlier reductions result in a lower maximum concentration but the same equilibrium concentration.

A per capita emission target for a certain year is not sufficient to assure that a specific concentration level is not exceeded. A target including both a maximum of accumulated emissions and a maximum of yearly emissions would be required.

From this study we can conclude that the emission target for 2050 is consistent with the long-term concentration target. However, further reductions after 2050 will be required to reach an equilibrium concentration below 550 ppmv. Which target that is set for 2050 is not crucial; it is the long-term reductions that are most important. The suggested emission level of 3.5 tonnes CO₂-equivalents for 2100 is too high, the required level would be 1.0-1.5 tonnes CO₂-equivalents per capita. The Swedish per capita emissions have not been at a level of 1.5 tonnes CO₂-equivalents since the beginning of the 1850s.

Finally we have learned that the Powersim model used in this project successfully simulates atmospheric concentrations due to emissions of greenhouse gases.

9 Acknowledgements

We would like to thank a number of persons that have been very important for the completion of this thesis project. Firstly, we would like to give our gratitude to our supervisor Lars Zetterberg that has guided us throughout the process. Without the assistance of Håkan Staaf and Stig Handå, parts of the emission inventory had been much more difficult to perform. We are grateful for Sara & Dean who have helped us to improve our English. We would also like to express our appreciation for the support from our examiner Conny Larsson and the advices given by our opponent Kerstin Strand. We are happy that so many friends listened to our presentation. Thank you also to Magnus & Welinton for always being there for us. Finally, we would also like to give each other special thanks for the fruitful collaboration.

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Appendix A

Gas properties

Table A.1 Properties of the Kyoto greenhouse gases emitted in Sweden. The Global Warming Potentials given in this table are valid for the time horizon (TH) 100 years. Source: Boucher et al. 2001, Table 6.7 & Table 6.1.

Gas	Atmospheric lifetime [yr]	GWP TH = 100 years	α , radiative efficiency [W/m ² ppbv]	Pre-industrial concentration
CO ₂	see Section 4	1		278 ppmv
CH ₄	12	23		700 ppbv
N ₂ O	114	296		270 ppbv
HFC-23	260	12000	0.16	0
HFC-32	5	550	0.09	0
HFC-125	29	3400	0.23	0
HFC-134a	13.8	1300	0.15	0
HFC-143a	52	4300	0.13	0
HFC-152a	1.4	120	0.09	0
CF ₄	50000	5700	0.08	40 pptv
C ₂ F ₆	10000	11900	0.26	0
SF ₆	3200	22200	0.52	0

Appendix B

Emission Inventory of Methane and Nitrous oxide

Emissions from the different emission sources of methane and nitrous oxide used in this study can be found in Figure B.1 and Figure B.2 respectively.

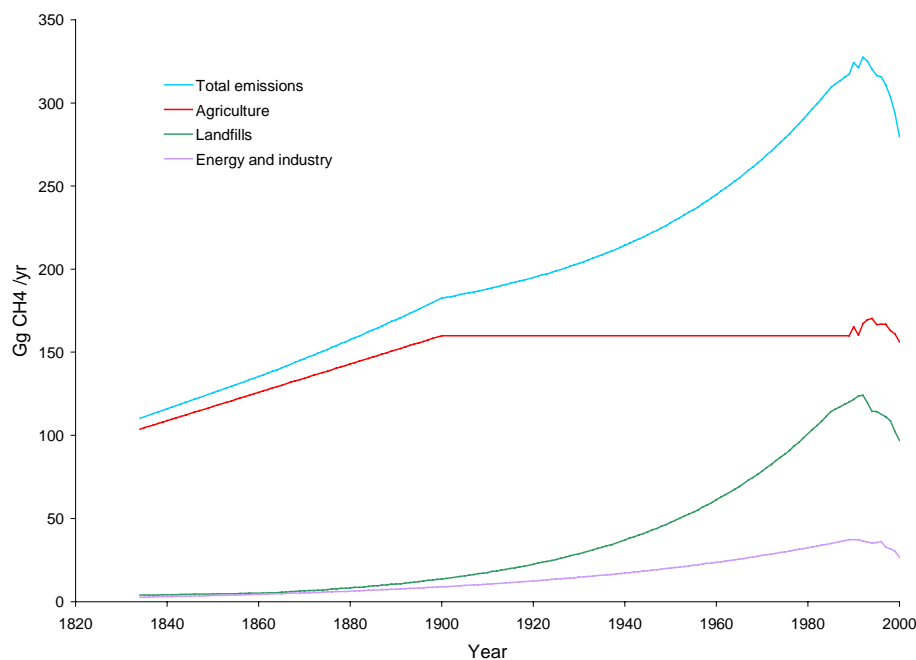


Figure B.1 Methane emissions 1834-2000 for the different sources considered in this study. Total emissions for the same time period are also included in the figure.

