EHNUR WP 2

REQUIREMENTS FROM CLIMATE PROTECTION, AND DEGREE TO WHICH THOSE CAN BE FULFILLED BY NUCLEAR ENERGY

NIKOLAUS MÜLLNER[1], HERBERT FORMAYER[2], IRENE SCHICKER[2], WOLFGANG REHM[1] AND HELGA KROMP-KOLB[2]

VIENNA, JUNE 2013

[1] Institute of Safety/Security and Risk Sciences, University of Natural Resources and Life Sciences

[2] Institute of Meteorology, University of Natural Resources and Life Sciences

Copyright

Vienna, May 2013

Media owner and editor:

University of Natural Resources and Life Sciences Vienna, Department of Water, Atmosphere and Environment, Institute of Safety and Risk Sciences, Borkowskigasse 4, 1190 Wien, Austria

URL: http://www.risk.boku.ac.at

EXECUTIVE SUMMARY

The EHNUR project addresses a hypothetical nuclear renaissance, its potential and limitations, and its possible contribution to achieving energy and climate policy objectives. Since advocates of a nuclear "renaissance" argue that a higher share of nuclear electricity generation is beneficial for the climate, EHNUR in this chapter takes a closer look at the question to which extent nuclear energy would have to be developed to make a significant contribution to the climate problem. Other chapters will then look at the feasibility of this development.

The climate system of the earth is powered by solar energy, most of which, however, is reflected, scattered or re-emitted into space. The radiation balance of the earth crucially depends on the reflectivity of its surface and the concentration of green house gases (GHG) in the atmosphere. With increasing concentrations of GHG such as e.g. carbon dioxide, methane, nitrous oxide and ozone more of the long wave radiation emitted by the earth is absorbed, which leads to global warming. GHG concentrations have increased so significantly since the end of the Second World War that the temperature increase of about 0.8°C on global average since the pre-industrial time is mainly attributed to GHG forcing. There is international agreement that global warming must not be allowed to exceed 2°C, a threshold beyond which important global ecosystems could collapse and a stabilisation of the climate might not be possible.

To fulfil the 2°C target with a probability of 50% respectively 70% the greenhouse gas concentrations must not exceed 450 ppm resp. 400 ppm CO2 eq. for any prolonged period of time. This can only be achieved if overall GHG emissions are capped and emission pathways therefore reach an early maximum followed by a rapid decrease. Pathways with a late peak, a large cap or a slow decrease require negative emissions towards the end of this century to achieve the 2°C target by e.g. combining sustainable biomass use with CCS.

Climate models show that for most emission paths discussed in the past (e.g. in the IEA World Outlooks), the 2°C target cannot be attained. Increasingly, however, energy scenarios also address the climate issue, and newer energy pathways have been devised that can be shown to meet the target. An essential aspect is the sector distribution of energy need and the energy mix assumed in the scenarios.

In the year 2010 the global greenhouse gas emissions stemmed to about 2/3 from energy related sectors, half of that related to energy production and conversion (including fuel flaring and fugitive emissions). Emissions from the electricity sector accounted for roughly 20% of total global emissions. This is a significant share, but only part of the problem. Since, from today's perspective, nuclear energy can primarily contribute in the area of electricity generation (assuming that the "hydrogen economy" cannot be achieved without major breakthroughs that are not yet visible), the potential contribution of nuclear to the solution is limited.

The present study estimates the current and possible future contributions of nuclear power to climate change mitigation by looking at different scenarios. The energy demand in the next decades was based on scenarios and projections by the IEA, more specifically, on the so-called "current policy scenario" of the World Energy Outlook 2012. In this scenario it is assumed that the policies implemented worldwide by 2012 will be maintained unchanged until the year 2035. The potential contribution of nuclear energy to avoid greenhouse gas emissions was evaluated based on different considerations for nuclear power plant build rates. First, build rates as predicted by scenarios from IAEA (IAEA, 2012) were considered. In a second step extreme build rates, which would substitute all coal-fired and gas-fired power plants, were evaluated. Finally, the results were compared with the completely different, normative scenario by (GEA, 2012) (that answers the question how to reach a desirable future, instead of trying to predict a plausible development).

The (IAEA, 2012) paper "Energy, Electricity and Nuclear Power Estimates for the Period up to 2050" projects 450 - 750 additional reactor blocks to the year 2030. This corresponds to GHG savings of 3%-5% of total emissions making different assumptions regarding emissions of substitutes. On the other hand, would nuclear power plants replace all existing thermal power plants and fully cover the projected growth in demand for electricity as well, GHG emissions of 28% of the total emissions could be avoided. But 4,000 new reactors with 1 GW electrical power each would have to be built by 2035. Even that would not turn the IEA business-as-usual scenario into a scenario that meets the 2°C climate target.

