The complexity of climate change mechanisms

- aspects to be considered in abatement strategy planning

PATHWAYS TO SUSTAINABLE EUROPEAN ENERGY SYSTEMS
and
NORDIC ENERGY PERSPECTIVES

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PATHWAYS TO SUSTAINABLE EUROPEAN ENERGY SYSTEMS

AGS, THE ALLIANCE FOR GLOBAL SUSTAINABILITY

and

NORDIC ENERGY PERSPECTIVES

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SUMMARY

During the last decades there has been a growing concern of a changed climate due to anthropogenic emissions of greenhouse gases (GHG) to the atmosphere. Climate models indicate how emissions interfere with climate processes and which temperature rise different emission scenarios may lead to. Through a literature survey, it has been our intention to single out some of the findings on the interaction between emissions of greenhouse gases and global radiative forcing, as well as on how the carbon and nitrogen cycles interfere with concentrations in the atmosphere and in what ways cost-effective abatement measures of greenhouse gases could be made. The focus in this respect has been on non-carbon dioxide greenhouse gases. The aspects dealt with in the report are summarised below.

The complexity of the climate system

- The Earth's climate system is a complex, interconnected system formed by the atmosphere, the oceans and other bodies of water, land surface, snow and ice cover together with all living organisms, and linked by flows of energy and matter.

- The carbon and nitrogen cycles are interwoven and influence the amount of carbon dioxide (CO_2), methane (CH_4) and nitrious oxide (N_2O) in the atmosphere, thus playing a part in climate change. There are however still many open questions on how these cycles interact with each other and what the implications of these interactions might be.

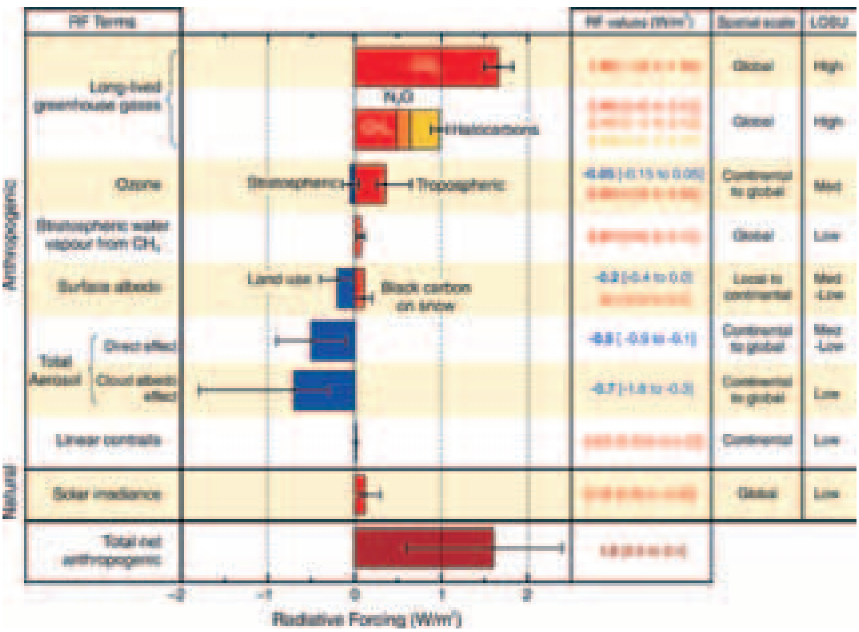
Atmospheric constituents and their effect on the climate

- Changes in the Earth's climate are influenced mainly by changes in the atmospheric composition of gases and particles, but also by changes in solar radiation and surface albedo. The most important component to influence the atmosphere is CO_2, which stands for 70 % of the global warming potential in the atmosphere.

- Other gases of great importance are long-lived gases like CH_4 (20 %), N_2O (5 %) and fluor-containing gases like HFCs, PFCs and SF_6 (5 %). All act on a global scale.

- Other more short-lived components in the atmosphere are water vapour (obvious climate effect on a daily basis), tropospheric ozone, and particles. The dispersion of these short-lived components is more regional, which also is true for their climate effect.

- The present level of scientific understanding is high regarding the radiative forcing of CO_2 and the other long-lived greenhouse gases. However, the total effect of particles and aerosols as well as changes in surface albedo and solar irradiance is less well known. The total uncertainty in radiative forcing caused by anthropogenic impact is more than ±50 %.



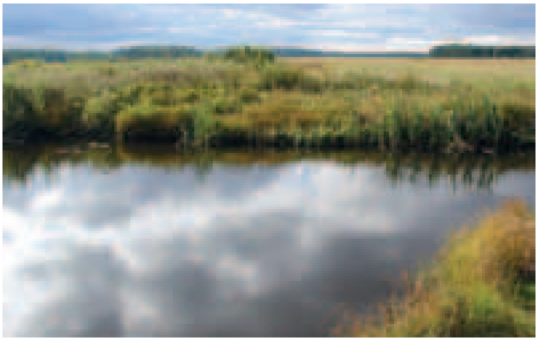
The figure shows the radiative forcing effect, together with the typical geographical extent (the spacial scale) and the assessed level of scientific understanding (LOSU), of different anthropogenic and natural parameters. The different parameters are shown as having either a cooling (a negative RF-value) or a warming (a positive RF-value) effect.
Source: IPCC (2007c)

Sources and sinks of non-CO_2 greenhouse gases

- Major sources of non-CO_2 greenhouse gas emissions are energy supply and use, agriculture, industrial processes and waste management.
- The estimates are for some sources (such as emissions from the LULUCF sector) and components (such as N_2O) connected with considerable uncertainties.
- Also for sinks, the atmospheric depletion of for example N_2O is still uncertain. The depletion of N_2O is linked to that of stratospheric ozone.
- Of the fluor-containing gases, most components are very stable and are only very slowly decomposed in the atmosphere.
- The estimates of total emissions of carbon dioxide are significantly better known than the emissions of CH_4 and N_2O.

Abatement measures and mitigation potentials for non-CO_2 greenhouse gas emissions

- Mitigation of greenhouse gases must consider not only CO_2 but also the other long-lived greenhouse gases.
- A so called multi-gas strategy has been found to achieving the same climate goal but at considerably lower costs than a CO_2-only strategy. Globally, the potential for "no-regret" non-CO_2 greenhouse gas abatement is significant. This is also shown to be the case for EU-27.
- On a global level the energy and agriculture sectors offer the greatest potential for cost-effective mitigation of non-CO_2 greenhouse gases. There is also a major potential in the waste and industrial processes sectors.
- Black carbon particles in the atmosphere are short-lived substances, which are not well mixed in the atmosphere and showing large regional variations, but with a considerable impact on the climate. Mitigation of these particles is considered to be a cost-effective way of reducing the impact on the global radiation balance.
- Methane mitigation shows the largest potential.



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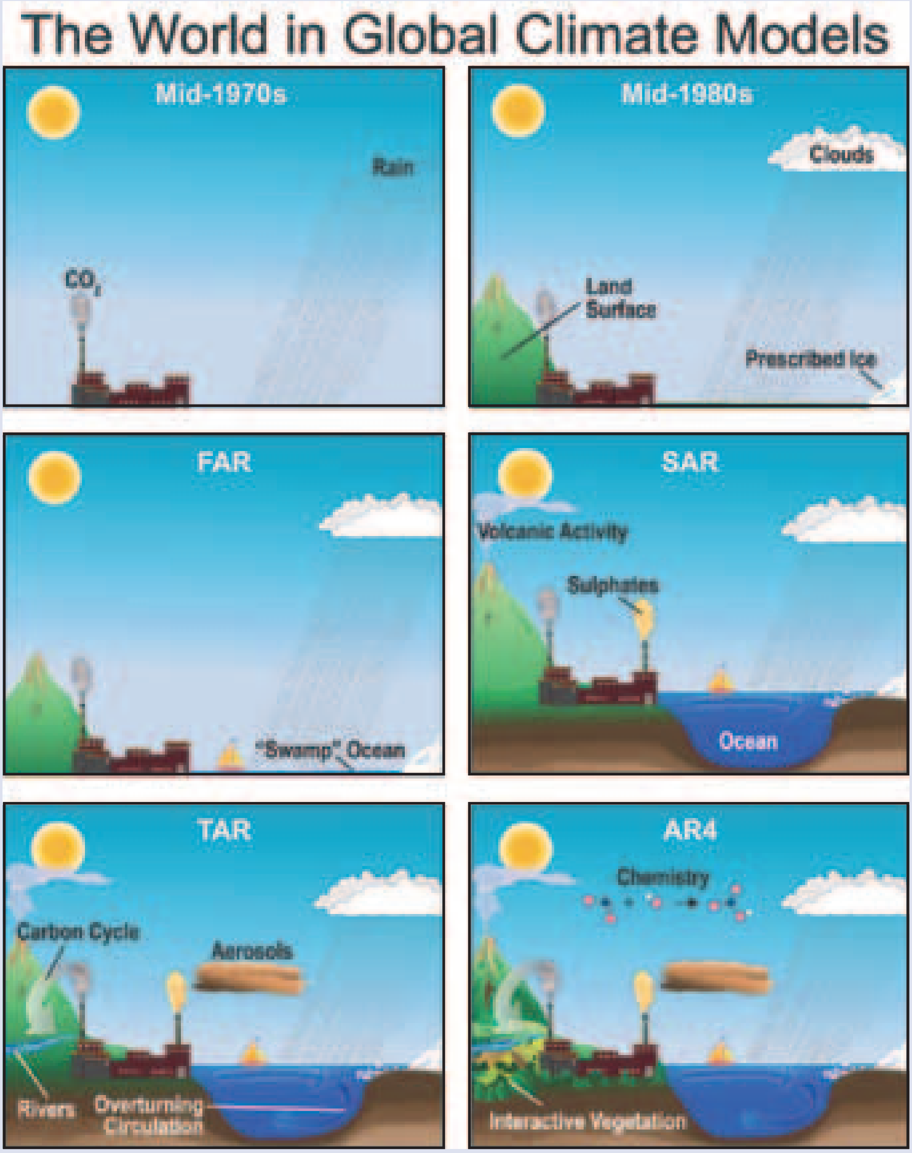
CONTENT

From IPCC (2007a). Climate Change 2007: The Physical Science Basis



The figures shows how the complexity of climate models has increased since the mid 1970s.

1. INTRODUCTION AND BACKGROUND

During the last decades there has been a growing concern of a changed climate due to anthropogenic emissions of greenhouse gases. Climate models indicate how emissions to the atmosphere interfere with climate processes and what temperature rise different emission scenarios may lead to. The model results have increased the apprehensions of severe future effects and international initiatives have been taken on concerted actions to reduce greenhouse gas emissions.

It is now clear to most scientists that through direct emissions to the atmosphere of gases, such as carbon dioxide, methane, nitrogen oxides and nitrous oxide, humans have perturbed the carbon and nitrogen cycles, thus affecting the climate system itself. There are however still many open questions concerning how these cycles interact with each other, and what the implications of these interactions will be.

1.1 The background of this literature review

Carbon dioxide emissions and their impact on climate has been an issue of concern for many years, mainly for the energy and transport sectors, and strategies have been elaborated to reduce the impact. Gradually, knowledge about emissions of other greenhouse gases besides carbon dioxide has increased as well as knowledge about these contributing sectors.

The climate models used in the research on climate change have become more complex and are today believed to be able to provide fairly reliable predictions of future temperature ranges and climate developments. However, the models still do not cover a complete set of possible mechanisms and they include considerable uncertainties. There is a wide consensus that the basis is robust for estimating the reductions necessary to achieve the goals for acceptable climate effects, at least as a first step.

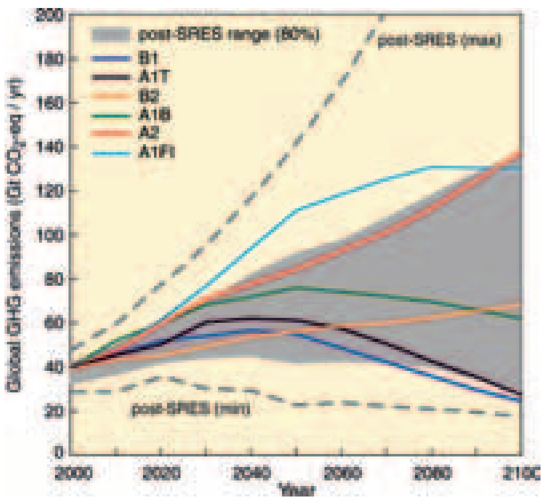


Figure 1: Scenarios for GHG emissions from 2000 to 2100 in the absence of additional climate policies. Source: IPCC (2007b)

In many sectors and for many areas, strategies to reduce carbon dioxide have been or are being elaborated. In addition, several studies, both on a global level and on a European level, have been made for abatement strategies concerning emissions of greenhouse gases other than carbon dioxide and the potential for emission reductions of these emissions in relation to carbon dioxide emissions.

Necessary emission reductions require far-reaching abatement measures, which may not even be technically and economically feasible from a present point of view. Questions asked in this review are: How important are the non-CO_2 greenhouse gases? What are the strategies and possibilities for these greenhouse gases? Is it possible to reduce the emissions from these sectors as much as is necessary and to what costs?

1.2 Aim of this document

Although carbon dioxide is the most important of the greenhouse gases, there are other compounds that have considerable influence on the climate system and therefore need to be considered when addressing goals and policies set up to prevent an escalation of global warming.

This literature review is produced as a joint activity within two comprehensive energy research projects: ”Nordic Energy Perspectives” (NEP) and ”Pathways to Sustainable European Energy Systems” (Pathways).

The aim of this review is to highlight some of the uncertainties concerning the causes of global warming, aspects that must be kept as a background of the strategies, and to show the complexity of the system. The review has a focus on non-CO_2 greenhouse gases, especially methane and nitrous oxide, and the review aims to provide examples from the literature on mitigation options and emission projections for these gases.

1.3 International Panel on Climate Change

Knowledge on human-induced climate change, and its consequences, has steadily increased during the last decades. The *Interngovernmental Panel on Climate Change* (IPCC), set up in 1988 by the World Meteorological Organisation (WMO) and the *United Nations Environment Programme* (UNEP), was established to provide decision-makers and others interested in climate change with an objective source of information about climate change. Its role is to assess the latest scientific, technical and socio-economic literature produced world-wide relevant to understanding the risk of human-induced climate change.

The *United Nations Framework Convention on Climate Change* (UNFCCC), building on the IPCC’s increasing certainty that climate change is being caused by human activities[1], was adopted in 1992 and came into force in 1994.

According to the UNFCCC, climate change refers to “*a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere, and that is in addition to natural climate variability observed over comparable time periods*”[2].

1) In the Fourth Assessment Report (2007), IPCC concluded that “Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.”
2) http://unfccc.int/resource/docs/convkp/conveng.pdf

KYOTO PROTOCOL

The target of the Kyoto Protocol is an average minimum reduction of 5.2 % in greenhouse gas emissions from 1990 levels in the first commitment period of 2008-2012.

Those countries that have ratified the protocol and belong to Annex I nations (37 industrialised countries including the Member States of EU-15) are under legally binding commitments to reduce their emissions of four greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and sulphur hexaflouride (SF_6), and two groups of GHG: hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

The protocol includes defined “flexible mechanisms” such as emission trading, clean development mechanisms and joint implementation as tools to meet the reduction targets.

The objective of the UNFCCC is to stabilise greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. At which level “a dangerous interference with the climate system” will take place is a question that has been much debated among scientists and policy makers around the world.

Within the EU it has been decided that the 27 Member States, to guarantee that the goal of the UNFCCC is met, have to contribute to limit global average surface temperature increase to not more than 2º C above pre-industrial level, the so called two-degree target. Since 1850, the global average surface temperature has risen by 0.76º C, and according to the *Fourth Assessment Report* (AR4) of the IPCC (IPCC 2007b), it is projected that, without further action to reduce GHG emissions, the global average surface temperature is likely to rise by a further 1.8-4.0º C in this century.

The first addition to the UNFCCC treaty, the *Kyoto Protocol*, was adopted in 1997 and entered into force in February 2005.

1.4 EU policies and the climate change issue

The EU and its Member States (at the time EU-15) ratified the Kyoto Protocol in 2002. Under the Kyoto Protocol, the Member States of EU-15 are committed to cutting their combined greenhouse gas emissions to 8 % below 1990 levels by 2012.

In January 2008, the European Commission put forward a set of legally binding targets for the EU to be achieved by 2020, in the so called Climate & Energy package. One of the key targets was to achieve at least a 20 % reduction in EU's greenhouse gas emissions (increased to 30 % in the context of a global and comprehensive international agreement). The total effort for greenhouse gas emission reductions according to this package is to be divided between the EU emission trading system (EU ETS) and non-ETS sectors (such as transport, housing, agriculture and waste).

The sectors covered by the EU ETS will have to reduce their greenhouse gas emissions by 21 % by 2020, compared to 2005 levels, while emissions from sectors not included in the EU ETS must cut their emissions by on average 10 % by 2020 compared to 2005 levels. In all, this would result in a total emission reduction of 14.4 % for EU compared to 2005, which is equivalent to a reduction of 20 % compared to 1990 levels.

Swedish Scientific Council on Climate issues on

REDUCTION TARGETS FOR REACHING THE 2° C TARGET

According to the Swedish Scientific Council on Climate Issues, commissioned by the Swedish Government in 2006, EU's two-degree target is likely to be achieved if GHG concentration in the atmosphere stabilises in the long term at 400 ppmv CO_2-equivalents (CO_2e). The concentration of GHG currently (2007) stands at approximately 450 ppmv CO_2e, a level which, in the long run, would impose a significant risk of not achieving the two-degree target.