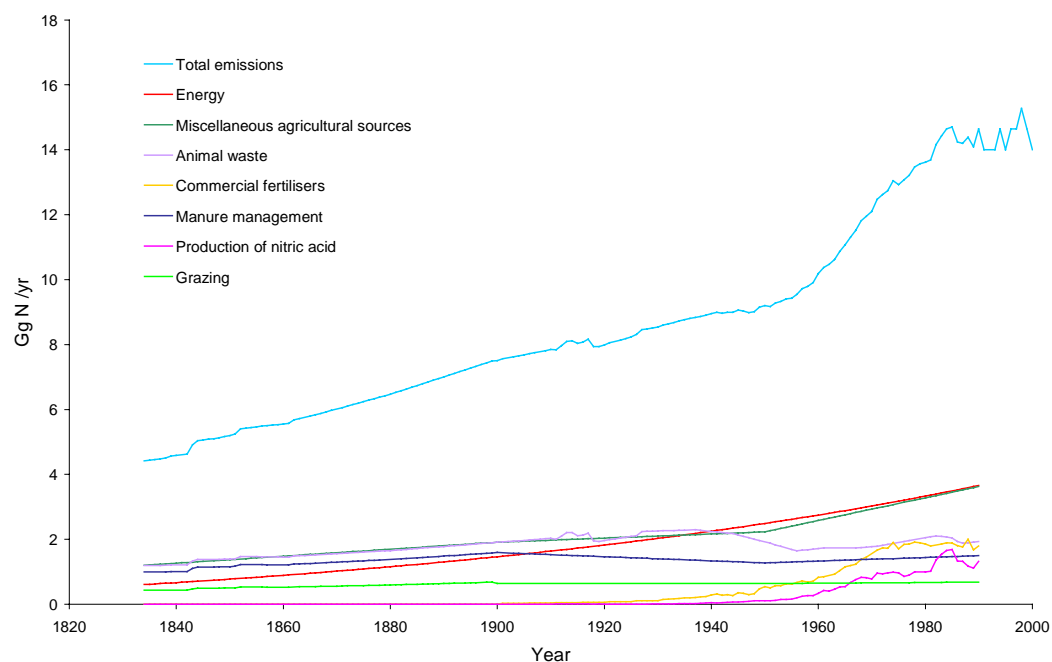


Figure B.2 Nitrous oxide emissions 1834-1990 for the different sources considered in this study. The total emissions are given for 1834-2000.

Appendix C

The Model

The graphical interface of Powersim Studio 2001 makes the model easy to comprehend. The structure of the model is given by the model diagram (Figure C.1 and Figure C.2). In Figure C.1, the diagram of the concentration calculations is given. The parameter called "Scenario" is a variable parameter given one of nine values selected by the user. The choice is made by clicking one of the buttons in the table "Scenario Choice". Each one of the scenarios is connected to a MS Excel Worksheet with emission data series. The model imports the data chosen with one value in each time step. The parameter called "Amount of GHG" represents the total amount of greenhouse gases in the atmosphere. The inflow to this parameter is the emissions and the outflow is governed by the parameter "Gas Depletion", Equation 2.1, where the decay of each gas is determined by its atmospheric lifetime. The parameter "Initial amount" is described in Section 4. The change in concentration is calculated by the factor called "Delta C" and is then added to the pre-industrial concentration in "Tot conc". The diagram of the calculations of radiative forcing is given in Figure C.2. The model calculations follow the equations given in this appendix.

The results given by the model are the total concentrations and the radiative forcing of each gas. The parameters; "Tot conc", "RF_CO2", "RF_X", "RF_CH4" and "RF_N2O" export these results to a MS Excel Workbook which can be viewed by the user after each simulation.