Based on these considerations, the following conclusions can be drawn:

- There is a considerable discrepancy between the reduction in GHG emission required to stabilize climate and what nuclear power can contribute.
- Although the expansion of nuclear power can contribute to reducing greenhouse gases, it cannot be the central pillar of climate policy.

Looking at the issue from the climate perspective, (GEA, 2012) came to the conclusion that none of the evaluated pathways make it necessary to use nuclear power. No matter if a high-energy demand pathway, a high-energy efficiency pathway or a mixed pathway is assumed, if technological breakthroughs in transport can be achieved and electric and hydrogen powered vehicles are going to be introduced, nuclear energy is limited to satisfy only a small fraction of global energy demand, and all pathways allow other energy sources to substitute nuclear energy. From a climate and energy pathway point of view the use of nuclear energy is optional.

Table of Contents

List of Figures

List of Tables

INTRODUCTION

Anthropogenic greenhouse gas emissions (GHG) lead to a higher average global temperature, which in turn leads to a change in climate with adverse effects on mankind (IPCC, 2013). The main source of GHG emissions are the various applications of fossil fuels. 81% of the total global primary energy demand in 2010 was covered by fossil fuels (IEA 2012).

The nuclear industry proposes that nuclear power could contribute to cut down GHG emissions and at the same time increase security of supply by reducing the dependence on fossil fuels. The term “nuclear renaissance” shows the expectation of reaching nuclear power plant build rates close to, or even exceeding the build rates of the 1970s (WNA, 2013).

The present study looks at the asserted nuclear renaissance from the perspective of climate protection. Based the boundaries that climate stabilisation imposes on the overall global GHG emissions the study investigates what changes to the energy supply system are necessary if the climate goals are to be met. Requirements that nuclear power would have to meet should it be used as sustainable energy supply for climate change mitigation are developed. These requirements are then compared with what nuclear power can offer, with the aim to provide an answer to the question what can nuclear power contribute to mitigate climate change.

Kromp-Kolb and Molin (2007) broadly discussed almost all aspects of nuclear energy, looking as well into the climate mitigation potential of nuclear energy (Weimann et al., 2007). But at that time the Kyoto aims were still a topic and climate as well as energy scenarios have changed since then. The present study, apart from using recent data, focuses on climate related aspects and is not only an update, but and considerable extension in this field.

Recently an ad-hoc OECD expert group focusing on this topic (OECD/NEA, 2012) presented scenarios of future energy demands, as well as possible factors influencing nuclear expansion. To evaluate the present contribution of nuclear energy to GHG mitigation, it was assumed that the current nuclear fleet would be substituted by coal fired power plants, gas fired plants or by a mix of various energy sources. The additional emissions were calculated. The current report deepens this information: On the one hand the possible contribution of nuclear energy to GHG mitigation is worked out in more detail, on the other hand literature - namely (GEA, 2012) - not available at the time was included in the analysis and conclusions of the present document. In addition, while (OECD/NEA, 2012) limits itself to evaluate emissions avoided by the current fleet of nuclear power plants, the present work also considers a possible future. The almost paradigmatic change of designing scenarios that can be seen in (GEA, 2012) has a profound influence on the present work.

METHODOLOGY, TERMINOLOGY AND BASICS

METHODOLOGY

The present study is essentially a literature review. In addition green house gas emission parameters are quantitatively assessed using simple arithmetic based on data found in literature.

TERMINOLOGY

Projections, predictions, forecasts and scenarios

The terms “projection”, “forecast/prediction” and “scenario” are used throughout the chapter as defined in (IPCC, 2013): The term "projection" is used as a description of the future and the pathway leading to it. When a projection is branded "most likely" it becomes a forecast or prediction. A forecast is often obtained using deterministic models, possibly a set of these, outputs of which can enable some level of confidence to be attached to projections. A scenario is a coherent, internally consistent and plausible description of a possible future state of the world. It is not a forecast; rather, each scenario is one alternative image of how the future can unfold. A projection may serve as the raw material for a scenario, but scenarios often require additional information (e.g., about baseline conditions). A set of scenarios is often adopted to reflect, as well as possible, the range of uncertainty in projections.