In order to meet the two-degree target, the Swedish Scientific Council on Climate Issues estimates that global emissions by 2050 would have to be reduced, to at least 50 % of the 1990 levels, and by the end of the century would have to be reduced virtually to zero. To stabilise the GHG concentration at the same level in the long-term, until 2150, the global GHG emissions in 2020 will need to be about 10 % lower than the 2004 level, which in turn corresponds to an increase in emissions of about 10 % if compared to 1990 levels.

The Swedish Scientific Council on Climate Issues further estimates that the EU Member States need to reduce their GHG emissions by 30-40 % until 2020 (compared to 1990 levels) and by 75-90 % until 2050 (compared to 1990 levels) in order to take their share of the global responsibility for achievement of the two-degree target.

Source: Vetenskapliga rådet för klimatfrågor (Swedish Scientific Council on Climate Issues) (2007)

1.5 Aspects to be considered in abatement strategy planning

Greenhouse gas emissions are of major importance today and the climate issue is expected to remain a question of utmost significance during coming decades and centuries. There are many actors involved worldwide and the number of parties to the UNFCCC have steadily grown. As of 3 December 2009, 189 countries and 1 regional economic integration organisation (the EEC) have deposited instruments of ratification, accession, approval or acceptance to the Kyoto Protocol.

The present basis for action is comprehensive and robust to its order of magnitude, even if there are large uncertainties involved in the overall understanding of the processes. In the strategies elaborated by different actors these large uncertainties in sources and sinks of greenhouse gases, the interconnections with the climate and available climate models, have to be considered in research projects and future action plans.

This report deals with aspects which are of importance for the work within both NEP and Pathways:

- Our climate is a complex system.
- A large number of parameters, influenced by human activities, control the climate in a considerable way.
- The knowledge on the climate issue is far from complete.

Considerable uncertainties are found

- There are large uncertainties connected to the impact on the climate by different atmospheric pollutants.
- Uncertainties are also large, concerning emitted amounts of non-carbon dioxide greenhouse gases and how different measures may lead to effective emissions reductions.

The uncertainties have to be handled in the analyses made

- The energy scenarios comprising considerable reductions of greenhouse gas emissions also have to deal with the uncertainties.
- Control measures leading to a simultaneous reduction of several greenhouse gases must be given priority to.
- We must understand that emission estimates and emission targets include uncertainties and are best available estimates in the present situation.

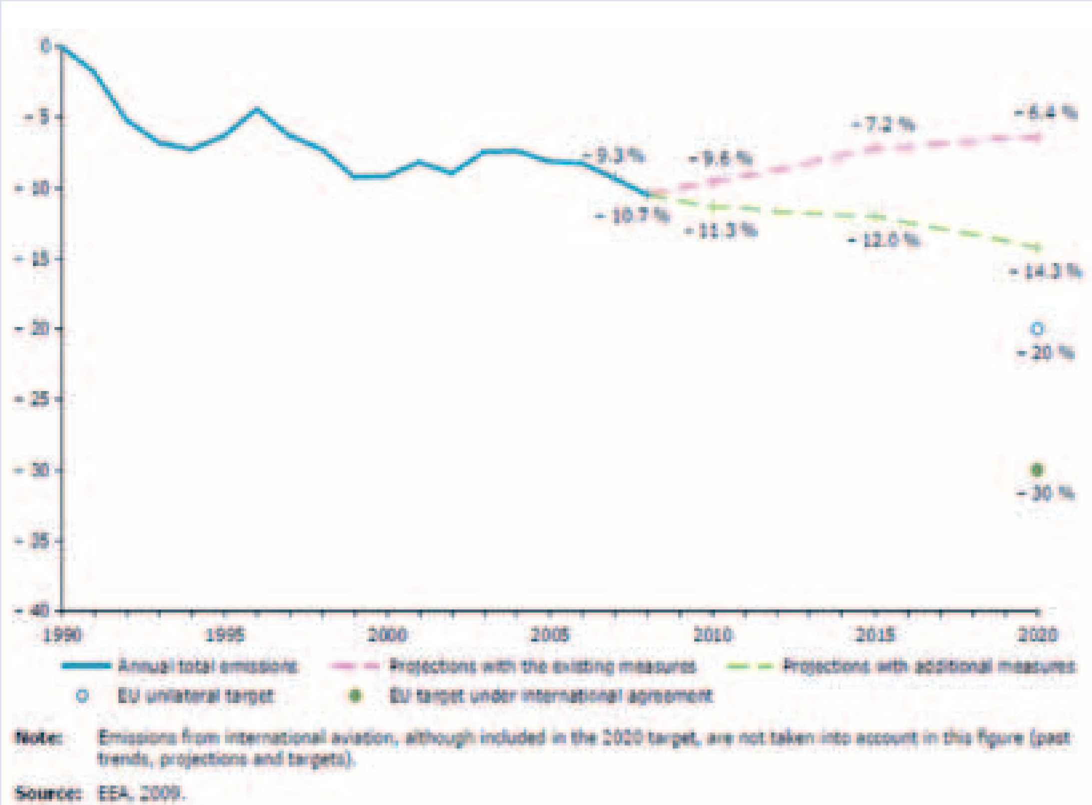


Figure 2: The figure shows the greenhouse gas emission trends and projections for the EU-27 up to 2020. In 2008 it is estimated that the EU-27 has reduced its domestic greenhouse gas emissions by approximately 10.7 % between 1990 and 2008. Projections with existing measures show how the emissions are expected to rise again up to 2020, although on a level 6 % below 1990 levels. However, by full implementation of the planned additional measures, the EU-27 domestic emissions are expected to decrease to 14 % below 1990 levels by 2020. Source: EEA (2009b)

2. THE COMPLEXITY OF THE CLIMATE SYSTEM

IN THIS CHAPTER

The Earth's climate system is a complex, interconnected system formed by the atmosphere, the oceans and other bodies of water, land surface, snow and ice cover together with all living organisms, and linked by flows of energy and matter.

The carbon and nitrogen cycles are interwoven and influence the amount of CO_2, CH_4 and N_2O in the atmosphere, thus playing a part in climate change. There are still many open questions on how these cycles interact with each other and what the implications of these interactions might be.

The Earth's climate system is a complex, interconnected system formed by the atmosphere, the oceans and other bodies of water (*the hydrosphere*), land surface (*the lithosphere*), snow and ice cover (*the cryosphere*) as well as all living organisms (*the biosphere*), and powered by solar radiation. Beside its own internal dynamics, the system is affected by changes in external factors, which include natural phenomena such as solar variations and volcanic eruptions, as well as human-induced changes in atmospheric composition.

The components of the climate system are linked by flows of energy and matter. Biogeochemical cycles, such as the carbon cycle and the nitrogen cycle, connect the atmosphere with land and oceans through a number of complex physical, chemical and biological processes, thus affecting the climate system. A large number of air pollutants are involved. Figure 3 (see next page) shows an overview of the processes in the atmosphere.

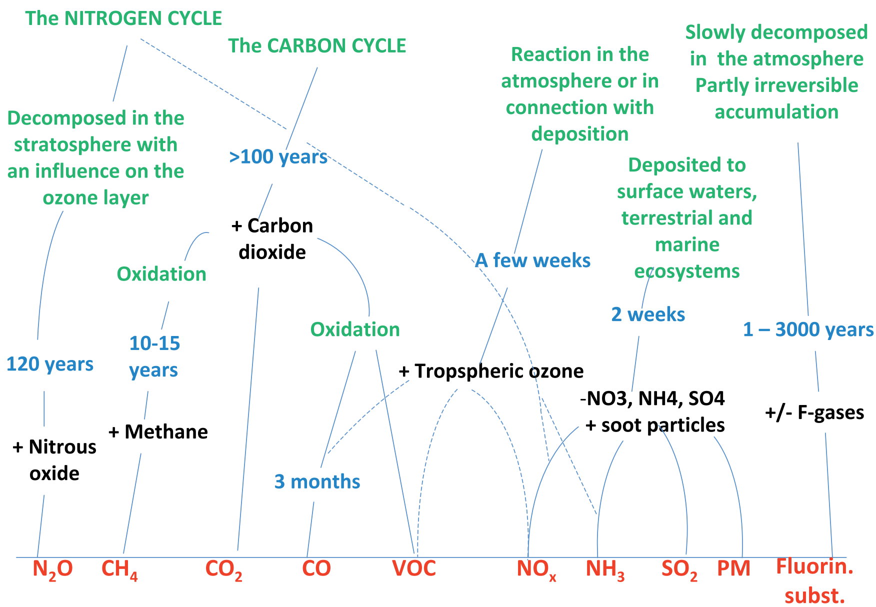


Figure 3: Emissions of air pollution to the atmosphere, processes of importance for their atmospheric conversion and removal, in addition to expected life time and estimated warming (+) or cooling (-) climate effect.

Substances emitted into the atmosphere are written in red letters in the figure. The resulting air pollutant in the atmosphere (gas or particle) and its influence on the radiation balance is written with black letters (positive + and negative -). Data on their estimated life time in the atmosphere are blue and the final fate is written with green.

The pollutants have different climate effects. Some have a strong influence, other are weaker. The long-lived gases are usually more important than the short-lived, but the effect depends on the time perspective. Many of the air pollutants have other effects in addition. These effects may be on a local or a regional scale or even longer hemispheric or global scale depending on their life time.

The local and long range effects include human health effects, corrosion and degradation of materials, acidification and eutrophication of terrestrial ecosystems as well as surface and coastal water ecosystems. These effects are in many areas serious and the pollutants are subject to national abatement programs to avoid transboundary pollution effects (e.g. within the *Convention of Long Range Transboundary Air Pollution*[3]). To a certain extent these action plans to reduce local effects include measures which also reduce greenhouse gases. Some actions may reduce both greenhouse gas emissions and emissions of traditional air pollutants. To some extent, however, the necessary measures are quite different and involve different sectors in society. This double gain of measures, have to be considered when valuing the costs of abatement strategies.

3) http://unece.org/env/lrtap/

2.1 The carbon cycle

The carbon cycle, among other things, regulates the amount of CO_2 and CH_4 in the atmosphere, and is thus of critical importance to the climate system. The oceans, vegetation, and soils are significant reservoirs of carbon, continuously exchanging carbon dioxide with the atmosphere.

Terrestrial plants and phytoplankton in the oceans convert the carbon dioxide in the atmosphere to other carbon compounds. Through plant, soil and animal respiration (including decomposition of dead biomass) carbon is returned to the atmosphere as CO_2 or, under anaerobic conditions, as CH_4. The global net carbon flux between terrestrial ecosystems and the atmosphere is therefore the result of a small imbalance between uptake through photosynthesis and release by various return processes such as respiration and soil disturbances.

Variations of climate and human activities have a major impact on the carbon flux, mainly through land use and land-use changes as well as indirectly through carbon dioxide fertilisation, nutrient deposition and air pollution.

Global terrestrial and oceanic carbon sources and sinks may vary significtantly in time, and the exchange of atmospheric CO_2 with the oceans and the terrestiral biosphere responds to inter-annual climate variations. It appears that the terrestrial biosphere drive most of the inter-annual variations in CO_2 flows.

The estimated store of carbon in the atmosphere is approximately 760 Gt C. The largest natural exchanges of carbon occur between the atmosphere and terrestrial biota (GPP about 120 Gt C per year, NPP about 60 Gt C per year[4]), and between the

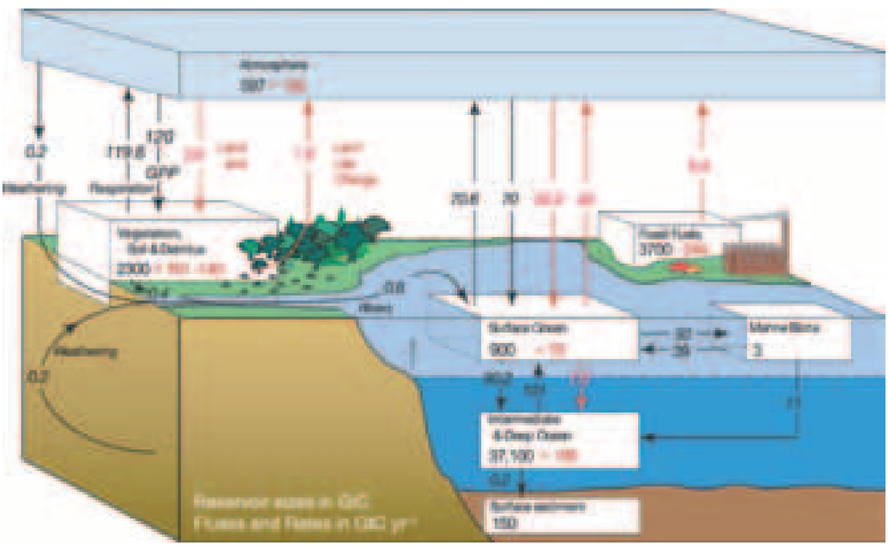


Figure 4:
The global carbon cycle for the 1990s showing the main annual fluxes in GtC. Black text and numbers are pre-industrial "natural" fluxes whereas red text and numbers are human induced "anthropogenic" fluxes.
Source: IPCC (2007a)

4) GPP, gross primary production, is the uptake of carbon from the atmosphere by plants. NPP, net primary production, is the remaining carbon when accounted for the carbon losses as a result of plant respiration, i.e. NPP = GPP – respiration by plants. Additional losses occur because of decomposition of dead organic matter, resulting in NEP, net ecosystem production (about 10 Gt C per year). Yet further losses caused by disturbances, such as fire, wind-throw, drought, pests and human activities results in the net imbalance of the terrestrial ecosystem, denoted NBP, net biome production, presently about 0.7 Gt C per year as a decadal average.

atmosphere and ocean surface waters (about 90 Gt C per year). Carbon emissions to the atmosphere from the use of fossil fuels and cement production are of the magnitude of 6 Gt C per year. Land-use changes, such as deforestation contributes to about 1.6 Gt C to the atmosphere annually.

Carbon monoxide, CO, is also emitted to the atmosphere, mainly from incomplete combustion. It does not have a direct effect on global temperature but contribute to pollution taking part in the atmospheric chemistry processes of photochemical smog formation. Carbon monoxide will, like other carbon containing substances such as hydrocarbons, eventually end up as carbon dioxide in the atmosphere.

2.1.1 Carbon in soil and vegetation

Soil is a major carbon pool in all ecosystems and globally, the amount of carbon stored in soils is much larger (some 1 700 Gt C) than the amount stored in vegetation (some 600 Gt C). Together, terrestrial vegetation and soil contain approximately three and a half times as much carbon as the atmosphere, in total some 2 300 Gt C. There are large local variations but, compared to temperate and tropical forests, boreal forests have a larger proportion of carbon stored in soils than in trees.

The amount of carbon in forest ecosystems are small compared to the amount present in oceans. Globally, some 5 % of the total global carbon stock that is part of the carbon cycle is found in forest ecosystems around the world. However, forest ecosystems play an important role in the climate system since all plants are able to take up carbon dioxide from the atmosphere through photosynthesis, in which carbon dioxide and water is converted to sugar (i.e. carbohydrates, which can be utilised by the plants as well as other organisms) and oxygen. Carbon dioxide is later released back into the atmosphere and/or soils when the plants use the sugar as energy. As long as the plant grows the uptake of carbon dioxide is larger than the amount released. When a plant eventually dies the biomass is slowly decomposed by decomposers, organisms gaining their energy and nutrition form dead organic material, and some of the carbon that is part of the plant is thus released back into the atmosphere again. A forest becomes a carbon sink when carbon assimilation exceeds soil respiration.

Land use, land-use change, and forestry, often denoted LULUCF, which include human activities such as urban settlements, agricultural production and clearing of forests, directly affect sources and sinks of CO_2, CH_4, and N_2O, thus influencing the biogeochemical cycles linked with the climate system. Land use change plays a major role in the carbon source/sink dynamics, since deforestation and conversion of woodlands for agricultural use effectively increases the flux of carbon to the atmosphere while at the same time reducing the land area that is available for active carbon sinks. Emissions and removals from the LULUCF sector are difficult to estimate because the emission generating processes in this sector are complex. It is especially difficult to assess which part of the emissions or removals that is caused by human activity and which part is natural.

On a European level croplands and grasslands are net sources of greenhouse gas emissions, whereas forests generally are considerable net carbon sinks. Globally however, carbon stocks in grasslands and savannas are stable over long time spans. Losses of carbon from these soils can occur if grazing pressure is high or if the frequency of fires increases. Peatlands and wetlands have large carbon pools due to anaerobic soil conditions and, in northern peatlands, the low temperature reduce the rate of decomposition, thus promoting accumulation of organic matter.

Because of their natural anaerobic condition wetlands and peatlands are large emitters of methane. When drained for agriculture or other land use, however, wetlands and peatlands instead emit carbon dioxide as well as nitrous oxide (depending on how much nitrogen that is available in the soil) due to the change to aerobic conditions.