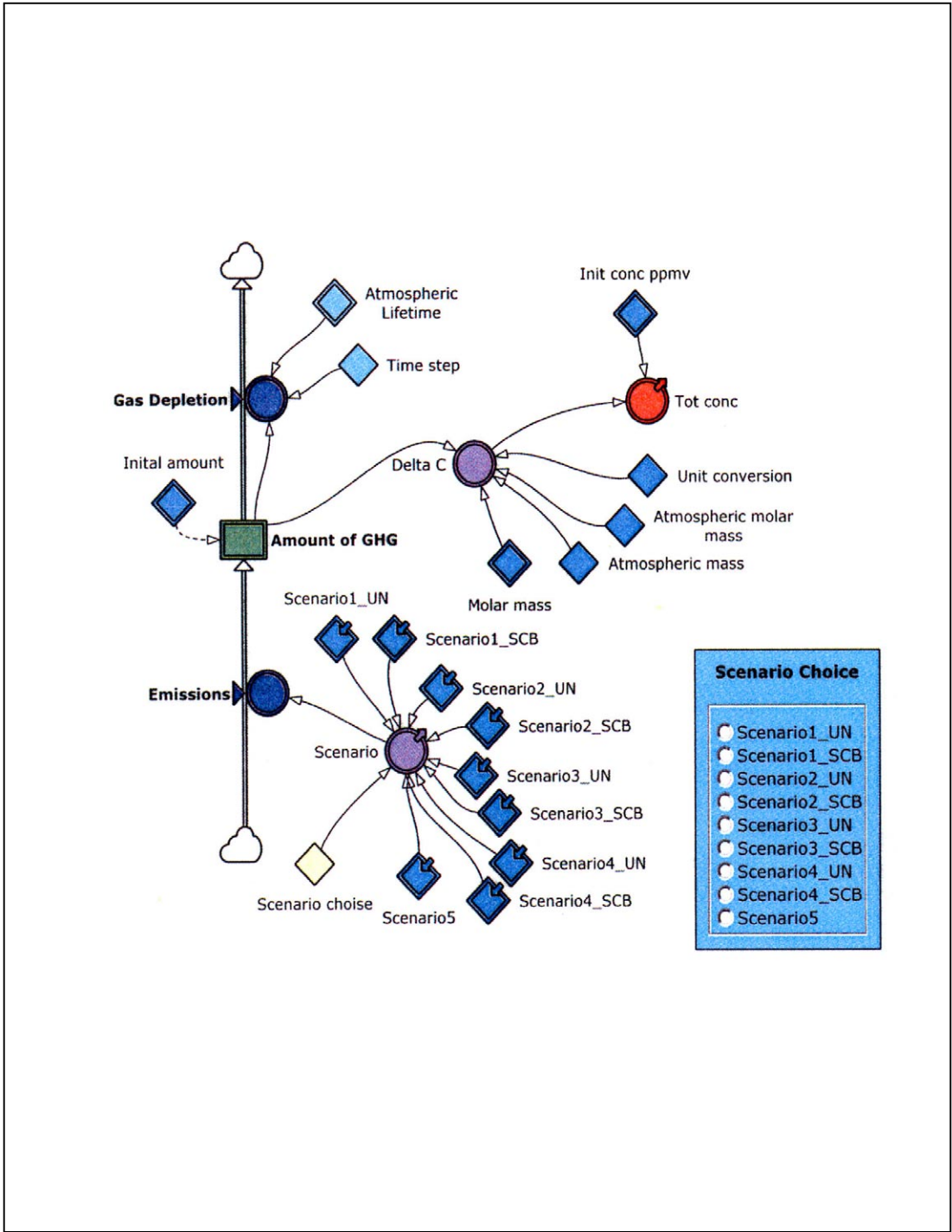


Figure C.1 This model diagram represents the part of the model that simulates concentrations.