CO2 equivalents

Carbon dioxide, CO2, is the most important contributor to anthropogenic climate change. Other greenhouse gases together contribute less than about 60% of the warming caused by CO2, even though per unit of weight their impact is in some cases many orders of magnitude larger than that of CO2. By expressing their emissions not in tonnes, but in tonnes of CO2 that would have the same warming effect (Global Warming Potential – GWP), short in tonnes of CO2 equivalents (t CO2-equ.), the contribution of different green house gases is made comparable and it becomes possible to express the combined effect of all GHG in a single number. Equivalent concentrations specify the contribution of a specific greenhouse gas converted into the concentration of CO2 that would cause the equivalent forcing (ppm CO2 equivalent). This rather simple concept is not quite as simple in practice, but conversion figures can be found in IPCC AR4, Table 2.14, p.212 (https://www.ipcc-wg1.unibe.ch/publications/wg1-ar4/ar4-wg1-chapter2.pdf). CO2 equivalents will be used extensively in the following.

CLIMATE (CHANGE) RESEARCH METHODOLOGY

DATA ANALYSIS

Reconstruction of past climate (paleo climate) is mostly based on indirect sources, only for some thousand years have humans made systematic meteorological measurements, and only over the last 150 years have such records become useful for climate reconstructions. Typical sources of information are oxygen isotope ratios of air bubbles enclosed in ice (as a proxi for temperature), fossils conserved in sediments of lava, chronologies of tree rings or coral reefs, indications of glaciation such as moraines and, for more recent periods, drawings and chronologies by humans.

Uncertainties are high and time resolution is low in these paleo climate reconstructions. The abundance of data increases closer to the present and a real step forward is achieved with the onset of the instrumental period. The meteorological services are among the best coordinated in the world and data collection is standardised to a large extent, making data comparable across the word. Data are exchanged internationally on a regular basis and essentially all routinely collected data sets are made accessible to researchers free of charge for non-commercial use. As these data originate from a network of irregularly distributed meteorological/climatological stations, thus calculations of spatial distributions or global averages of e.g. the temperature require schemes to account for representativeness of stations and to handle data-scarce regions. Since several such schemes exist, global average temperatures published for any specific year by different research groups might differ slightly. Thus, the year 1998 was for some time the hottest year on the CRUTEM4 record, while the GISS record considered the year 2005 and 2010 to be hotter. The main difference between these two calculations is the spatial resolution and the way the schemes treat the data scarce arctic (Hansen 2006)

Extreme events are defined as an occurrence of a weather event whose parameter is above/below a threshold close to the upper/lower boundaries of the observed range of that parameter for given time frames of e.g. hours, days, months, years. Extreme events are also characterised by their spatial scale (thunderstorms, heat waves, floodings, …) and complexity (one or more parameters affected) and by the economic and societal loss. Several indices are defined (extreme indices). Threshold indices are normally defined as number, percentage, or fraction within the time frame with maximum/minimum temperature or precipitation below/above the 1st/5th/10th/90th/95th/99th percentile with respect to a reference time period (1961-1990 or 1971-2000). Duration indices are defined based on the length scale of e.g. number of consecutive days of excessive warmth, cold,dryness . Other indices define the societal impacts as e.g. intensity of daily rainfall and ensuing foods. One has to keep in mind that extreme events and their definition are strongly dependant on the region and local structures.

CLIMATE MODELS

Climate models are the primary tools to investigate the climate system and its response to different driving forces as well as to calculate climate scenarios on various time scales. Models currently used range from energy balance models (simple) to Earth system models (very complex). For future climate scenarios, especially the ones used for the IPCC reports, complex General Circulation Models (GCMs) and very complex Earth System Models (ESMs) are applied. The climate system is a highly complex system with various feedback loops and it is far from being fully understood. Thus, also the physics of climate models are not perfect. Complexity of models and spatial and temporal resolution of models are also limited by availability of computational capacity.

Models differ essentially regarding the modelling area covered (global, regional, local) and regarding the systems and processes they aim to simulate (comprehensiveness and complexity of the models):

Atmosphere-Ocean General Circulation Models (AOGCMs): AOGCMs are coupled atmosphere-ocean models and are now standard models for future climate projection simulations. They help to understand the dynamics within the climate system, especially of the physical components and include ocean-atmosphere feedback mechanisms. They are applied using various horizontal and vertical resolutions, depending also on the time frame they are used for.