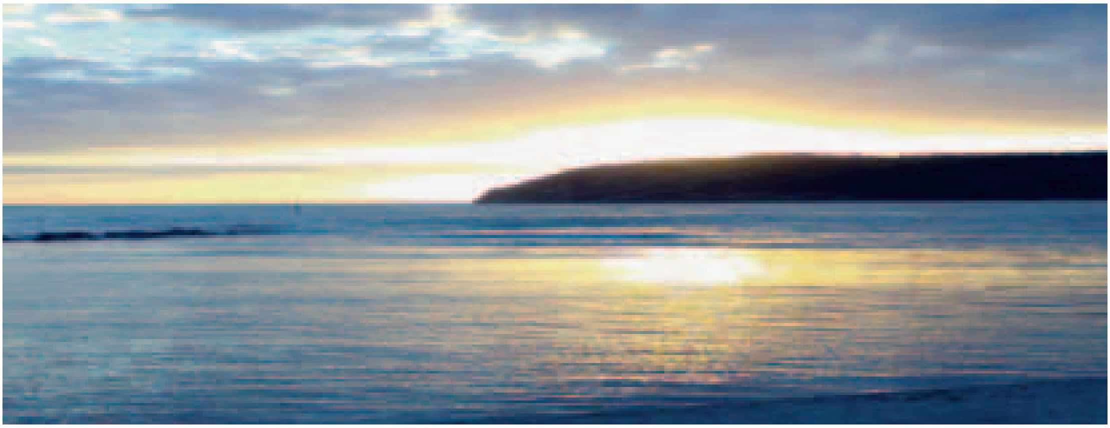
Land-use changes due to deforestation by humans are estimated to have emitted about 20 % of the total amount of the carbon dioxide emitted to the atmosphere during the 1990ties. Ploughing and soil preparation after deforestation increase the oxygen content of the soil, thereby increasing the rate of decomposition of humic substances in the soil and releasing the carbon stored in it.

But although there is a net loss of carbon to the atmosphere due to deforestation and fossil fuel combustion, the amount of carbon dioxide in the atmosphere have not increased as much as could be expected during the last decades. This can be attributed to the fact that the remaining forests have stored more and more carbon because of better forestry methods but also due to the fact that air pollution such as nitrogen compounds, but also carbon dioxide itself, have a positive influence on the growth in forests. There is however a saturation point for when terrestrial plants seize to act as a sink for anthropogenic carbon. At CO_2 concentrations between 800 and 1 000 ppmv in the atmosphere, a concentration that may be reached early in the next century if the present emissions rate continues, terrestrial plants will become less of a sink for CO_2. Although the combined effects of higher CO_2 concentrations, higher temperatures, and changes in disturbance and soil conditions lead to considerable uncertainty about the ability of terrestrial ecosystems to mitigate against rising CO_2 concentrations in the coming decades. Evidence though points to that the sink strength of terrestrial plants will almost certainly weaken.

If global warming continues and heat, drought and fires are becoming more frequent the present role of terrestrial ecosystems as carbon sinks can be delimited and even turn into a source of carbon emissions, thus further accelerating global warming.

2.1.2 Carbon in the oceans

Oceans are large reservoirs of carbon, and contain about 50 times the amount of carbon in the atmosphere. Approximately 93 % of the total global carbon reservoir taking part in the carbon cycle is found in the oceans, mainly in the deep oceans. The amount in the surface parts of the oceans is estimated to about 1 000 Gt C. Around 92 Gt C per year dissolves into the ocean forming bicarbo-



nate ions. A somewhat smaller amount is emitted back into the atmosphere. The net transport into the ocean is around 2 Gt per year.

The increased dissolution of carbon dioxide in the oceans due to increasing atmospheric concentrations increases the ocean concentrations of bicarbonate and thus decreasing pH. However, when the pH decreases, so does the carbonate ion. When the carbonate ion concentration in the oceans is undersaturated, this may lead to dissolution of calcium carbonate structures. The pH-drop is therefore expected to have negative consequences, mainly for the oceanic calcifying organisms such as corals, echinoderms and crustaceans.

Large amounts of carbon are stored in the deep part of the oceans. An estimate indicate a magnitude of 38 000 Gt. Carbon in the form of bicarbonate ions combine with calcium to form limestone rock (Calcium carbonate), adding to the store of carbon in surface sediments. This flow is estimated at 0.2 Gt per year. The carbon amount stored in surface sediments and in rock is estimated at 100 million Gt. Plant and animal remains buried deep in the ocean bottoms will over periods of million years be converted into fossil fuels such as petroleum and coal. The amount of carbon stored in this way is estimated to be around 3 500 Gt.

Oceans capacity for storing carbon is also affected by global warming. If the global average temperature continues to rise, oceans capacity as a carbon sink diminishes, and as more carbon dioxide is stored in the oceans, less is able to be stored in the future due to a slow recirculation of surface water and deep water.

2.1.3 Greenhouse gas emissions due to use of biomass

The carbon stocks in biomass can be used to produce energy, as a way to avoid greenhouse gas emissions from fossil fuels. Burning of biomass is not considered to contribute to an increase of CO_2 in the atmosphere. This can be motivated by the two following reasons:

1) If new plants are allowed to replace the harvested and burned plant biomass, the amount of CO_2 that the new plants will capture from the atmosphere will balance the amount of CO_2 emitted during the combustion of the harvested and burnt plant biomass;

2) Also, when a plant eventually dies and decomposes, whether harvested or not, the same amount of CO_2 will be emitted as would have been the case if the plant was burnt.

The carbon stock in harvested plant biomass is thus considered to be part of the carbon cycle, compared to fossil fuels such as coal and oil, that, although originating from dead plants and animals, which for a long time have been parted from the carbon cycle.

However, as long as deforestation is not counteracted by replacing dead plants with new plants there is a net emission of carbon to the atmosphere. Between the year 2000 and 2005, the world's total area of forest ecosystems decreased by almost 0.002 % each annually, due to the fact that more trees was cut down than was replaced.

When considering climate effects and biofuels it is also necessary that greenhouse gas emissions from the use of fuels from biomass are considered from a systems perspective. Even if tailpipe emissions from the use of biofuels are regarded as zero in emission inventories, there is a considerable amount of greenhouse gas emissions connected to the production of some biofuels, because of the fossil fuel use for harvesting and transport of the biofuels.

A much debated article by Crutzen et al. (2008) questioned the way IPCC estimates the climate impact for biofuels. According to Crutzen et al. as much as 3-5 % of the nitrogen that is used for the cultivation of biofuel crops are converted to N_2O which is thus released into the atmosphere, a 3-5 times higher value than IPCC is using in its emission inventories. If this is correct it would mean that many of the biofuel crops that are cultivated can have even higher emissions of greenhouse gases than fossil fuels seen in a systems perspective.

There is however still many open questions regarding this issue, but the fact is that the size of N_2O emissions and the formation of the emissions are highly uncertain.

Therefore, the potential for biofuels to reduce greenhouse gas emissions depends on many factors including the source of the biomass, its net land-use effects and how much N_2O that is formed during cultivation.

2.2 The interacting nitrogen cycle

The nitrogen cycle includes the flow of nitrogen-containing compounds in the atmosphere, their chemical processes and deposition to vegetation, soil and water, via uptake in plants and microorganisms and then further back into the atmosphere. The cycle includes both oxidized compounds, such as nitrogen oxides, nitric acid and nitrate in particles or solution, and reduced nitrogen compound such as ammonia and ammonium ions on particles and in solution.

The cycle is integral to the climate system in three ways. It regulates the amount of nitrous oxide (N_2O) in the atmosphere. It has an influence via

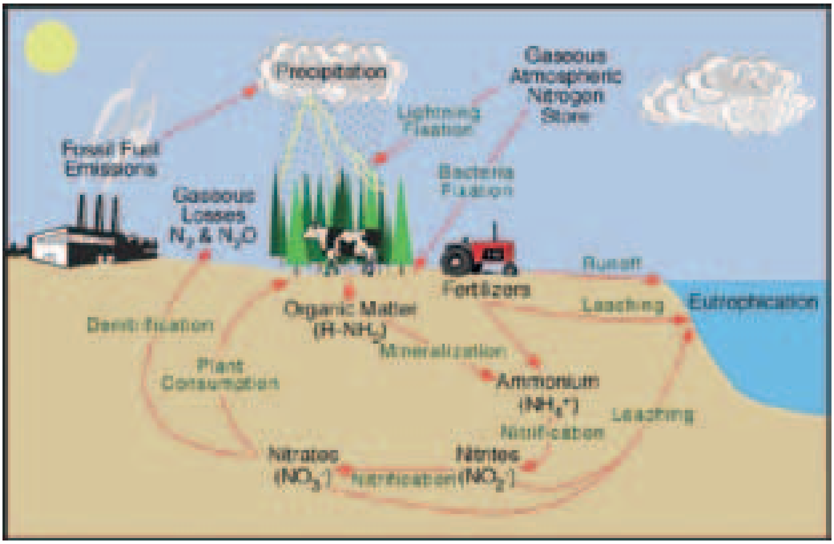


Figure 5: The nitrogen cycle. Source: http://www.physicalgeography.net/fundamentals/9s.html

nitrogen oxides (NO_x) through the formation of tropospheric ozone (O_3), which is a large contributor to greenhouse radiative forcing (explained further below) and finally through the formation of nitrate particles in the atmosphere, which have a cooling effect.

Nitrogen fixating bacteria or blue-green algae play an important part in the nitrogen cycle by converting N_2 from the atmosphere to NH_4+, a more reactive form of nitrogen that can be used by plants (in contrast to atmospheric N_2). Other biological processes within the nitrogen cycle include nitrification (bacterial oxidation of NH_4+ to NO_2 and NO_{3-}), denitrification (bacterial reduction of NO_{3-} back to N_2) and mineralisation, which refer to a process that releases nutrients in inorganic forms during the decomposition of organic matter (in this case the process of ammonification in which organic N is converted to NH_4+). Nitrous oxide is formed during both nitrification (as a by-product) and denitrification (as an intermediate).

All biotic sinks for CO_2 require other nutrients in addition to carbon, such as nitrogen and phosphorus. The problem today however is that there is too much of these nutrients available for organisms to use. Massive production and industrial use of artificial nitrogen fertilisers worldwide have led to a range of environmental problems such as eutrophication and acidification. Deposition and fertilisation of nitrogen compounds increase the nutrient supply to plants, thereby stimulating productivity and the uptake of CO_2 from the atmosphere.

Nitrogen compounds thus have the potential to enhance the carbon sink in nitrogen-limited ecosystems. This ability however become decreasingly effective in the long-term perspective, since the effect seems to decrease with increasing nitrogen load. Also, the negative consequences of the nitrogen additions due to humans are both substantial and manifold and there is still much to understand about the implications of nitrogen accumulation in the environment and how nitrogen interacts with other biogeochemical cycles.

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2.2.1 Interaction between the carbon and nitrogen cycle

There is a growing awareness about the importance of the interactions between the major biogeochemical cycles such as the nitrogen and carbon cycle, and the effects of the human perturbation on these cycles and what implications this might have on the climate and the Earth as a system. The complexity of these interactions is considerable, and many of the mechanisms of these interactions are yet poorly understood. This lack of knowledge is becoming more pressing, since lack of consideration of these climate-relevant feedback mechanisms involving the nitrogen and carbon cycle leads to substantial uncertainties in climate-change projections.

In figure 6 some of the interacting drivers of the nitrogen-carbon-climate interactions are shown.

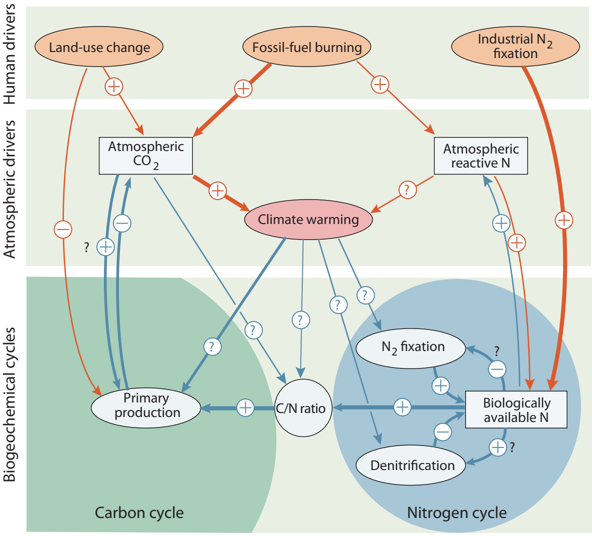
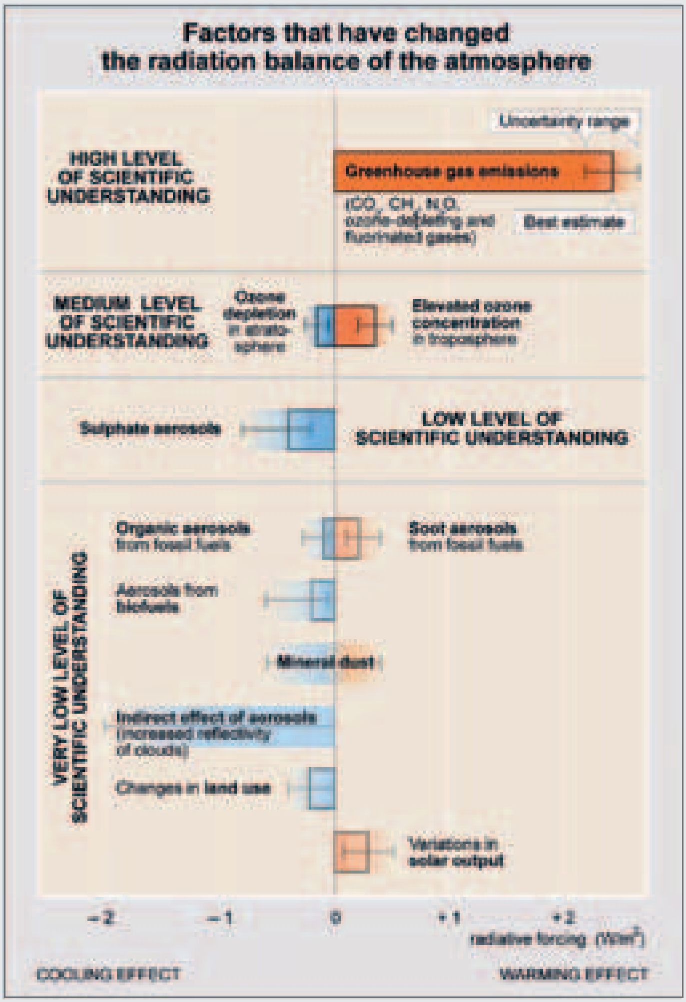


Figure 6: The figure shows the complexity of the interactions between the nitrogen cycle and the carbon cycle and how they influence the climate. Some of the main interacting drivers of the nitrogen cycle during the twenty-first century are shown. Plus signs indicate that that the interaction increases the amount of the factor shown; minus signs indicate a decrease; question marks indicate an unknown impact or, when next to at plus or minus sign, they indicate a high degree of uncertainty. Orange arrows denote the direct anthropogenic impacts, and blue arrows denote natural interactions, many of which could also be anthropogenically modified. Arrow thickness denotes strength of interaction. Important to note is that only selected interactions are shown. Source: Gruber & Galloway (2008)



Source: Bernes (2007), IPCC (2007a)

3. ATMOSPHERIC CONSTITUENTS AND THEIR EFFECT ON THE CLIMATE

IN THIS CHAPTER

Changes in the Earth's climate are influenced mainly by changes in the atmospheric composition of gases and particles, but also by changes in solar radiation and surface albedo. The most important component to influence the atmosphere is CO_2, which stands for 70 % of the global warming potential in the atmosphere.

Other gases of great importance are long-lived gases like CH_4 (20 %), N_2O (5 %) and fluor-containing gases like HFC, PFC and SF_6 (5 %). All act on a global scale.

Other more short-lived components in the atmosphere are water vapour (obvious climate effect on a daily basis), tropospheric ozone, and particles. The dispersion of these short-lived components is more regional, which also is true for their climate effect.

The present level of scientific understanding is high for the radiative forcing of CO2 and the other long-lived GHG. However, the effect of particles and aerosols as well as for surface albedo and solar irradiance is less well known. The total uncertainty in radiative forcing caused by anthropogenic impact is more than ±50 %.

3.1 Radiation balance

The balance between incoming solar radiation and the reflected, outgoing radiation is termed radiation balance. Changes in atmospheric concentration of gases and particles affect the radiation balance and, in turn, changes in the Earth's radiation balance affect the climate system both directly and indirectly through a number of feedback mechanisms.

The Earth's radiation balance is influenced by three fundamental causes:

- **Changes in incoming solar radiation**, for example due to changes in the Earth's orbit or in the Sun itself;
- **Changes in albedo effect**, that is, a surface's ability to reflect light, for example due to changes in the atmosphere's content of particles, changes in vegetation and snow cover, and changes in cloud cover, all of which affect how much of the incoming solar radiation that is reflected;
- **Changes in amount of outgoing longwave radiation** from Earth back towards space, due to changes in the atmosphere's greenhouse gas concentration.

3.2 Changes in incoming solar radiation

Solar radiation drives the atmospheric circulation. Since solar radiation represents almost all of the energy available to the Earth, the understanding of the interaction between solar radiation, the atmosphere and the Earth's surface and its effect on the Earth's energy budget, is fundamental. Periodic variations are observed for the incoming solar radiation, the principal variation occur on an 11-years solar (sun spot) cycle. But also periodic changes are seen, changes which may be due to slight variations in Earth´s orbit.