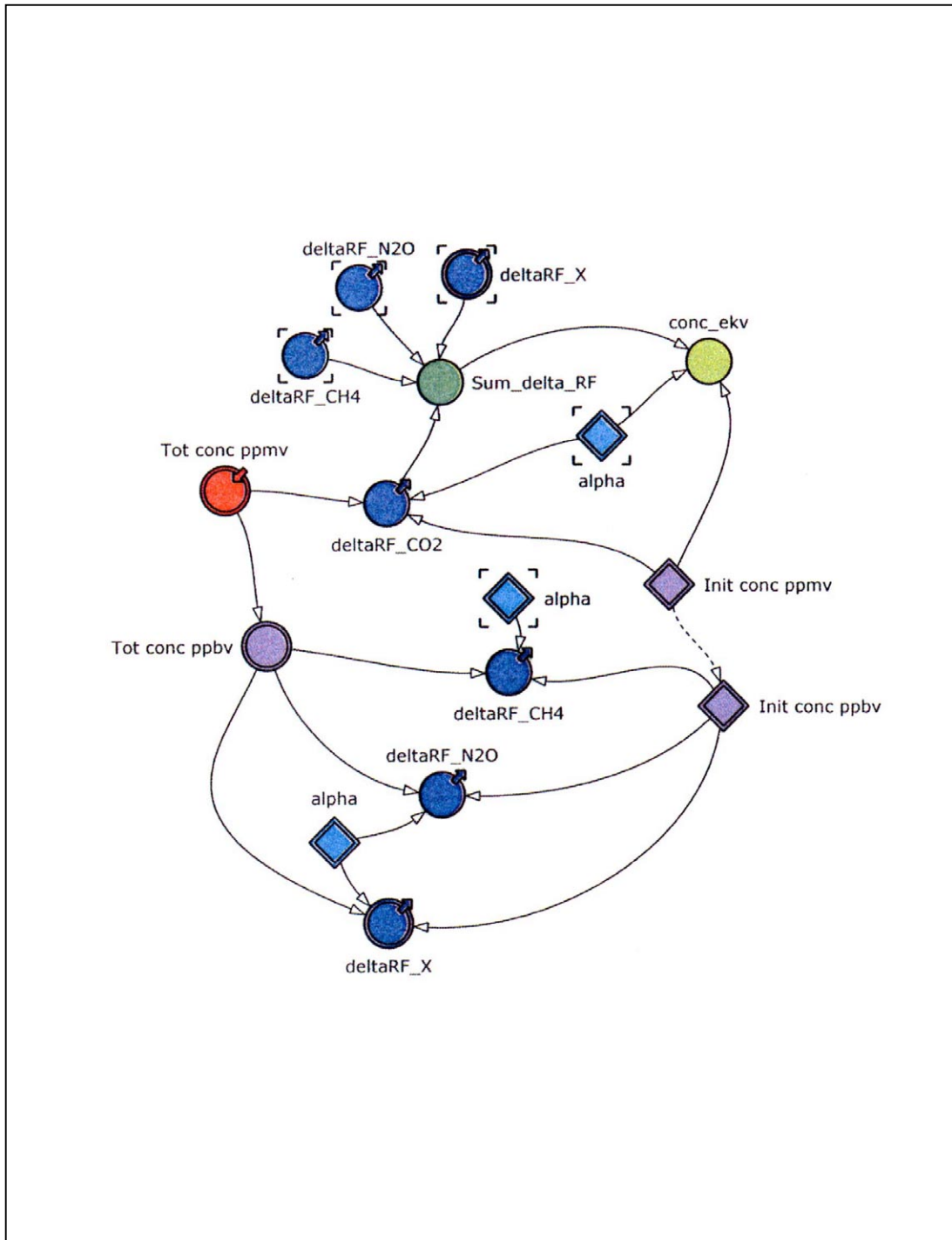


Figure C.2 This model diagram represents the part of the model that calculates radiative forcing and the concentration given in CO₂-equivalents.

```

mainmodel Component 1 {
  const alpha {
    autotype Real
    dim 1..12
    init {5,35;0,036;0,12;0,16;0,09;0,23;0,15;0,13;0,09;0,08;0,26;0,52}
  }
  level Amount of GHG {
    autotype Real
    unit kton
    dim 1..14
    init 'Initial amount'
    inflow { autodef Emissions }
    outflow { autodef 'Gas Depletion' }
  }
  const Atmospheric Lifetime {
    autotype Real
    unit yr
    dim 1..14
    init {6,993;71,109;815,727;12;114;260;5;29;13,8;52;1,4;50000;10000;3200}
  }
  const Atmospheric mass {
    autotype Real
    unit kg
    init 5,136e18
  }
  const Atmospheric molar mass {
    autotype Real
    unit M
    init 28,96
  }
  aux conc_ekv {
    autotype Real
    def ('Init conc ppmv'[1]+'Init conc ppmv'[2]+'Init conc ppmv'[3])*EXP(Sum_delta_RF/alpha[1])
  }
  aux Delta C {
    autotype Real
    unit ppmv
    dim 1..14
    def ('Amount of GHG'*Unit conversion/'Molar mass')/('Atmospheric mass'/'Atmospheric molar mass')*1e6
  }
  aux deltaRF_CH4 {
    autotype Real
    def alpha[2]*(SQRT('Tot conc ppbv'[2])-SQRT('Init conc ppbv'[2]))-
      (((0,47*LN(1+2,01e-5*(Tot conc ppbv'[2]*Init conc ppbv'[3])^0,75+
        5,31e-15*Tot conc ppbv'[2]*(Tot conc ppbv'[2]*
        'Init conc ppbv'[3])^1,52))-(0,47*LN(1+2,01e-5*
        ('Init conc ppbv'[2]*Init conc ppbv'[3])^0,75+5,31e-15*Init conc ppbv'[2]*('Init conc ppbv'[2]*Init conc ppbv'[3])^1,52))))
  }
  aux deltaRF_CO2 {