Earth-System Models (ESMs): ESMs are currently the most complex climate models as they represent the overall Earth system. In the ongoing fifth phase of the Coupled Model Intercomparison Project (CMIP5) they are the state-of-the-art models. They not only include ocean-atmosphere-cryosphere-landuse feedback loops but also biogeochemical cycles (carbon cycle, stratospheric ozone,…).

Earth-System Models of Intermediate Complexity (EMICs): EMICs are similar to ESMs and include relevant components but are often used for idealised simulations of at lower horizontal resolutions.

They are also applied for specific scientific questions (e.g. climate feedbacks on the centennial scale) or as test-beds for Earth system components to be included in future ESMs.

Energy Balance Models (EBMs): EBMs analyse the Earth's energy budget and estimate changes in the climate system. They vary in complexity, but in their simplest form they provide only globally/zonally averaged values and exclude spatial dimensions. Their only parameter is temperature and the aim is to calculate the temperature at the surface, T_s, where the model calculates T_e. ΔT refers to the greenhouse effect: $T_s = T_e + \Delta T$

Regional Climate Models (RCMs): RCMs are limited area models (LAMs) with more complex physical representations and higher resolutions than GCMs. They are used to downscale the results of AOGCMs for a geographical region to provide more detail and to possibly improve results of AOGCMs due to the enhanced topography. The lateral boundary conditions for RCM have to be taken from GCMs.

CLIMATE MODEL LIMITATIONS AND UNCERTAINTIES

Climate model limitations are due to different factors. The following limitations are currently the major limitations not only in climate modelling but partly also in weather forecast/mesoscale modelling:

- Model parameterisations: When the physics of processes are not fully understood or processes are of much smaller scale than the model resolution, these processes are 'parameterised' to captures the phenomenology of the process and its sensitivity to change without explicitly modelling the very small scale details. Such processes cannot be ignored as they sometimes have feedbacks on large scale processes (e.g. cloud formation).
- External Forcing: Inaccuracies in the model's representation of the external forcings can arise (e.g. volcanism). For climate projections assumptions on the future development of anthropogenic and natural forcings have to be made.
- Internal forcing: Representation of interconnections between different spheres, internal oscillations and feedback loops.
- Computational aspects: Climate model simulations places highest demands on computational resources. Spatial and temporal resolution and mathematical representation of physical processes have to be optimized to the availability of computational power and storage, and do not always match the needs odf the physical/chemical processes.

A possibility to quantify uncertainty is the use of a variety of models for the same experiment. The ongoing CMIP5 experiments for example will provide a multi-model context for 1) assessing the mechanisms responsible for model differences in poorly understood feedbacks associated with the carbon cycle and with clouds, 2) examining climate "predictability" and exploring the ability of models to predict climate on decadal time scales, and, more generally, 3) determining why similarly forced models produce a range of responses. Generally it is assumed that model errors tend to cancel or reduce each other and results become more robust if independent models are used and thus uncertainty decreases with increasing number of models used for the analysis.

Model uncertainties can also be quantified using and exploring relationships between the past and present climate and model simulations. In general, model skills are evaluated using simulations of the past and comparing them with observations (station data, radio-soundings, remote sensing data, gridded observation data, …). Statistical measures and metrics (e.g. BIAS, RMSE, …) are defined to quantify how well e.g. important processes are represented by the model. The calculated model BIAS is assumed to also quantify the model's skill in simulating climate projections.