Solar radiation reaches the Earth's surface either by being transmitted directly through the atmosphere (”direct solar radiation”), or by being scattered or reflected to the surface (”diffuse sky radiation”). About 50 % of solar (or shortwave) radiation is reflected back into space, while the remaining shortwave radiation at the top of the atmosphere is absorbed by the Earth's surface and re-radiated as thermal infrared (or longwave) radiation.

Over longer periods of time, changes in components of the radiation balance can be manifested as climate change. However, there are still many open questions of how the Sun is affecting Earth's climate, and many researchers in the solar research field propagates for a more dynamic view on the Sun than the one currently used in climate models and how it affects the climate on Earth.

The Sun.
Photo: http://photojournal.jpl.nasa.gov/jpeg/PIA03149.jpg

3.3 Changes in albedo effect

The albedo (whiteness effect) of surfaces on the Earth affects the absorption and the reflectance of incoming solar radiation. Dark surfaces absorb radiation and light surfaces reflect it. The albedo effect is quantified as part of the light reflected. Estimates of the albedo effect range from up to 90 % for fresh, clean snow, to about 4 % for charcoal. Generally, land areas have higher albedo values than ocean areas, and albedo values have a seasonal variability mainly due to changes in vegetation, cloudiness as well as snow and ice cover. Earth's average albedo is around 30 %.

A classic feed-back mechanism due to changes in albedo effect is seen when a snow-covered area warms up and the snow melts, decreasing the albedo. Consequently, more sunlight is absorbed, and the temperature tends to increase. Examples of the feed-back mechanism are seen around tree trunks in a snow-covered landscape in spring.

The albedo of the Earth's surface is regularly estimated via satellite sensors. Data are translated by models into estimates of reflectance effect. Human activities have changed the albedo of various areas around the Earth, via activities such as forest clearance and farming. Quantification of this effect on a global scale is, however, difficult and no data are available on a possible trend.

3.4 Changes in amount of outgoing long wave radiation

There are a number of natural ways of impact on the radiation balance. Such as changes in solar activity and changes in the Earth's atmosphere due to explosive volcanic eruptions, emitting sulphur compounds and particles. The major impact is however caused by the greenhouse gas emissions due to human activities. At present energy, transport, industrial activities and agriculture produce large direct emissions of greenhouse gases. However, also via land use changes, human activities contribute to greenhouse gas emissions.

Radiative forcing (RF) is a measure of the impact on the radiation balance, measured in Watts per m^2, used for assessing and comparing the many different factors, both natural and anthropogenic, that influence and drives climate change. Positive forcing indicates a warming of the system and negative forcing indicates a cooling. Figure 7 shows the RF of different factors.

Compared to the rather small differences in radiative forcing between present day and the start of the preindustrial era, usually defined as the year 1750, due to natural changes, the net radiative forcing resulting from human activities is significant.

RF from greenhouse gases has increased by more than 20% since 1990, most of which can be attributed to CO_2 emissions.

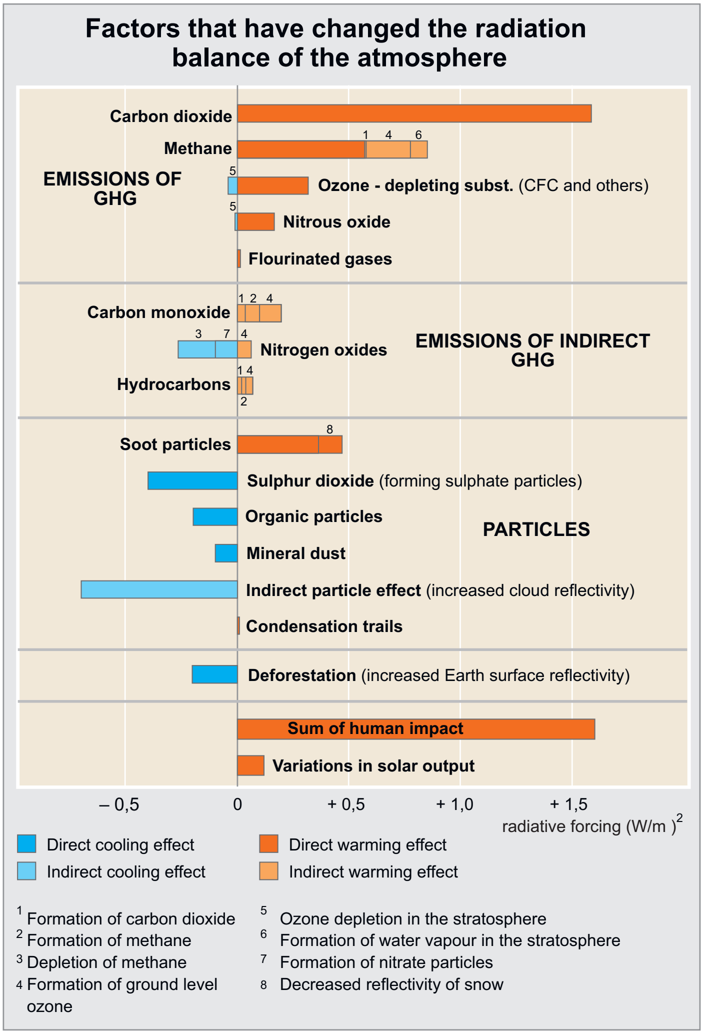


Figure 7: The figure shows how different factors affect the radiation balance of the atmosphere. Besides the increasing concentration of greenhouse gases, which is well known, the effects of the other parameters are less known. Thus, the estimations of these parameters have a higher uncertainty.
Source: Bernes (2007), IPCC (2007a)

3.5 Greenhouse gases and global warming potential

Greenhouse gases are gases, which due to their chemical characteristics, are capable of absorbing and re-emitting infrared radiation. Some of the greenhouse gases occur naturally, such as water vapour, CO_2, O_3, CH_4 and N_2O besides being emitted through human activities. Others, such as the fluorinated gases, only occur due to human activities.

The greenhouse gases have varying impacts on the climate. Depending on its properties, such as atmospheric lifetime, the degree of infrared absorption and the spectral location of its absorbing wavelengths, a greenhouse gas is more or less potent with regards to how much it affects climate change and contributes to global warming. Of great importance for the climate effect are substances with a greenhouse gas effect emitted in large amounts and having a long residence time in the atmosphere (the so called long-lived greenhouse gases, LLGHG). The most important of these are carbon dioxide (contributing globally with approximately 70 %), methane (20 %), and nitrous oxide and fluorinated gases (approximately 5 % each). These are also the compounds included in the Kyoto Protocol.

The Global Warming Potential (GWP) is introduced as a comparative index based on the radiative forcing of a unit mass of a given greenhouse gas, relative that of carbon dioxide, in the present-day atmosphere. It is seen in a specified time horizon. In the Kyoto Protocol this time frame is set to 100 years. Simply speaking, the GWP compares the relative capacity of each greenhouse gas to absorb heat. Although widely debated, GWPs remain the recommended measure of how to compare future climate impacts of emissions of long-lived greenhouse gases. As mentioned, carbon dioxide is used as a reference gas, and all GWPs depend on the absolute global warming potential (AGWP) for CO_2.

Global warming potentials for different greenhouse gases in a 100 years perspective, according to IPCCs Second Assessment Report (SAR), is shown in table 1. In the Kyoto Protocol it was concluded that the GWPs from SAR should be used for the emission inventories of the participant countries. However, the GWPs are constantly being re-evaluated and since the Second Assessment Report of the IPCC some of the values have been adjusted. For example, in the Fourth Assessment Report (2007) the GWP of methane in a 100 year perspective has been raised to 25 while the GWP for N_2O has been lowered to 296.

Gases having a somewhat shorter life time in the atmosphere, such as methane, will in a shorter time perspective be more important for the total global warming potential. Gases with a longer life time will be of more importance when a longer time perspective is applied.

Table 1: Global warming potential for different greenhouse gases according to the IPCC's Second Assessment Report

Gas	GWP
CO_2	1
CH_4	21
N_2O	310
HFC's	150-11 700
PFCs	6 500-9 200
SF_6	23 900

A long residence time in the atmosphere lead to a global distribution of the gases which involves a climate impact independent of where the gases are emitted. Carbon dioxide and nitrous oxide have a residence time in the atmosphere of more than 100 years. Methane has a residence time of 10-15 years.

There are also indirect radiative effects connected to some of the gases. The indirect effects that are being discussed in the Fourth Assessment Report are linked to ozone formation or destruction, enhancement of stratospheric water vapour, changes in concentrations of the OH radical with the main effect of changing the lifetime of methane, and secondary aerosol formation. Generally, the uncertainties of the indirect GWPs are much higher than for the direct GWPs, and in many cases the indirect GWP depend on the location and time of the emissions. The re-assessed GWP for methane in the Fourth Assessment report compared to the Second and Third Assessment Report is due to the new estimates of the indirect effects of methane.

Carbon dioxide CO_2

Carbon dioxide is the most important anthropogenic greenhouse gas, and it has the largest RF of the long-lived greenhouse gases in the atmosphere. The global atmospheric concentration of CO_2 has increased from a pre-industrial level of around 280 ppm to 379 ppm in 2005 mainly due to emissions from the use of fossil fuels but also because of land use changes.

Carbon dioxide is also the only greenhouse gas which is not chemically altered in the atmosphere. It can be removed by uptake into the oceans, through uptake by living organisms and by mineralisation to carbonate.

Methane CH_4

Methane has the second largest RF of the long-lived greenhouse gases. CH_4. Methane has a GWP that is 20 - 25 times greater than carbon dioxide, making it more potent as a greenhouse gas than CO_2. However, the emitted amounts are smaller. Due to its shorter atmospheric lifetime, approximately 12 years, a much smaller reduction of methane emissions is needed, compared to what is needed for CO_2 and N_2O, in order to stabilise the atmospheric concentration of methane at current levels.

Nitrous oxide N_2O

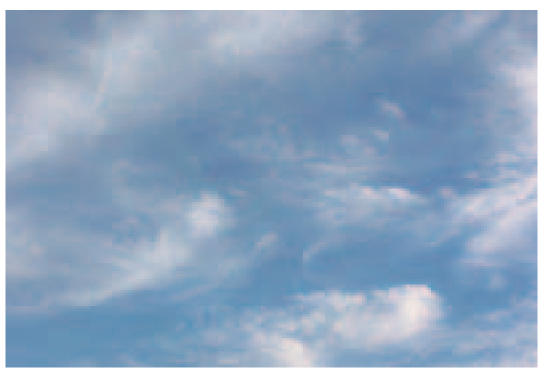
N_2O has a atmospheric lifetime of approximately 120 years, and it's heat trapping effects are about 300 times greater than CO_2. N_2O is the major source of ozone-depleting nitric oxide (NO) and nitrogen dioxide (NO_2) in the stratosphere and is thus routinely reviewed in the ozone assessments.

Fluorinated gases

Fluorinated gases such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6), are the most potent groups of greenhouse gases because of their high GWP and extremely long atmospheric lifetimes. Because some of these gases can remain in the atmosphere for centuries, their accumulation is virtually irreversible once emitted.

Other compounds in the air

In addition to the greenhouse gases mentioned above there are a number of other gases and compounds absorbing radiation that are emitted in considerable amounts, although their residence time is short and therefore they are not uniformly dispersed in the atmosphere. The impact is on continental or regional scale over areas with large emissions such as Europe or southern Asia. However,



their impact on the climate may be considerable and therefore they have to be considered when evaluating the climate effect. For some of these compounds, like black carbon and tropospheric ozone, there have been suggestions to include their impact in the mitigation strategies.

Stratospheric ozone

Stratospheric ozone is one of the major natural greenhouse gases, absorbing ultraviolet radiation from the Sun. Living organisms are adapted to the protection of the UV-radiation, provided by the ozone layer. The stratospheric ozone layer is being depleted by very stable compounds like CFCs emitted to the air and transported to stratosphere. To limit the destruction of the ozone layer and protect it for the future, these substances are subject to phase out, based on the Montreal Protocol that was put into force in 1989. Another threat to the stratospheric ozone layer however is nitrous oxide, which is relatively stable in the troposphere, but photolysed in the stratosphere. The phase out of CFCs has made N_2O the dominant ozone-depleting substance. Limiting N_2O emissions would therefore both enhance the recovery of the ozone layer as well as reduce the anthropogenic forcing of the climate system.

There are also a number of compounds in the lower atmosphere, the troposphere, having an impact on climate with a shorter geographical dispersion, from a local/regional to continental scale. These comprise water vapour, tropospheric ozone, sulphur and nitrogen compounds and particles.

Water vapour

Water vapour is maybe the most important natural greenhouse gas, having the most obvious impact on every-day radiation and climate.

Troposheric ozone

Tropospheric ozone is formed by reactions between carbon-containing substances, such as hydrocarbons and carbon monoxide, and nitrogen oxides in the presence of sunlight. It is estimated that 15 to 20 percent of the warming effect could be contributed to tropospheric ozone.

Particles

Sulphur and nitrogen oxides contribute to the climate change by the formation of particles in the atmosphere (secondary particles). Particles are also emitted directly to the atmosphere in the form of soot particles or black carbon (primary particles).

Sulphur dioxide, nitrogen oxides and ammonia form very fine sulphate-, nitrate- and ammonium particles (submicron particles, <1 µm), with a relatively long lifetime in the atmosphere. They are dispersed over continents without being deposited to water and ecosystems. These fine particles reflect solar radiation and counteract warming.

Soot particles (i.e. black particles) can absorb heat, as well as reflect solar radiation. Their ability to absorb heat have the largest impact when present over land covered with snow and ice but also over land areas covered by clouds, since nearly all incoming radiation over these areas otherwise would have been reflected back to space.

> **” Scientists estimate that nearly 50 per cent of the emissions causing global warming in the 21st century are from non-CO_2 pollutants ranging from black carbon and low-level ozone to methane and nitrogen compounds”.**
>
> *Achim Steiner, Executive Director of the UN Environmental Programme. UNEP Press release Sep. 4, 2009*

Since particles act as condensation nuclei, they also influence cloud formation as well as precipitation. The added effect on particle's radiative forcing is therefore difficult to assess. One estimate indicates that the present concentrations of sulphate particles in the northern hemisphere may lower the temperature by approximately 0.5º C. The Fourth Assessment Report (AR4) of the IPCC states that it is

- very likely (>90 % probability) that greenhouse gases emitted by human activities account for most of the observed increase in global average temperatures since the mid-20th century
- likely (>66 % probability) that, without the cooling effect of atmospheric aerosols, greenhouse gas emissions alone would have caused a greater increase in global mean temperature than what have been observed during the last 50 years.

Particles in the atmosphere have been shown to have dramatic climatic effects during large volcanic eruptions, such as the Tambora eruption in 1815. Estimates suggest that the eruption cooled the atmosphere in the northern hemisphere by 0.4-0.7°C. In North America and Europe the eruption was followed by what was called the year without a summer, when crops were destroyed due to snowfalls and frost in summertime.

The relative importance in Sweden of the most dominating greenhouse gases emitted – carbon dioxide, methane and nitrous oxide – is in agreement with the situation in other developed countries. Methane contributes significantly more in the developing countries, due to less use of fossile fuels and to agricultural activities, such as rice production. Figure 8 show the difference between developed countries and developing countries regarding the size of the emissions of the different greenhouse gases.

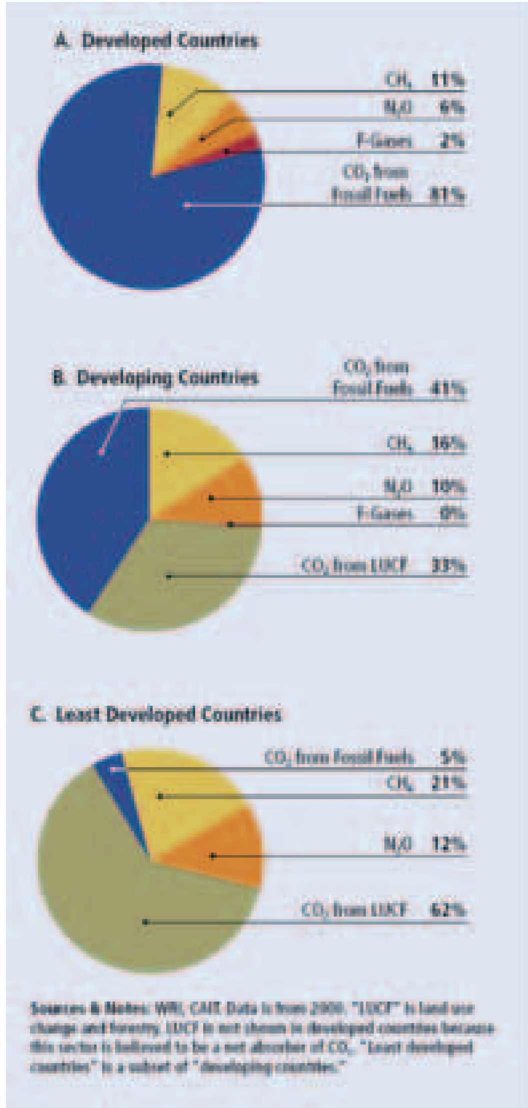


Figure 8: Emission profiles by gas and sources for different groups of countries.
Source: Baumert, Herzog, Pershing (2005).