```

```

autotype Real
def alpha[1]*LN(('Tot conc ppmv'[1])/('Init conc ppmv'[1]))
}
aux deltaRF_N2O {
  autotype Real
  def alpha[3]*(SQRT('Tot conc ppbv'[3])-SQRT('Init conc ppbv'[3]))-
    ((0,47*LN(1+2,01e-5*('Tot conc ppbv'[3]*'Init conc ppbv'[2])^0,75+
    5,31e-15*'Tot conc ppbv'[3]*('Tot conc ppbv'[3]*
    'Init conc ppbv'[2])^1,52))-(0,47*LN(1+2,01e-5*
    ('Init conc ppbv'[2]*'Init conc ppbv'[3])^0,75+5,31e-15*
    'Init conc ppbv'[3]*('Init conc ppbv'[2]*'Init conc ppbv'[3])^1,52)))
}
aux deltaRF_X {
  autotype Real
  dim 1..9
  def {alpha[4]*('Tot conc ppbv'[4]-'Init conc ppbv'[4]);
    alpha[5]*('Tot conc ppbv'[5]-'Init conc ppbv'[5]);
    alpha[6]*('Tot conc ppbv'[6]-'Init conc ppbv'[6]);
    alpha[7]*('Tot conc ppbv'[7]-'Init conc ppbv'[7]);
    alpha[8]*('Tot conc ppbv'[8]-'Init conc ppbv'[8]);
    alpha[9]*('Tot conc ppbv'[11]-'Init conc ppbv'[9]);
    alpha[10]*('Tot conc ppbv'[10]-'Init conc ppbv'[10]);
    alpha[11]*('Tot conc ppbv'[11]-'Init conc ppbv'[11]);
    alpha[12]*('Tot conc ppbv'[12]-'Init conc ppbv'[12])}
}
aux Emissions {
  autotype Real
  unit kton/yr
  dim 1..14
  def Scenario
}
aux Gas Depletion {
  autotype Real
  unit kton/yr
  autodim 1..14
  def 'Amount of GHG'*(1-EXP(-'Time step'/'Atmospheric Lifetime'))/'Time step'
}
const Init conc ppbv {
  autotype Real
  autodim 1..12
  Init 'Init conc ppmv'*1000
}
const Init conc ppmv {
  autotype Real
  dim 1..12
  Init {278;0,700;0,270;0;0;0;0;0;0,00004;0;0}
}
const Inital amount {
  autotype Real
  unit kton

```

```

dim 1..14
init {5,12626184e7;2,2005805828e8;3,2117425224e8;2,6895762714e6;3,0968761098e5;9,9335305061e1;
0;0;0;0;1,0542628183;4,6822443315e2;70,3428909613;56,985423912}
}
const Molar mass {
  type Real
  unit M
  dim 1..14
  init {43,9992;43,9992;43,9992;16,04308;44,0074;70,01437;41,02071;120,02237;102,03194;84,04151;66,
05108;88,0048;138,0128;146,0544}
}
aux Scenario {
  autotype Real
  unit kton/yr
  dim 1..14
  def {Scenario1_UN;Scenario1_SCB;Scenario2_UN;Scenario2_SCB;Scenario3_UN;Scenario3_SCB;
Scenario4_UN;Scenario4_SCB;Scenario5}[INDEX('Scenario choise')]
}
const Scenario choise {
  type Integer
  init 0
}
const Scenario1_SCB {
  autotype Real
  unit kton/yr
  dim 1..14
  init 0
}
const Scenario1_UN {
  autotype Real
  unit kton/yr
  dim 1..14
  init 0
}
const Scenario2_SCB {
  autotype Real
  unit kton/yr
  dim 1..14
  init 0
}
const Scenario2_UN {
  autotype Real
  unit kton/yr
  dim 1..14
  init 0
}
const Scenario3_SCB {
  type Real
  unit kton/yr
  dim 1..14