3.6 Link between emissions and global warming

According to IPCC, the combined anthropogenic radiative forcing (RF) indicates that "*it is extremely likely that humans have exerted a substantial warming influence on climate*"[5]. The link between concentrations of greenhouse gases in the atmosphere and climate impact is shown by climate models which presently are considered to provide fairly reliable prognoses of climate effects caused by atmospheric concentrations of greenhouse gases.

IPCC has estimated the RF by different atmospheric constituents and other factors such as solar irradiance. Figure 9 below shows the warming effect of the long-lived greenhouse gases, to which there is a relatively small uncertainty linked. The figure also indicates that the thinning of the ozone layer in the stratosphere has a cooling impact, however relatively small. The RF values of surface albedo is both negative and positive, and the magnitude of these values is relatively more uncertain. The RF value of particles is negative, indicating a cooling effect, however with a large uncertainty.

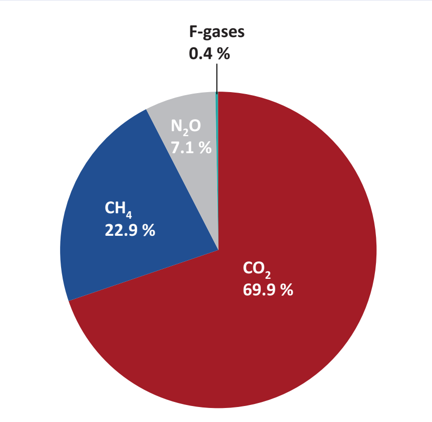


Figure 9: Contribution of anthropogenic emissions of greenhouse gases to the enhanced greenhouse effect from pre-industrial to Present (measured in Watts/ m^2). Please note that gases regulated under the Montreal Protocol are excluded.
Källa: (EPA, 2006b)

As a conclusion, the present level of scientific understanding (LOSU) is high for the radiative forcing of CO_2 and the other long-lived GHG. However, the effect of particles and aerosols as well as for surface albedo and solar irradiance is less well known. The total uncertainty in radiative forcing caused by anthropogenic impact is more than ±50 %.

It can also be concluded that by considering only the three most important greenhouse gases, the link between emission and global warming may be less certain, not least on a regional scale where more short-lived air pollutants such as particles and ground level ozone may contribute.

In comparison with models results, the observed warming in Northern Europe during the last decades is higher than expected. Questions have been raised whether this could be a consequence of the drastic decrease in sulphur dioxide emissions in Europe, and the connected decrease in cooling sulphate aerosol concentrations in the atmosphere.

5) Extremely *likely* represents a confidence level of 95% or higher

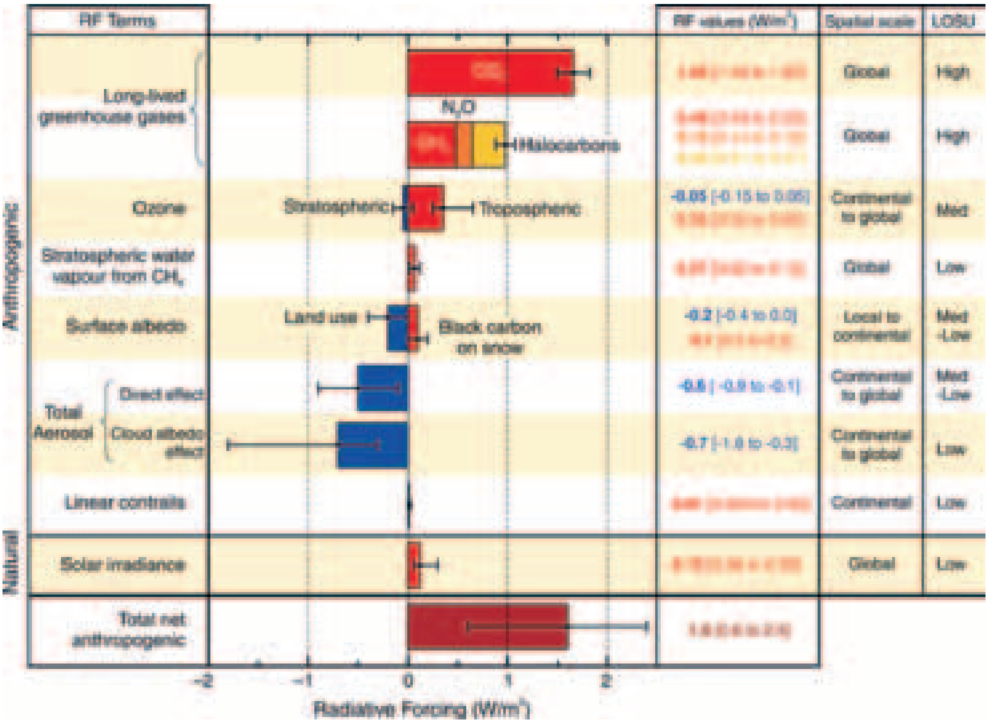


Figure 10: Global average radiative forcing (RF) estimates uncertainty and ranges in 2005 with respect to 1750 carbon dioxide (CO_2), methane (CH_4), nitrious oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. The range for linear contrails does not include other possible effectsof aviation on cloudness.
Source: IPCC (2007c)

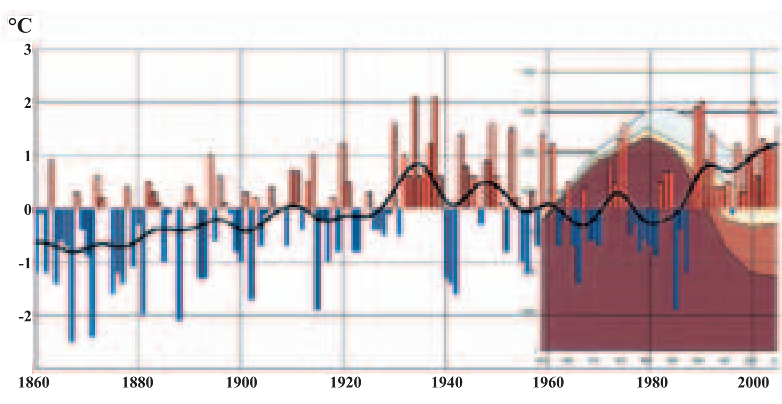


Figure 11: Are the decreased sulphur emissions in Europe and increased temperature connected? Or is the decrease in sulphur emissions (sulphate particles in the air) and the rapid increase in temperature in Northern Europe a mere coincidence?
Source: Hansson (2008)

3.7 Climate impact and air pollution effects

Most greenhouse gases have a long time of residence in the atmosphere, from one year to thousands of years. There are also more short-lived gases and particles in the atmosphere (such as the traditional air pollutants nitrogen oxides, sulphur dioxide, hydrocarbons and particles) which absorb radiation and consequently have an impact on climate. These compounds are subject to emissions reductions strategies due to their local and long range (over country borders and continents) impact on human health and ecosystems function and production.

The traditional air pollutants are to some extent emitted from the same processes as carbon dioxide. Consequently, the combat of air pollution will in many cases lead to reduced emissions of carbon dioxide. Many of these substances have a negative impact on human health and ecosystems, but they also have an impact on the global radiative balance.

4. SOURCES AND SINKS OF NON-CO_2 GREENHOUSE GASES

IN THIS CHAPTER

Major sources of non-CO_2 greenhouse gas emissions are energy supply and use, agriculture, industrial processes and waste management. The estimates are for some sources (such as emissions from the LULUCF sector) and components (such as N_2O) connected with considerable uncertainties.

Also for sinks, the atmospheric depletion of for example N_2O is still uncertain. The depletion of N_2O is linked to that of stratospheric ozone.

Of the fluor-containing gases, most components are very stable and only slowly decomposing in the atmosphere.

The estimates of total emissions of carbon dioxide are significantly better known than the emissions of CH_4 and N_2O.

4.1 Sources of greenhouse gases

Carbon dioxide is the major greenhouse gas accounting for around two thirds of the global greenhouse gas emissions. In 2000 the non-CO_2 greenhouse gases were responsible for about 30 % of the enhanced, human-induced greenhouse effect since preindustrial times.

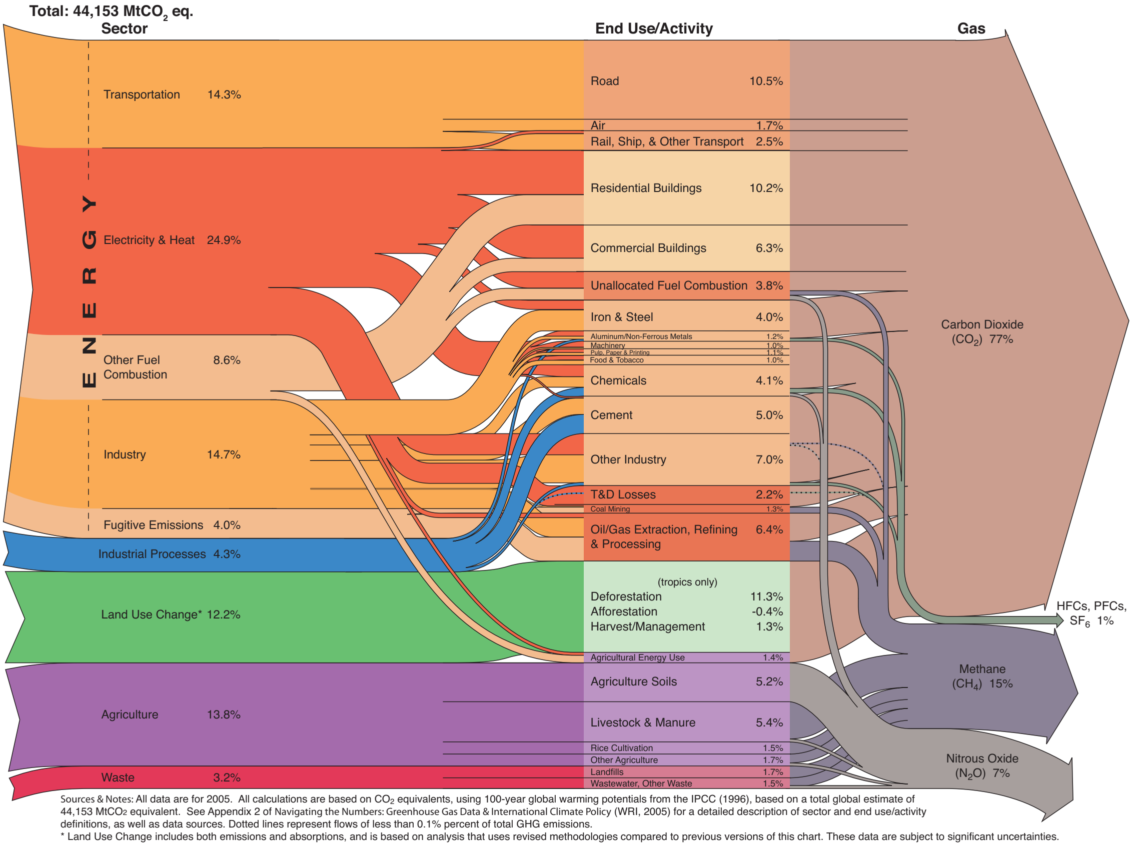


Figure 12: World Greenhouse Gas Emissions in 2005. Source: Herzog (2005)

In the EU-27, emissions of carbon dioxide account for approximately 83 % of total GHG emissions, whereas methane and nitrous oxide account for approximately 8 % each. The fluorinated gases account for approximately 1-2 %.

This means that the non-CO_2 greenhouse gas emissions cannot be disregarded when strategies to combat climate change are elaborated. It must however, be kept in mind that, compared to estimations of CO_2 emissions, there are large uncertainties in the estimations of non-CO_2 GHG emissions.

The major sources of greenhouse gas emission in the EU-27 are energy supply and use (mainly CO_2

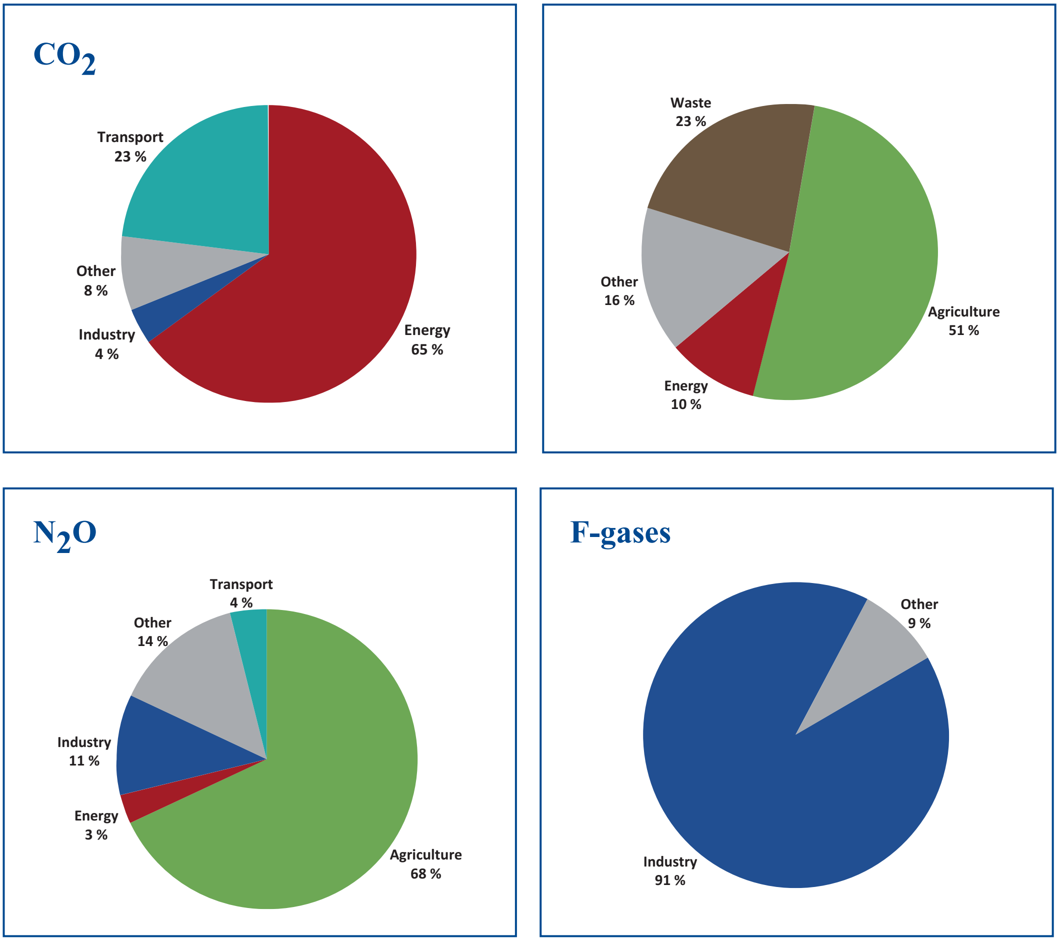


Figure 13: The shares of the largest source categories of emissions of CO_2, CH_4, N_2O and F-gases for EU-15 in 2007. Source: EEA (2009b).

from fossil fuel combustion in electricity and heat production, refineries, manufacturing industries and households and services), transport (mainly CO_2 from fossil fuel combustion but also N_2O from catalytic converters in vehicles), agriculture (mainly CH_4 from enteric fermentation and manure management and N_2O from soils and manure management), industrial processes (mainly CO_2 from cement production, N_2O from chemical industries and HFCs, used to replace CFCs in cooling appliances and from production of thermal insulation foams), and waste management (mainly CH_4 from waste disposal sites). Energy-related emissions (energy supply and use together with transport) account for around 80 % of total emissions, industrial processes for some 8 %, agriculture for some 9 % and waste for approximately 3 %.

Table 2: Global greenhouse gas emissions for 2000 ($MtCO_2$-eq) Source: EPA (2006a)

Sectors	CO_2	CH_4	N_2O	F-gases	Global Total	Percentage of Global Total GHGs
Energy	23 408	1 646	237		25 291	61%
Agriculture	7 631	3 113	2 616		13 360	32%
Industry	829	6	155	380	1 370	3%
Waste		1 255	106		1 361	3%
Global Total	31 868	6 021	3 114	380	41 382	
Percentage of Global Total GHGs	77%	15%	8%	1%		

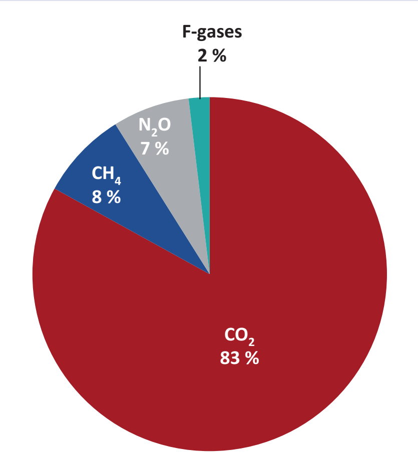


Figure 14: Share of 2007 greenhouse gas emissions in the EU-27, by gas[6].
Source: EEA (2009a).

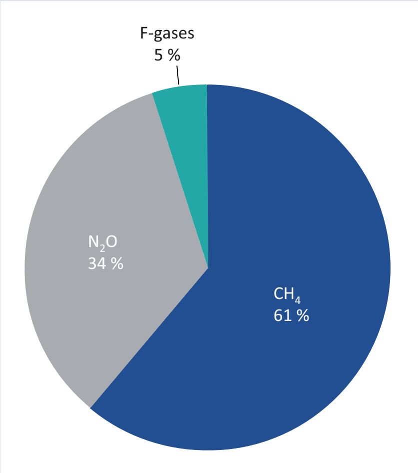


Figure 15: Percentage share of global Non-CO_2 emissions by type of gas in 2005. CO_2-equivalency based on 100-year GWP. The total emissions of non-CO_2 GHG amounted to 10 280 Mt CO_2-eq in 2005. Source: EPA (2006b)

6) Emissions from international aviation and international maritime navigation, not covered by the Kyoto Protocol, are not included here. If included in the total, the share of CO_2 would reach 84 % of total greenhouse gas emissions.