```

```

    Init 0
}
const Scenario3_UN {
    type Real
    unit kton/yr
    dim 1..14
    init 0
}
const Scenario4_SCB {
    autotype Real
    unit kton/yr
    dim 1..14
    init 0
}
const Scenario4_UN {
    autotype Real
    unit kton/yr
    dim 1..14
    init 0
}
const Scenario5 {
    type Real
    unit kton/yr
    dim 1..14
    init 0
}
aux Sum_delta_RF {
    autotype Real
    def deltaRF_CO2+deltaRF_N2O+deltaRF_CH4+deltaRF_X[1]+deltaRF_X[2]+deltaRF_X[3]+deltaRF_X[4]+
        deltaRF_X[5]+deltaRF_X[6]+deltaRF_X[7]+deltaRF_X[8]+deltaRF_X[9]
}
const Time step {
    autotype Real
    unit yr
    init 1
}
aux Tot conc {
    autotype Real
    dim 1..12
    def {'Delta C'[1]+'Delta C'[2]+'Delta C'[3]+'Init conc ppmv'[1];
        'Delta C'[4]+'Init conc ppmv'[2];
        'Delta C'[5]+'Init conc ppmv'[3];
        'Delta C'[6]+'Init conc ppmv'[4];
        'Delta C'[7]+'Init conc ppmv'[5];
        'Delta C'[8]+'Init conc ppmv'[6];
        'Delta C'[9]+'Init conc ppmv'[7];
        'Delta C'[10]+'Init conc ppmv'[8];
        'Delta C'[11]+'Init conc ppmv'[9];
        'Delta C'[12]+'Init conc ppmv'[10];
        'Delta C'[13]+'Init conc ppmv'[11];
    }
}

```

```

        {'Delta C'[1]+'Delta C'[2]+'Delta C
    }
    aux Tot conc ppbv {
        autotype Real
        autodim 1..12
        def 'Tot conc ppmv'*1000
    }
    aux Tot conc ppmv {
        autotype Real
        dim 1..12
        def 0
    }
    const Unit conversion {
        autotype Real
        unit kg/kton
        init 1e6
    }
}
unit g {
    def kg/1000
}
unit kg {
    def ATOMIC
}
unit kton {
    def 1e6*kg
}
unit m {
    def ATOMIC
}
unit M {
    def g/mole
}
unit m3 {
    def m*m*m
}
unit mole {
    def ATOMIC
}
unit ppmv {
    def m3/m3
}

```

Appendix D

Choice of Time Step and Integration Method

In order to select the most appropriate integration method and time step, simulations were performed with the purpose of investigating the sensitivity of those parameters. Concentrations of carbon dioxide due to historical emissions of carbon dioxide were simulated and compared to measured atmospheric concentrations. Simulations were performed with four different combinations of integration methods and time steps, testing the Runge-Kutta, 4th order, and the Euler integration methods along with the time step of one year or one month.

As can be seen in the Tables D.1 and D.2 the results differ very little between the different setups. No difference in relative error was observed between the simulations performed with the Runge-Kutta and the Euler integration method with the time step of one month. The only difference noticed was that simulations performed with the Euler method were faster. A slight difference was noted between the methods when simulating with a time step of one year. For some years the Runge-Kutta seemed to result in lower relative errors. Therefore the integration method chosen was Runge-Kutta and a time step of one year.

Table D.1 Carbon dioxide concentrations simulated with Runge-Kutta, 4th order, integration method. The concentrations are compared to measured atmospheric concentrations.

Time step		1 year		1 month	
Year	Estimated or measured concentration ¹¹ [ppmv]	Simulated concentration [ppmv]	Relative error [%]	Simulated concentration [ppmv]	Relative error [%]
1900	298	289	3.0	289	3.0
1925	303	295	2.6	295	2.6
1960	316	309	2.2	309	2.2
1970	325	319	1.8	319	1.8
1980	338	334	1.2	334	1.2
1990	354	349	1.4	350	1.1

Table D.2 Carbon dioxide concentrations simulated with Euler integration method. The concentrations are compared to measured atmospheric concentrations.

Time step		1 year		1 month	
Year	Estimated or measured concentration ¹¹ [ppmv]	Simulated concentration [ppmv]	Relative error [%]	Simulated concentration [ppmv]	Relative error [%]
1900	298	289	3.0	289	3.0
1925	303	295	2.6	295	2.6
1960	316	309	2.2	309	2.2
1970	325	318	2.2	319	1.8
1980	338	333	1.5	334	1.2
1990	354	349	1.4	350	1.1

¹¹ The measured values were obtained from [http://www.rivm.nl/env/int/hyde/aos_ghg_conc.html] and IPCC 2001.

Appendix E

Model Validation

The model was validated for concentration calculations for carbon dioxide, methane and nitrous oxide (Equations 2.1 and 4.1). To validate the model the most appropriate method was to compare model results, based on historical global emission data, with actual measured atmospheric concentrations. It was not possible to validate from 1750 since the available global historical emission data starts in the 1850s. The validation was therefore initiated in 1860 for carbon dioxide and methane and in 1890 for nitrous oxide. The results from the validation can be seen in tables E.1, E.2 and E.3.

Table E.1 Validation of carbon dioxide. Emission data was obtained from Marland & Boden (2002) and Houghton (1999).

Year	Measured concentration ¹² [ppmv]	Simulated concentration [ppmv]	Relative error [%]
1860	288	285	1.2
1900	298	287	3.7
1950	311	300	3.6
1960	316	306	3.2
1970	325	316	2.8
1980	338	330	2.2
1998	354	346	3.1

¹² The values of the measured concentrations were obtained from
[http://www.rivm.nl/env/int/hyde/aos_ghg_conc.html] and IPCC 2001.

Table E.2 Validation of methane. Emission data was obtained from Edgar-Hyde 1.4 (2001).

Year	Measured concentration¹³ [ppbv]	Model concentration [ppbv]	Relative error [%]
1900	974	1017	4.4
1960	1272	1402	10.2
1970	1421	1550	9.1
1980	1569	1719	9.6
1992	1714	1887	10.1

Table E.3 Validation of nitrous oxide. Emission data was obtained from Edgar-Hyde 1.4 (2001) .

Year	Measured concentration¹³ [ppmv]	Model concentration [ppmv]	Relative error [%]
1900	292	290	0.7
1960	293	296	1.2
1970	299	302	1.1
1980	303	311	2.8
1992	311	323	3.7

The reason for not validating for all gases implemented in the model was the lack of global emission data and measured atmospheric concentrations. Since the relative contribution of those gases to the total greenhouse effect is small, it was considered to be of less importance. Note that this is not a regular validation since there are uncertainties in the input data. Therefore the model was not calibrated according to the results. However, the results have been used for estimating the uncertainty of simulated concentrations. An approximate value of the uncertainty of simulated concentrations around 550 ppmv CO₂-equivalents, including carbon dioxide, methane and nitrous oxide, is ± 30 ppmv.

The reliability of the model was also investigated by comparing model results with the results of other models using the same input data. Comparisons with simulations of the

¹³ The values of the measured concentrations were obtained from
[http://www.rivm.nl/env/int/hyde/aos_ghg_conc.html] and IPCC 2001.

Illustrative Marker Scenario B1, described in the IPCC 2001, for carbon dioxide only were carried out. The differences between our Powersim model and two other models, the Bern-CC and the ISAM model presented in the IPCC (2001) are shown in Figure E.1. The input data for the Powersim model was extended until 2300 and the emissions were held at a constant level from 2100 until 2300.