4.1.1 Sources of methane

Methane is emitted to the atmosphere from a variety of sources. The gas is produced whenever organic matter decomposes under anaerobic conditions, i.e. in the absence of oxygen. Methane in the atmosphere originates from both biogenic and non-biogenic sources.

Biogenic sources, i.e. sources produced by life processes such as plants and animals, include sources like wetlands, rice cultivation, livestock, landfills, forests, oceans and termites.

Non-biogenic sources of CH_4 include emissions from fossil fuel mining and burning, e.g. coal, natural gas (in which CH_4 is the major constituent) and petroleum, burning of biomass and waste treatment as well as emissions from geological sources such as natural gas seepage in sedimentary basins and geothermal processes including volcanoes.

Methane emission sources can also be divided into natural and anthropogenic sources. Wetlands, oceans, forests, fire, termites and geological sources are defined as natural sources, while fossil fuel combustion, some biomass burning, landfills and waste treatment as well as livestock and rice cultivation are sources caused by human activities. Natural wetlands are the largest single source of CH_4 emissions.

To influence the concentration of methane in the atmosphere, emissions can be reduced or the efficiency of sinks (removal mechanisms) increased. Measurements indicate that although the abundance of methane has increased by approximately 30 % during the last 25 years, its growth rate has decreased substantially. This decrease in growth rate is not understood, nor the future implications. It may be related to changes in the imbalance between CH_4 sinks and sources. There are, however, considerable uncertainties regarding the importance of some methane sources as well as their trends. Emissions inventories based on bottom up studies may, according to some studies, underestimate the emissions substantially. Some previously unknown sources of methane have also been discovered.

Agriculture

The main agricultural sources are enteric fermentation and manure management in livestock production, while a relatively small part comes from fertilisation of soils. Globally, livestock are the major source of anthropogenic emitted methane. Ruminant livestock, for example, account for about one third of the total anthropogenic methane emissions.

Enteric fermentation

Ruminants (e.g. cattle, buffaloes, goats, sheep and camels) produce significant amounts of methane as part of their digestive processes, which involves microbial fermentation of fibrous feeds, so called enteric fermentation. This process takes place in the rumen, or the large fore-stomach, and the produced methane (a by-product of the process) is exhaled by the animal, and is thus released into the atmosphere. In monogastric animals, including humans, methane is also produced in the digestive processes, although in much smaller quantities than in ruminant animals.

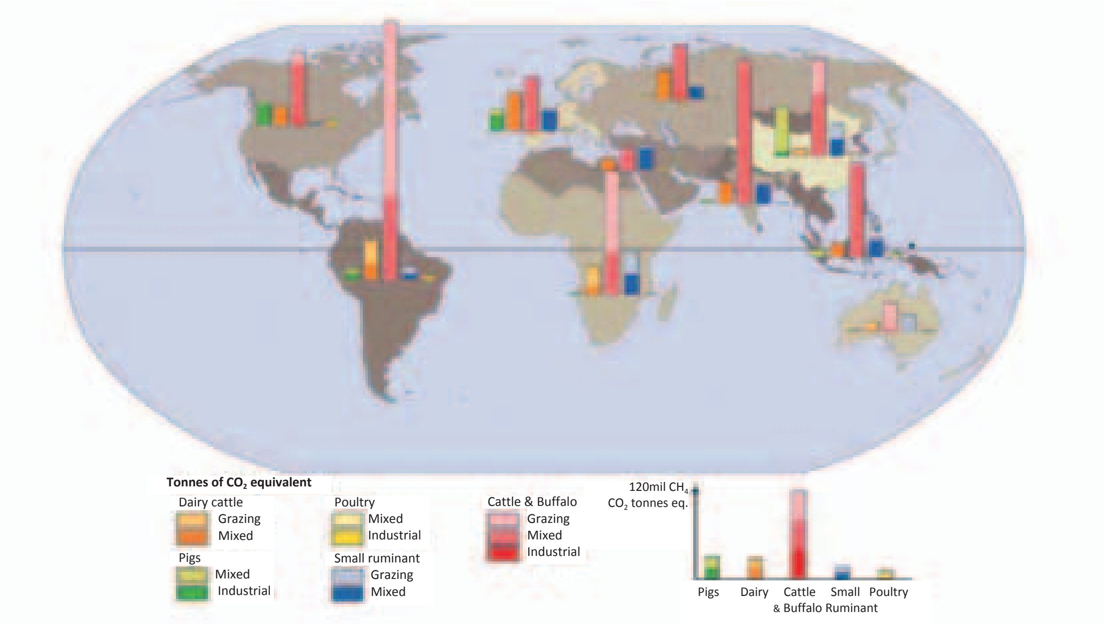


Figure 16: Total methane emissions from enteric fermentation and manure per species and main production system. Source: FAO, 2006

The amount of methane produced in enteric fermentation varies highly due to variations in, for example, the quantity and quality of the feed, animal body weight, age and amount of exercise. It also varies among animal species and among individuals of the same species, thus complicating a global estimate of the total methane emissions from enteric fermentation in livestock.

Manure management

Beside the methane emitted from enteric fermentation, livestock also give rise to methane from the anaerobic decomposition of organic material in manure. Most of this methane is formed when manure from livestock is managed in liquid forms, in lagoons or holding tanks. Manure handled in a dry form, however, like when deposited on fields and pastures, does not produce significant amounts of methane. Emissions from livestock manure are affected by several factors that influence the growth of the bacteria that are responsible for methane formation, including moisture, ambient temperature and storage time. The amount of emissions also depends on the manure's energy content, mainly determined by livestock diet. Feed with higher energy content for example produces manure with more volatile solids, thus increasing the substrate from which CH_4 is produced.

Although the emissions of methane from manure management are significantly lower than from enteric fermentation, manure management contributes more than the burning of residues and rice cultivation.

On a species level, pig/swine production contributes to the largest share of emissions from manure management (globally, representing almost 50 % of total livestock manure emissions), followed by dairy cattle.

Rice cultivation

Flooded rice fields, where decomposition of organic material can take place anaerobically, produce emissions of methane. However, the magnitude of the latter emissions is not well known.

Waste

The waste handling sector is the fourth largest sector in the EU-15, when it comes to total greenhouse gas emissions, and it is the second largest sector after agriculture concerning emissions of methane. Methane emissions from managed and unmanaged waste disposal on land, as a result of anaerobic microbial decomposition of organic matter, account for a majority of these emissions. Methane is also produced from anaerobic decomposition of organic matter by bacteria in sewage facilities (i.e. from waste water handling).

The amount of methane generated in the waste sector is determined by factors such as quantity of waste disposed per capita, composition of waste disposed and type of waste disposal site, i.e. landfill versus open dump.

Other sources

Fugitive emissions from oil and natural gas fuels production and handling

Most of the methane emissions in this sector are fugitive emissions occurring during exploration, production, processing, transport and storage of oil and natural gas. Distribution and transport of natural gas are the main source of emissions.

A Study by Swedish Waste Management ("Avfall Sverige") shows

The Contribution of the Waste Sector to the EU Renewable and CO_2 Targets

The study shows that the renewable parts of the waste streams (for waste remaining after material recycling) can contribute with as much as 30 % of the 20 % CO_2 reduction target and 20 % of the 20 % RES target to 2020. This can be achieved by the avoidance of landfilling and replacing fossil fuels with waste fuels for heat and electricity production.

Fugitive emissions from solid fuels

During mining of coal, methane trapped in the coal seams can be emitted into the atmosphere. The size of emissions are due to variations in coal rank (refers to the degree of coal formation; high rank coals such as bituminous coal contain larger amounts of methane than low rank coals such as lignite), mining depth (in general, the amount of methane is larger at higher depths), gas content and mining methods. Underground mines give rise to more CH_4 emissions than surface mines.

Emissions of methane may also occur during processing and delivery of the extracted fuels because coal normally continues to emit gas after it has been mining, although at a slower rate. Unless completely flooded, abandoned coal mines may continue to emit methane, especially if the mines had significant emissions during operation. Even sealed mines may emit methane due to migration of gas through cracks and fissures in the overlying strata.

Fuel combustion

Methane is produced only in small quantities during incomplete combustion under low oxygen surplus and low temperature.

Industrial processes

A small part of the total estimated methane emissions is released from various industrial processes such as aluminum production, ferro-alloy production, steel production and ammonia production.

LULUCF

Methane emissions also arise because of changes in land use, such as clearing of forests for agricultural use.

4.1.2 Sources of nitrous oxide

Primary emission sources of N_2O are nitrification (oxidation) and denitrification (reduction) processes in soils; i.e. it is formed in both aerobic and anaerobic conditions. The largest anthropogenic sources of nitrous oxide emissions are fertilisation of agricultural soils together with land use changes and industrial processes.

The amount of N_2O emitted from soils is generally limited by the nitrogen content of the soil. Nitrogen may remain in agricultural soils for decades, even after a complete stop for manuring. It is therefore likely that N_2O would continue to be emitted from these soils for a period as long as 50 years. Atmospheric deposition of nitrogen compounds, and leaching of nitrates through irrigation and groundwater, can therefore affect the size of "natural" emitted N_2O.

Other sources of N_2O from human activities are vehicle catalysts, fuel combustion and waste water treatment. Globally, it is estimated that human activities amounts to about one third of all N_2O emissions, although there are large uncertainties in the estimations. A major part of these emissions are estimated to come from agricultural activities such as crop and livestock production.

Approximately two thirds of the naturally emitted N_2O is formed in soils and about one third in oceans. Nitrogen fertiliser inputs to phosphorous-limited tropical ecosystems, generate NO and N_2O fluxes that are 10 to 100 times greater than when the same fertiliser addition is made to nitrogen-limited ecosystems in the northern hemisphere. Most of the N_2O, both natural and anthropogenic emissions, thus originates from tropical soils.

Agriculture

The agricultural sector is the largest source of N_2O emissions and the emissions derive from three main sources: direct emissions from applied fertilisers, emissions from storage of manure and indirect emissions from nitrogen lost to the agricultural system, e.g. through atmospheric deposition, leaching or runoff.

Manure contains various forms of complex nitrogen compounds. When applying manure to land, as a fertiliser, the nitrogen compounds, due to various bacteria present in soil, will break down, and under the right conditions, lead to the release of nitrous oxide. The size of these N_2O emissions depends on nitrogen availability, soil moisture content and temperature; the first being the most important factor. N_2O will also form during handling and storage of manure, however, compared to the total nitrogen excreted only a very small amount is converted to N_2O. In contrast to methane emissions, emissions of N_2O are most likely to occur in dry waste-handling systems where both aerobic and anaerobic conditions are present.

Fuel combustion

Nitrous oxide is also formed in combustion processes, mainly as a by-product of the fuel-NO mechanism. The temperature span where N_2O is formed lies between 530º C and 930º C, with a maximum at around 730º C. An increase of the pressure of the combustion gases or an increase in the amount of oxygen increases the emissions of N_2O.

Techniques to lower NOx emissions, such as fluidised bed combustion (FBC) and Selective Non Catalytic Selective Reduction (SNCR), can also lead to emissions of N_2O. The lower combustion temperature in FBC for example leads to higher emissions of nitrous oxide. In NCSR injections of ammonia or urea into the flue gas, in order to reduce emissions of NO, leads to emissions of nitrous oxide.

Transport

Emissions of N_2O from the transport sector are mainly related to the use of catalysts, at reducing conditions. Emissions of N_2O are considerably higher from vehicles fitted with catalysts, especially aged catalysts (e.g. after use of 15000 km), than from vehicles with no catalysts.

Industrial processes

Adipic and nitric acid production are the two main industrial processes that contribute to emissions of N_2O.

Adipic acid is used mainly as raw material in manufacturing of nylon for industrial carpets and some low temperature lubricants. Nitrous oxide is a by product of the final oxidation step when cyclohexane is oxidised with nitric acid to produce adipic acid.

Nitric acid is – besides being used for production of adipic acid – mainly used as a feedstock in fertiliser production and in the production of explosives. Most of the nitric acid is produced through the catalytic oxidation of ammonia, a process in which nitrous oxide is formed as a by-product.

Also, there are a number of other chemical processes that can give rise to N_2O. Generally, these are processes that involve either a nitrogen compound, or a catalytic reduction step. Examples of processes are furnace steel plant, aluminium production, petroleum products processing and pulp and paper processes. However, the size of these emissions is small compared to other sources.

Waste

N_2O is emitted from waste handling, although in small amounts compared to other sources. The emissions stem from incineration of waste, waste water treatment and burning of agricultural residues, e.g. straw burning. The emissions from incineration of waste are of the same order as those originating from combustion of fossil fuels. Emissions from waste water treatment are due to denitrification processes used in waste water treatment plants.

LULUCF

As microbiological processes in soils are the primary sources of N_2O, human activities such as changes in land-use practices and forestry methods modify soil emissions and cause emissions of N_2O. The present knowledge on N_2O emissions from these sources however is limited and the uncertainties are large.

Other sources

A small amount of N_2O emissions are fugitive emissions related to solvent use or of oil and natural gas recovery.

4.1.3 Sources of fluorinated gases (F-gases)

These gases have a number of industrial uses and few (if any) have natural sources.

Hydrofluorocarbons

HFCs have mainly been developed to replace ozone-depleting substances, like CFCs and HCFCs. Refrigeration, air-conditioning units, as well as heat pumps, are therefore some of the sources for emissions of HFCs.

Perfluorocarbons

The most common PFCs, namely tetrafluoromethane (CF_4) and hexaflurومethane (C_2F_6), are used mainly in aluminium production and in semiconductor manufacture.

Sulfur Hexafluoride

SF_6 is mainly used for insulation in electric power transmission and in various applications in the magnesium and semiconductor industries.

The fluorinated gases are not, in contrast to the former used carbon containing freons (CFCs), harmful to the stratospheric ozone. According to Regulation (EC) No 842/2006 some products containing fluorinated gases are already prohibited to place on the European market.

4.2 Sinks of greenhouse gas emissions

Sinks of methane

Major sinks of CH_4 are oxidation by reaction with OH radical mainly in the troposphere (some 90 % of the removal), microbial uptake in soils (around 7 %) and by the reaction with chlorine atoms in the oceans (less than 2 %).

Sinks of nitrous oxides

N_2O is photolysed in the stratosphere in a process, where it ends up as either nitrogen or oxygen gas or as nitrogen monoxide. Ozone is depleted by the process.

Table 3: Summary of the main sources of non-CO_2 greenhouse gases. Source: EPA (2006b)

Methane	Nitrous Oxide	High GWP Gases
Energy Coal Mining Activities Natural Gas and Oil Systems Stationary and Mobile Combustion Biomass Combustion	**Energy** Biomass Combustion Stationary and Mobile Combustion	**Industrial** (category and gas) Substitutes for Ozone-Depleting Substances: • HFCs, PFCs HCFC-22 Production: • HFC-23
Industrial Other Industrial Non-Agriculture • Chemical Production • Iron and Steel Production • Metal Production • Mineral Products • Petrochemical Production • Silicon Carbide Production	**Industrial** Adipic Acid and Nitric Acid Production Other Industrial Non-Agricultural: • Metal Production • Miscellaneous Industrial Processes	Primary Aluminium Production: • PFCs Magnesium Manufacturing: • SF_6 Electrical Power Systems: • SF_6
Agriculture Manure Management Enteric Fermentation Rice Cultivation Other Agricultural: • Agricultural Soils • Field Burning of Agricultural Residues • Prescribed Burning of Savannas	**Agriculture** Manure Management Agricultural Soils Other Agricultural: • Field Burning of Agricultural Residues • Prescribed Burning of Savannas	Semiconductor Manufacturing: • HFC, PFCs, SF_6
Waste Landfilling of Solid Waste Wastewater Other Non-Agricultural (included with waste totals*): • Solvent and Other Product Use • Waste Combustion	**Waste** Human Sewage Other Non-Agricultural (included with waste totals*): • Fugitives from Solid Fuels • Fugitives from Natural Gas and Oil Systems • Solvent and Other Product Use • Waste combustion	

* Other Non-Agricultural is included in the waste sector because waste combustion is the dominant sub-source of emissions

Sinks of fluorinated gases

The fluorinated gases are only very slowly removed from the atmosphere. HFC-emissions can be regarded as mainly irreversible accumulation. PFCs have extremely stable molecular structures and it is only when they reach the mesosphere, at the boundary of space, that they begin, very slowly, to break down by high-energy ultraviolet rays from the Sun. The removal is extremely slow and is considered to take thousands of years. The same can be said for SF_6.

4.3 Uncertainties in emission estimates

There are large uncertainties in the estimations of some of the greenhouse gas emissions. Generally, estimations of CO_2 emissions are the most certain, although there are some sources with higher uncertainty than others. Especially CO_2, CH_4 and N_2O from agriculture and waste management are highly uncertain. Emissions from the LULUCF sector is also very uncertain. For example, changes in carbon stocks of trees are estimated to contain uncertainties of around ± 30-100 %. Also, carbon

±30-100 %

stocks changes in soils and emissions and removals from land use changes are estimated to be large. Uncertainties in carbon stock changes from activities such as deforestation, forest management, cropland management and grazing land management are estimated to vary between ± 50-100 %.