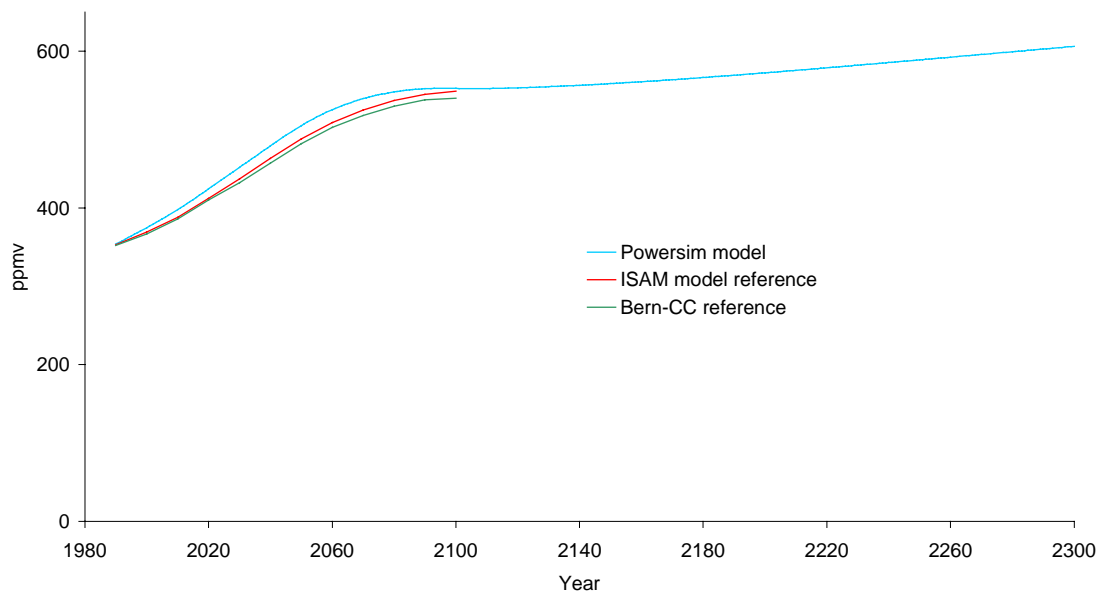


Figure E.1 Comparison between Powersim model and two other models, the Bern-CC and the ISAM model (IPCC, 2001). All models have simulated the concentrations of carbon dioxide due to the emissions given by the Illustrative Marker Scenario B1.

Appendix F

Future Contribution to Global Concentrations

The results of simulating the Swedish future contribution to the global enhancement of greenhouse gas concentrations are presented in Table F.1 and F.2. The tables include the Swedish future concentration increase for the nine scenarios presented in Section 3.3. The minimum value in the stated interval is the result when using UN population development while the maximum value is the result when using SCB development. The relation between the total accumulated population in Sweden and the world for the different years, the fairness factor, is also presented in the table, see designation F. A fair concentration for the years in question has been calculated by multiplying the global concentration increase by the fairness factor. The global concentration has been assumed to be 500 ppmv for all years. The results from reducing the emissions to a level of 3.4 tonnes CO₂ per capita in 2050 and 2.6 tonnes CO₂ per capita in 2100 are shown in Table F.1. The results from reducing to a level of 3.4 tonnes CO₂ per capita in 2050 and 0.77 tonnes CO₂ per capita in 2100 are shown in Table F.2.

Table F.1 The table shows Swedish future concentrations for different scenarios, given in ppmv. The target for 2050 is 3.4 tonnes CO₂ per capita and for 2100 the target is 2.6 tonnes CO₂ per capita. The lower value in the intervals is the result from the UN scenarios and the higher from the SCB scenarios. The fair concentration is based on a global concentration of 500 ppmv carbon dioxide. The fairness factor used for calculating the fair concentration is designated by F.

Year	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	F	Fair conc.
2050	0.39-0.40	0.40-0.41	0.41-0.43	0.42-0.43	0.48	0.18-0.19	0.40-0.42
2100	0.40-0.43	0.40-0.44	0.42-0.45	0.42-0.46	0.64	0.15-0.16	0.33-0.36
2300	0.47-0.55	0.47-0.55	0.48-0.56	0.48-0.56	1.10	0.11-0.13	0.24-0.29

Table F.2 The table shows Swedish future concentrations for different scenarios, given in ppmv. The target for 2050 is 3.4 tonnes CO₂ per capita and for 2100 the target is 0.77 tonnes CO₂ per capita. The lower value in the intervals is the result from the UN scenarios and the higher from the SCB scenarios. The fair concentration is based on a global concentration of 500 ppmv carbon dioxide. The fairness factor used for calculating the fair concentration is designated by F.

Year	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	F	Fair conc.
2050	0.39-0.40	0.40-0.41	0.41-0.43	0.42-0.43	0.48	0.18-0.19	0.40-0.42
2100	0.36-0.39	0.37-0.40	0.38-0.41	0.39-0.42	0.64	0.15-0.16	0.33-0.36
2300	0.29-0.32	0.30-0.33	0.30-0.33	0.31-0.34	1.10	0.11-0.13	0.24-0.29



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