±50-100 %

Regarding CH_4 it is estimated that the uncertainty measured in emission inventories can be around ± 20-30 %. Generally the uncertainty is higher in developing countries compared to developed countries. Sectors with higher uncertainty are enteric fermentation, rice cultivation, landfills, coalmines and residential biofuel use. Emissions of CH_4 from combustion are largely dependent on process conditions such as temperature, combustion technology and fuel quality, and the uncertainty in CH_4 emissions from stationary combustion is therefore relatively large, some estimations vary between ±50-150 %.

±50-150 %

For N_2O emissions the uncertainty is high, estimations of the uncertainty range from ±30 to over 200 %, some suggest even higher uncertainty for certain sectors. However, even in relatively certain sectors, such as emissions from power plants and industry, the uncertainty of N_2O emissions carry uncertainties between 30-70 %. N_2O emissions from combustion depend on combustion processes and are sensitive to nitrogen oxide reduction technologies which make the uncertainty relatively large. The largest uncertainties are found in emissions from agricultural soils.

±30-70 %

The uncertainty of HFC emissions ranges from 15% in some developed countries to 50 % in others. For PFC the uncertainty ranges from 20-100%, whereas typical SF_6 emissions uncertainties in industrialised countries currently range between 25 and 50 %. The uncertainty of HFC is mainly due to storage and leakage losses, while the PFC uncertainty can be attributed to differing estimation methods as well as a high variability in the generation of PFC in industrial processes.

5. ABATEMENT MEASURES AND MITIGATION POTENTIALS FOR NON-CO_2 EMISSIONS

IN THIS CHAPTER

Mitigation of greenhouse gases must consider not only CO_2 but also the other long-lived greenhouse gases.

A so called multi-gas strategy has been found to achieving the same climate goal but at considerably lower costs than a CO_2-only strategy. Globally, the potential for "no-regret" non-CO_2 greenhouse gas abatement is significant. This is also shown to be the case for EU-27.

On a global level the energy and agriculture sectors offer the greatest potential for cost-effective mitigation of non-CO_2. There is also a major potential in the waste and industrial processes sectors.

Black carbon particles in the atmosphere are short-lived substances, which are not well mixed in the atmosphere and showing large regional variations, but with a considerable impact on climate. Mitigation of these particles is considered a cost-effective way of reducing the impact on the global radiation balance.

Methane mitigation shows the largest potential for a cost-effective reduction.

5.1 Estimations of emission targets in order to meet the 2ºC target

There are a number of estimates made of the necessary reductions of greenhouse gas emissions needed in order to control global warming. The European 2ºC target was first established in 1996 in preparations for the Kyoto negotiations. The target was set up with the objective of limit a global mean temperature increase to no more than 2ºC over pre-industrial level. In order to meet the target with at least a 50 % probability, it is estimated that atmospheric greenhouse gas concentration must stabilise at a level below 440 ppmv (parts per million by volume) CO_2-eq. Recent estimations though indicate that a much lower concentration is needed. The Swedish Scientific Council on Climate Issues states that the concentration of greenhouse gases in the atmosphere must stabilise at level of 400 ppmv.

As this literature review has shown, translating the atmospheric concentration requirements into reliable emission pathways that will meet this target is a rather difficult task, considering all the uncertainties that are connected with the climate change mechanisms. Table 4 presents some possible reduction targets needed for meeting the 2ºC target, both on a global scale and within the EU. The targets are set up as reductions in greenhouse gas emissions compared to 2004 levels when considering the situation globally and compared to 1990 levels considering the situation within Sweden and EU.

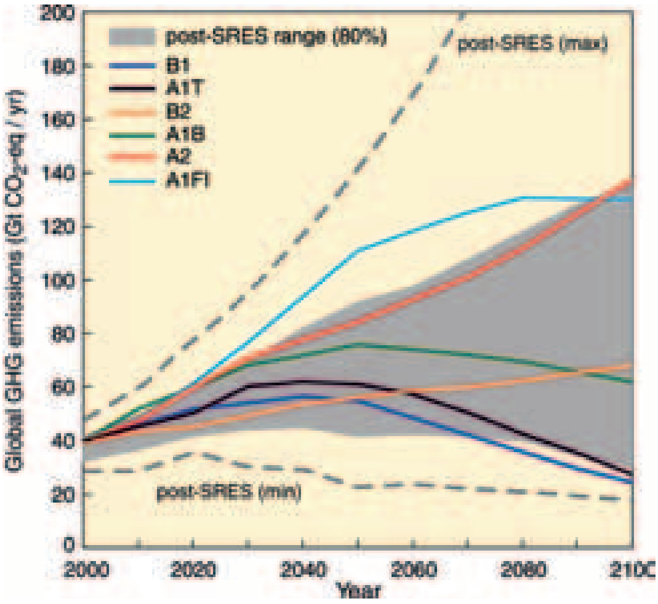


Figure 17: Non-mitigation scenarios (SRES) for GHG emissions from 2000 to 2100 in the absence of additional climate policies. Source: IPCC (2007b).

Table 4: Possible reduction targets needed for meeting the 2°C target.
Source: Vetenskapliga rådet för klimatfrågor (Swedish Scientific Council on Climate Issues) (2007)

	2020	2050	2100
Globally	-10%	-50%	-100%
Within EU	-30-40%	-75-90%	-100%
Within Sweden	-20-25%	-70-85%	-100%

A recent study by European researchers shows

Why non-CO_2 emissions should not be overlooked

Nitrous oxide and methane contributions to the GHG balance in Europe, mainly through agricultural emissions, effectively cancel out the benefits provided by carbon sequestered in forests and grasslands. If the emissions of these two gases would be eliminated it would offset all the non-biological GHG emissions in Europe, that is, essentially all the emissions caused by human activities. The study suggests that policy approaches should specifically target emissions from agriculture. Since the biggest source of agricultural nitrous oxide is the overuse of fertiliser, reducing the use of fertiliser could have be significantly effective. Capturing methane produced by animals in intensive farming reduces GHG emissions, and at the same time provides an important source of renewable energy.

However, the study also warn that Europe's carbon sink is under threat and that policies encouraging the use of wood biomass for energy production soon could contribute to the releasing of carbon that has been locked away for years. This is expected to happen when forests planted after the World Wars is soon to be harvested, thus releasing carbon that is today seen as a carbon sink.

Source: Schulze, E.D., Luyssaert, S., Ciais, P. et al. (2009). Importance of methane and nitrous oxide for Europe's terrestrial greenhouse-gas balance. Nature Geoscience. 2:842-850

5.2 Possible measures of reductions of non-CO_2 greenhouse gas emissions

A study from the USEPA have considered the potential for reducing non CO_2 greenhouse gases and concluded that there is a large potential for "no regret" abatement, i.e. measures with no or very low costs. The global potential for reducing emissions to a cost of \$0/t CO_2-eq is estimated to be 600 million metric tons CO_2-eq, 5 % of the baseline scenario emissions. At a price of \$10/t CO_2-eq, the potential is larger than 2 000 Mt CO_2-eq. At \$20/t CO_2-eq, the potential increases to 2200 Mt CO_2-eq, equal to 17 % of the baseline scenario. The sectors having the largest potential globally for low-cost reductions of greenhouse gases, are energy and agriculture sectors. Of the non-CO_2 greenhouse gases, methane mitigation has the largest potential. China, USA, EU, India, and Brazil are the countries with the largest emissions and consequently offer the largest reduction potential.

A number of technologies and measures are possible to reduce emissions of non-CO_2 greenhouse gases. In this review we have mainly considered mitigation potentials as suggested in the reports from IPCC, EPA, IIASA and McKinsey & Company.

Measures to reduce methane emissions

One of the most important measures to reduce methane emissions is to avoid the disposal of biodegradable solid waste to landfills, but instead re-

Table 4: Possible measures of reductions of non-CO_2 greenhouse gas emissions

Gas	Sector	Abatement technology description
CH_4	Agriculture	Farm-scale and community-scale anaerobic digestion of animal manure Dietary changes for dairy cows and cattles Alternative rice strains and improved aeration of rice fields Ban on agricultural waste burning
	Waste	Waste diversion options: recycling of paper and wood waste, composting and biogasification of food waste, and waste incineration Landfill options: gas recovery with flaring or gas utilisation
	Wastewater	Domestic urban wastewater collection with aerobic or anaerobic treatment with or without gas recovery Domestic rural wastewater treatment in latrines or septic tanks Industrial wastewater treatment with aerobic or anaerobic treatment with or without gas recovery
	Coal mining	Recovery with flaring or utilisation of gas
	Gas distribution	Replacement of grey cast iron networks and increased network control frequency
	Gas and oil production & processing	Recovery and flaring of gas
N_2O	Agriculture	Reduced and/or improved timing of fertiliser application Use of advanced agro-chemicals (e.g. nitrification inhibitors) Precision farming
	Energy combustion	Combustion modifications in fluidised beds
	Industrial processes	Catalytic reduction in nitric and adipic acid production
	Wastewater	Optimisation of operating conditions in wastewater plants
	Direct N_2O use	Replacement/reduction in use of N_2O for anaesthetic purposes
HFC	Aerosols	Alternative propellant
	Stationary air conditioning and refrigeration	Good practice: leakage control, improved components, and end-of-life recollection Process modifications for commercial and industrial refrigeration
	Mobile air conditioning and refrigeration	Alternative refrigerant: pressurised CO_2 Good practice: leakage control, improved components, and end-of-life recollection
	HCFC-22 production	Incineration: post combustion of HFC-23
	Foams	Alternative blowing agent for one component and other foams
PFC	Primary aluminium production	Conversion of SWPB or VSS to PFPB and retrofitting of VSS and SWPB
	Semiconductor industry	Alternative solvent use: NF_3
SF6	Magnesium production and casting	Alternative protection gas: SO_2
	High and mid voltage switches	Good practice; leakage control, improved components, and end-of-life recollection
	Other SF6 use	Ban of use

cycle, compost or incinerate organic waste or by controlling and/or make use of landfill emissions. Such measures are already being implemented within EU as a consequence of the Landfill directive. Methane emission can also be avoided by increased collection and treatment of wastewater.

Other control methods include gas recovery at coal mines and gas and oil production sites in addition to controlling fugitive emission from gas distribution systems. Methane from the agriculture sector can be controlled through anaerobic digestion of animal manure. This can be made on farm scale, if the farm is big, or on a large community scale. Also dietary changes for cattle and ban on agricultural waste burning adds to the emission reduction of methane.

Measures to reduce nitrous oxides emissions

Nitrous oxides emissions can be reduced by agriculture process changes, such as optimising the procedure for fertiliser application, and use of agriculture chemicals to avoid nitrification. Energy combustion emissions can be reduced by modifying the combustion in fluidised beds. Industrial emissions can be decreased by catalytic reduction in the production of nitric acid and adipic acid. Other possible measures are changes in operating conditions in wastewater treatment plants and lowered use of N_2O as anaesthetic gas.

Measures to reduce emissions of fluorinated gases

Emissions from the use of fluorinated greenhouse gases can be reduced by the selection of alternative chemicals; such as aerosol propellants, blowing agents and refrigerants. Good practice involving leakage control, improved components and end-of life collection of gases in stationary and mobile refrigeration, together with process modification for commercial and industrial refrigeration units also contribute to emission reduction.

5.3 Costs for reductions of non-CO_2 greenhouse gas emissions

Most mitigation scenarios for greenhouse gas emissions reduction mainly include measures for reducing CO_2 emissions. This is considered to be partly due to a lack of consistent information on the reduction potential for the non-CO_2 greenhouse gases. However, analyses of the effects of including also the non-CO_2 gases in mitigation scenarios have shown that major cost reductions can be obtained through relatively cheap abatement measures, at least for some of the non-CO_2 gases. Also, there is an increase in flexibility.

One IPCC discussion paper presented an analysis of a multi-model comparison on scenarios which included non-CO_2 gases. The multi-gas strategy was found to achieve the same climate goal, but at considerably lower costs than a CO_2-only strategy (Figure 18). The cost reduction could amount to about 30-50 %. Further, the contribution by the non-CO_2 gases for the total reductions is very large early in the scenario period, some 50-60 % during the first two decades.

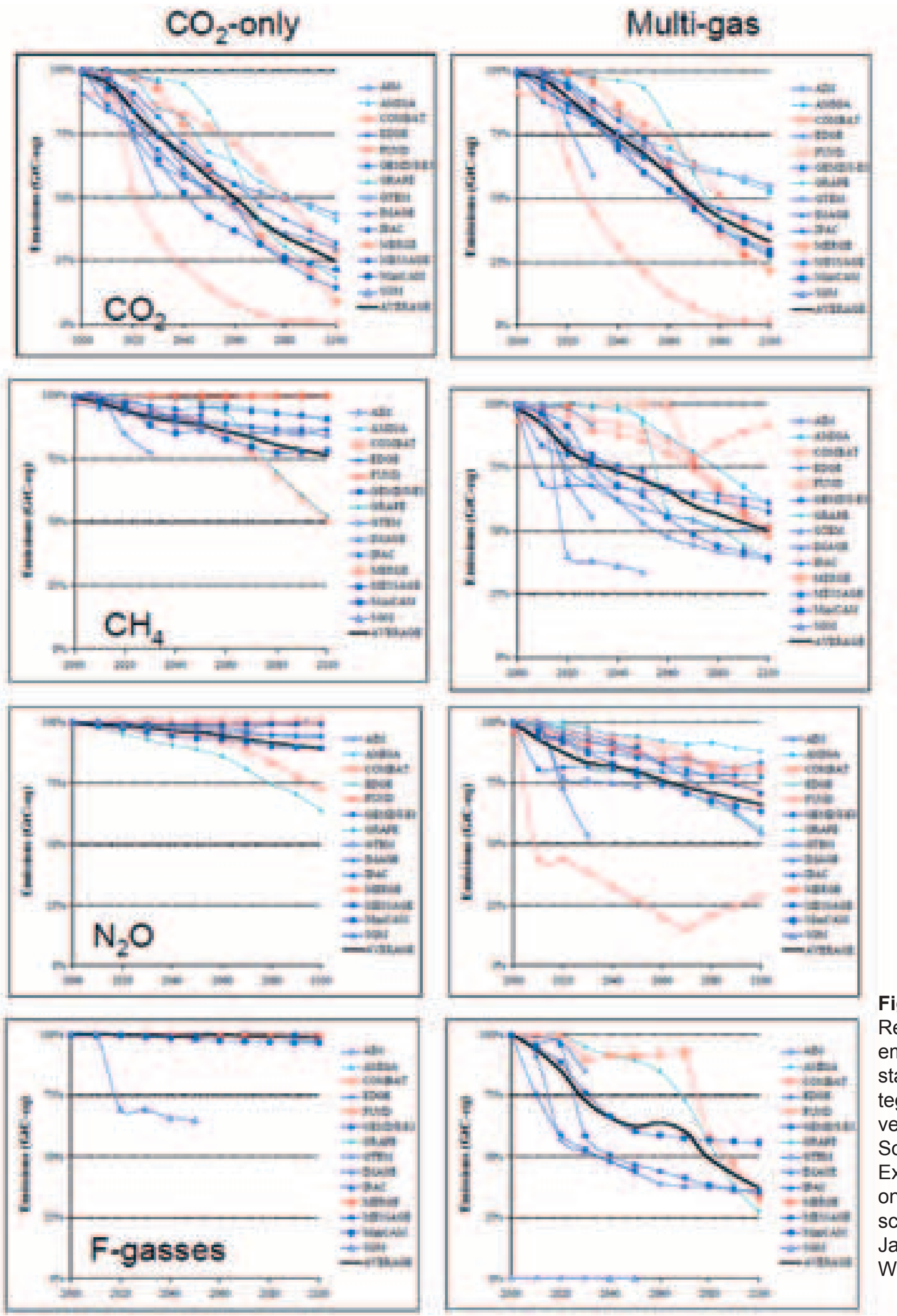


Figure 18: Reductions of emissions in the stabilisation strategies, CO_2-only versus multigas. Source: IPCC Expert Meeting on emission scenarios, 12-14 January 2005, Washington D.C.

In a study by McKinsey & Company (Pathway to Low Carbon Economy) cost curves were estimated for a large number of possible control options for reducing all greenhouse gas emissions, see figure 19. The basis the abatement for potentials and costs to reduce non-CO_2 greenhouse gases is to a large extent based on the EPA report Global Anthropogenic Emissions of Non-CO_2 GHG 1990-2020.

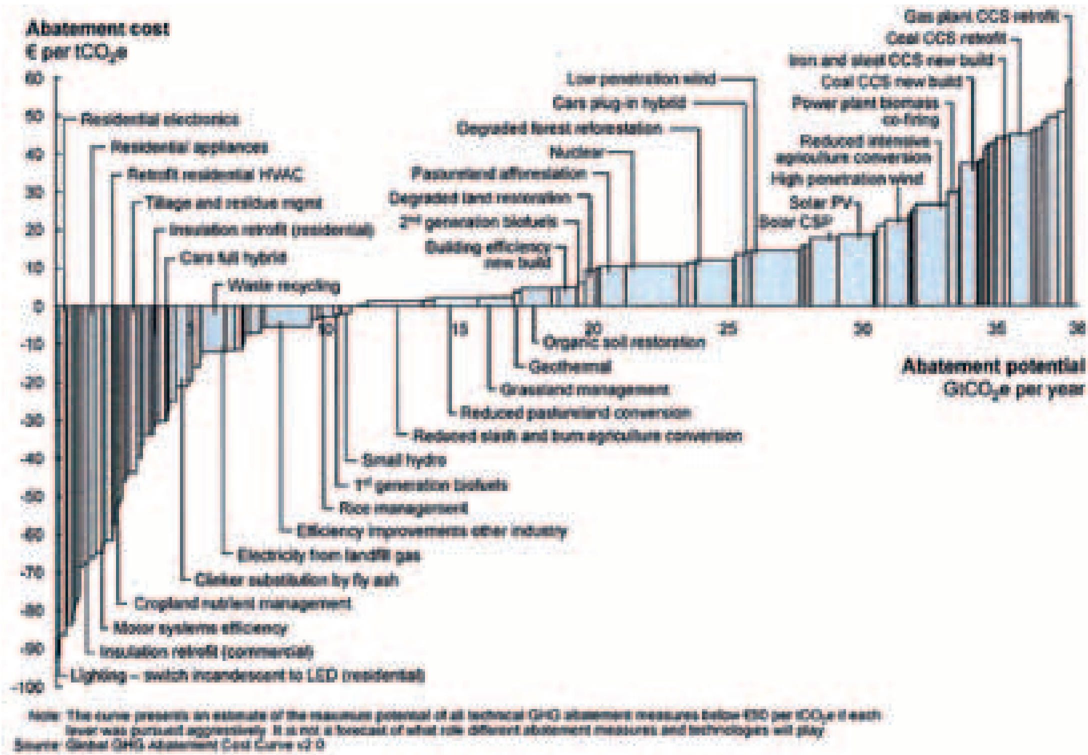


Figure 19: Global GHG abatement cost curve beyond business-as-usual - 2030.
Source: McKinsey & Company (2009)

Figure 20 shows a number of measures that can be applied at a negative cost, i.e. the measure require no substantial cost.

The McKinsey & Company study points out measures for all sectors. The abatement potential in the agriculture sector is large, although the uncertainties around the potential are significant.

Some of the measures pointed out for this sector:

- Improved grassland management is the single largest abatement lever, which consists of increased grazing intensity, increased productivity, irrigation of grasslands, fire management, and species introduction.
- Land degraded by excessive disturbance, erosion, organic matter loss, acidification, for in-

stance, can be restored through revegetation, improved fertility, reduced tillage, and water conservation.

- Management of cropland to reduce GHG emissions consists of improved agronomy practices, reduced tillage of the soil, reduced tissue removal, improved nutrient management, and better rice management and rice-nutrient management practices.
- Dietary additives and feed supplements can reduce methane emissions from livestock.

[McKinsey, 2009]

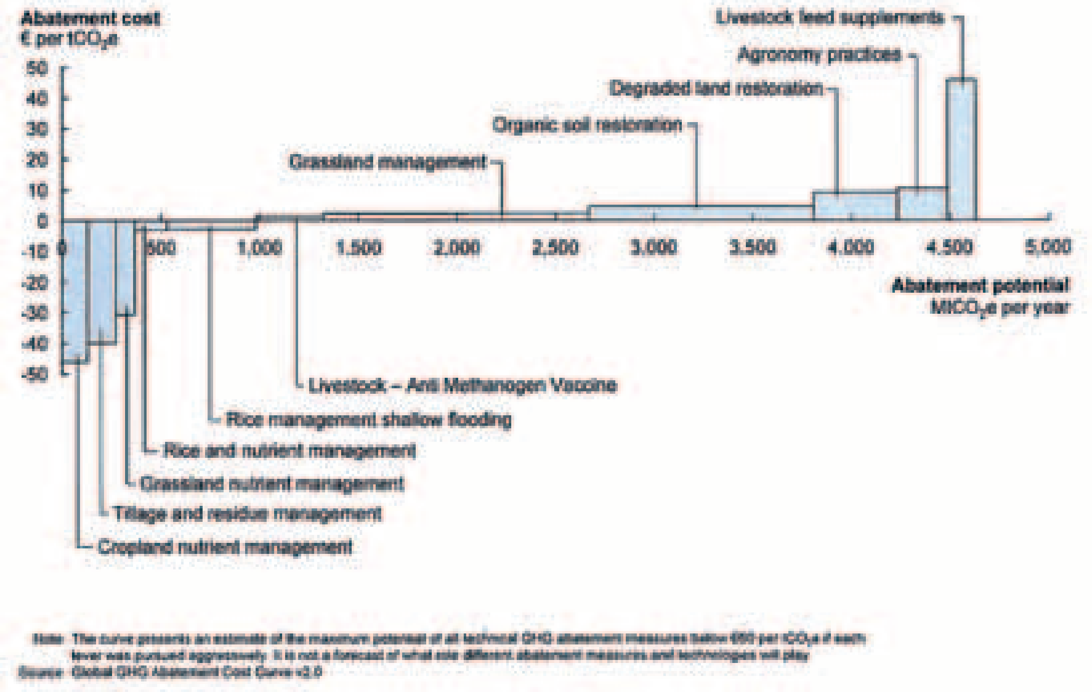


Figure 20: Global GHG abatement cost curve for the Agriculture sector.
Source: McKinsey & Company (2009)

The US EPA report (2006) *Global Mitigation of Non-CO_2 Greenhouse Gases* analyses the global mitigation potential for the non-CO_2 greenhouse gases. It includes marginal cost curves illustrating the abatement potential of these gases by sector and by region. Major findings of the EPA report are that on a global level, the energy and agricultural sectors offers the greatest potential for cost-effective mitigation of non-CO_2 greenhouse gases. However, in the absence of a carbon price incentive, there is also a major potential in the waste and industrial processes sectors. The report finds that methane mitigation show the largest potential and also that the largest emitters on a global level - United States, China, EU-15, Brazil and India - offer large potential mitigation opportunities for the non-CO_2 emissions.

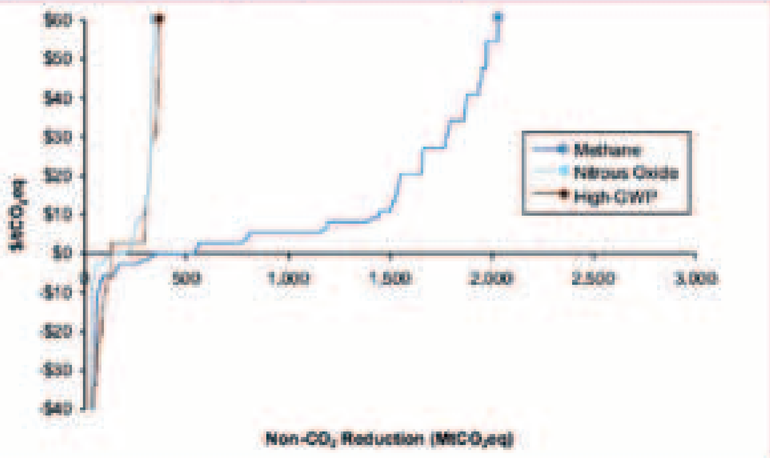


Figure 21: Global 2020 MACs by Non-CO_2 Greenhouse Gas Type. Source: EPA (2006a)

For the EU member states IIASA has provided estimates of the greenhouse gas reduction potential. The IIASA atudy shows the importance of reducing and controlling CH_4, N_2O and F-gases. Optimisation runs with the GAINS model were made based on the economic situation in early 2008. The IIASA study (Amann, 2008) includes possible measures and their economic potential in relation to a baseline scenario showing the estimated business as usual case from 2005 to 2020. The reported results for Europe show the potential of reducing non-CO_2 greenhouse gas emissions in comparison to CO_2 emission reductions. The IIASA calculations mainly include technical measures. Considerable emission reductions can however be achieved by non-technical measures including life style changes.

The results from IIASA states that, in addition to the baseline scenario a further reduction of 286 Mt CO_2-eq is considered to be technically feasible and would result in a decline in total emissions of non CO_2 emissions by 36 % between 2005 and 2020 at a total cost of €21 billion per year. Of these 44 Mt CO_2-eq could be implemented by measures for which cost savings are larger than the technical life time investments and operating costs. These measures include farm-scale anaerobic digestion for larger farms and leakage control at compressor stations in gas transmission pipelines. Control options with a marginal cost of less than €25/ton CO_2-eq include control of N_2O emissions in industry (HNO_3 production) reduced application of fertilisers on agricultural land and combustion modifications in fluidised bed combustion.

For EU-27 the baseline emissions up to 2020 of total non-CO_2 greenhouse gases are projected to decline by 6.2 %. Methane emissions are expected to decrease by 19 %, while N_2O emissions increase by 3.9 and F-gases with 12 %. The decrease is equal to 255 Mt CO_2-eq in relation to 2005 and 313 Mt CO_2-eq in relation to 1990.

For the measures possible for EU-27, the costs involved are:

- The full set of additional measures involves marginal costs up to €300 per t CO_2-eq, with average costs of €30 per t.
- Of the total potential, 44 Mt CO_2-eq would be available at no additional cost (cost savings).
- For a carbon price at €20/t CO_2, non-CO_2 emis-

sions could be reduced by 21% compared to 2005, with an average cost of €2,4/t CO_2-eq.
- For a carbon price at €50/t CO_2 the reduction potential increases to 25% and the average costs increase to €10/t CO_2-eq.

Globally, there are also a considerable potential to reduce climate impact by reducing the emissions of black carbon particles. These are short-lived in the atmosphere and there is a considerable variation of concentrations in the atmosphere between regions. The so called black smoke cloud over south Asia is well known. The contribution of these particles to the climate impact is considered equivalent to around half of the impact by anthropogenic emissions of carbon dioxide. Effective measures could be to replace the biomass burning for cooking purposes to other techniques. An important step to achieve such abatement is to include the particles in the future climate agreements.

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Nordic Energy Perspectives

NORDIC ENERGY PERSPECTIVES

Nordic Energy Perspectives (NEP) is an interdisciplinary Nordic energy research project with the overall goal of demonstrating means for stronger and sustainable growth and development in the Nordic countries.

A Nordic venue and a forum for dialogue

Many of the most important public and private stakeholders within the Nordic energy field are participating in the project. Therefore, Nordic Energy Perspectives has become a venue – a forum – for discussions and dialogue, based on unbiased facts, among politicians, decision-makers and other participants from the Nordic energy field.

Towards a sustainable Nordic energy system

The NEP project shows that the EU energy and climate package affects all energy markets and all sectors. NEP shows the consequences for - and values of - the development and integration of the energy markets (for electricity, gas, district heating and fuels) in a Nordic and North European perspective. NEP has analysed the consequences of increased use of energy efficiency, renewable energy and other energy solutions with low CO_2 emissions, both in a Nordic and in a global perspective.

The opportunities in focus!

NEP has identified a lot of opportunities for the future, but also challenges. By choosing the right set of policy instruments and regulation in our Nordic countries, we may ensure that the opportunities and synergies provided by the EU energy and climate package are exploited for the benefit of our energy systems. Flexibility and diversity are key words. NEP focuses on sustainability driven strategies and business opportunities of Nordic industry. Renewable energy and other low CO2 technologies are examples of opportunities for energy companies, were the Nordic countries have an advantage compared to most European countries. Opportunities for Nordic clean tech industries are highlighted. Nordic energy intensive industry is analyzed.

A unique set of energy models and professional researchers

The NEP project involves 15-20 experienced energy researchers from the Nordic countries and, which is unique, most of the professional energy models (and modellers) that frequently provide national authorities and ministries with facts and insights for decisions.

More information at Nordic Energy Pespectives website:
www.nordicenergyperspectives.org

Nordic Energy Perspectives

Pathways to sustainable European energy systems

The European pathways project is a five year project with the overall aim to evaluate and propose robust pathways towards a sustainable energy system with respect to environmental, technical, economic and social issues. The focus is on the stationary energy system (power and heat) in the European setting. Evaluations will be based on a detailed description of the present energy system and follow how this can be developed into the future under a range of environmental, economic and infrastructure constraints. The proposed project is a response to the need for a large and long-term research project on European energy pathways, which can produce independent results to support decision makers in industry and in governmental organizations. Stakeholders for this project are: the European utility industry and other energy related industries, the European Commission, EU-Member State governments and their energy related boards and oil and gas companies. The overall question to be answered by the project is:

How can pathways to a sustainable energy system be characterized and visualized and what are the consequences of these pathways with respect to the characteristics of the energy system as such (types of technologies, technical and economic barriers) and for society in general (security of supply, competitiveness and required policies)?

This question is addressed on three levels; by means of energy systems analysis (technology assessment and technical-economic analysis), a multi-disciplinary analysis and an extended multi-disciplinary policy analysis. From a dialogue with stakeholders, the above question has been divided into sub-questions such as:

- What is the critical timing for decisions to ensure that a pathway to a sustainable energy system can be followed?
- What are ”key” technologies and systems for the identified ”pathways” - including identification of uncertainties and risks for technology lock-in effects?
- What requirements and consequences are imposed on the energy system in case of a high penetration of renewables?
- What are the consequences of a strong increase in the use of natural gas?
- What if efforts to develop CO_2 capture and storage fail?
- Where should the biomass be used – in the transportation sector or in the stationary energy system?
- Are the deregulated energy markets suitable to facilitate a development towards a sustainable energy system?
- Will energy efficiency be achieved through free market forces or regulatory action?
- What are the requirements of financing the energy infrastructure for the different pathways identified?

In order to address the sub-questions in an efficient and focussed way the project is structured into 10 work packages addressing topics such as description of the energy infrastructure, energy systems modelling, technology assessment of best available and future technologies and international fuel markets. In planning of the project significant efforts have been put into ensuring that the project should not only be strong in research but also in management, communication and fundraising.

The global dimension will be ensured through integration with the other three regional AGS pathway projects in the Americas, East Asia, and India and Africa.

More information at Pathways website:

www.ags.chalmers.se/pathways

The Alliance for Global Sustainability

The Alliance for Global Sustainability (AGS) brings together four of the world's leading technical universities – the Massachusetts Institute of Technology, The University of Tokyo, Chalmers University of Technology and the Swiss Federal Institute of Technology – to conduct research in collaboration with government and industry on some of society´s greatest challenges.

The AGS represent a new synthesis of multidisciplinary and multi-geographical research that draws on the diverse and complementary skills of the AGS partners. In addition to academic collaborations each of the universities has extensive experience in working with stakeholders, particularly a growing number of visionary leaders from industry who recognise their fundamental role in achieving sustainable development.

More information at AGS website:
globalsustainability.org

FOUR UNIVERSITIES

The Alliance for Global Sustainability is an international partnership of four leading science and technology universities:

CHALMERS Chalmers University of Technology, was founded in 1829 following a donation, and became an independent foundation in 1994.Around 13,100 people work and study at the university. Chalmers offers Ph.D and Licentiate course programmes as well as MScEng, MArch, BScEng, BSc and nautical programmes.

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ETH Swiss Federal Institute of Technology Zurich, is a science and technology university founded in 1855. Here 18,000 people from Switzerland and abroad are currently studying, working or conducting research at one of the university's 15 departments.

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MIT Massachusetts Institute of Technology, a coeducational, privately endowed research university, is dedicated to advancing knowledge and educating students in science, technology, and other areas of scholarship. Founded in 1861, the institute today has more than 900 faculty and 10,000 undergraduate and graduate students in five Schools with thirty-three degree-granting departments, programs, and divisions.

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UT The Univeristy of Tokyo, established in 1877, is the oldest university in Japan. With its 10 faculties, 15 graduate schools, and 11 research institutes (including a Research Center for Advanced Science and Technology), UT is a world-renowned, research oriented university.

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The complexity of climate change mechanisms

- aspects to be considered in abatement strategy planning

Greenhouse gas emissions are of major importance today and the climate issue is expected to remain a question of utmost significance during coming decades and centuries. Climate models indicate how emissions interfere with climate processes and which temperature rise different emission scenarios may lead to. Through a literature survey, it has been our intention to single out some of the findings on climate change mechanisms , such as the interaction between emissions of greenhouse gases and global radiative forcing, on how the carbon and nitrogen cycles interfere with concentrations in the atmosphere and in what ways cost-effective abatement measures of greenhouse gases could be made. The focus in this respect has been on non-carbon dioxide greenhouse gases.

The present basis for action is comprehensive and robust to its order of magnitude, even if there are large uncertainties involved in the overall understanding of the processes. In the strategies elaborated by different actors these large uncertainties in sources and sinks of greenhouse gases, the interconnections with the climate and available climate models, have to be considered in research projects and future action plans.

This literature review is produced as a joint activity within two comprehensive energy research projects: "Nordic Energy Perspectives" (NEP) and "Pathways to Sustainable European Energy Systems" (a five year project within The AGS Energy Pathways Flagship Program).

Nordic Energy Perspectives is an interdisciplinary Nordic energy research project with the overall goal of demonstrating means for stronger and sustainable growth and development in the Nordic countries.

The Pathways project has the overall aim to evaluate and propose robust pathways towards a sustainable energy system with respect to environmental, technical, economic and social issues. Here the focus is on the stationary energy system (power and heat) in the European setting.

The AGS is a collaboration of four universities that brings together world-class expertise from the member institutions to develop research and education in collaboration with government and industry on the challenges of sustainable development.