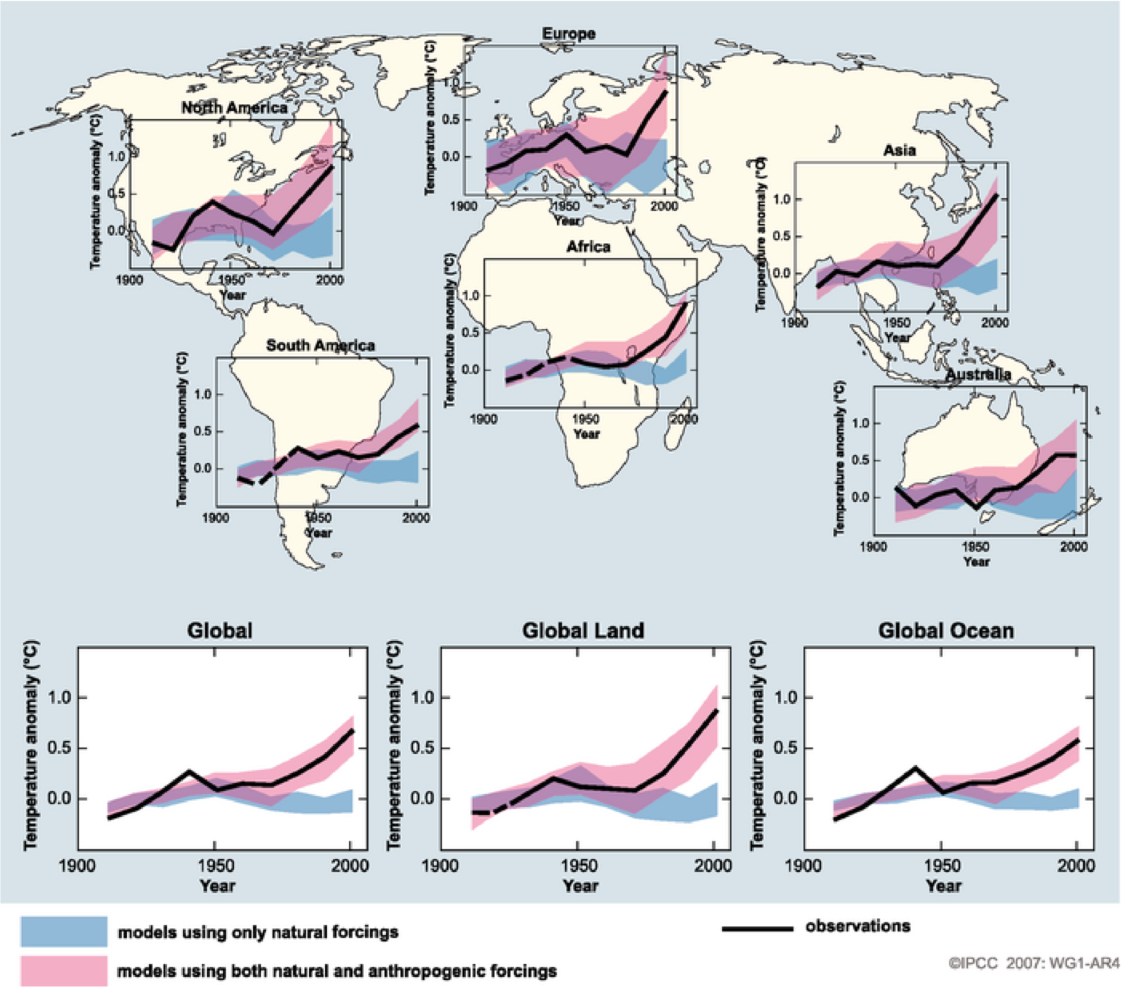


FIGURE 1: OBSERVED CONTINTENTAL AND GLOBAL SCALE CHANGES IN SURFACE TEMPERATURE AND SIMULATED CHANGES USING MODELS WITH ONLY NATURAL FORCING (BLUE, 5- 95 % RANGE OF 19 SIMULATIONS AND 5 CLIMATE MODELS) AND NATURAL AND ANTHROPOGENIC FORCING (RED, 5-95% RANGE FOR 58 SIMULATIONS OF 14 CLIMATE MODELS). DECADAL AVERAGES ARE BASED ON THE 1906 – 2005 PERIOD. DASHED LINES INDICATE A SPATIAL COVERAGE OF LESS THAN 50%.

Despite all the above mentioned model limitations and uncertainties current state-of-the-art climate models and the models used in the IPCC AR4 report are quite reliable as they simulate the physical processes realistically. The fundamentals on which climate models are based are established physical laws, e.g. the conservation of mass, energy, and momentum. They are able to represent the observed temperature developments during the 20th century on a continental scale (Figure 1). Multi-model ensembles, as the PRUDENCE project (Christensen et al., 2007), the ENSEMBLES project (Hewitt and Griggs, 2004), or the latest CMIP5 project (Taylor et al., 2012) are nowadays standard to account for model spread (Meehl et al., 2007, Tebaldi and Knutti, 2007). Also, models are able to simulate important aspects of past climate (near past and Holocene and last glacial maximum) and current climate and climate system (e.g. monsoon, storm tracks,…) and their skills are increasing, despite the above mentioned limitations. Thus the considerable confidence placed in climate model skills in their ability to simulate the past and future climate and climate changes is well founded.

SCENARIOS FOR THE FUTURE DEVELOPMENT OF THE ANTHROPOGENIC FORCING

Climate models, when used to assess future developments of the climate and the possible impacts of future climate change need input regarding the driving forces. Thus assumptions must be made regarding GHG and aerosol concentrations. These, however, depend on natural and anthropogenic forcing and cannot be predicted in a reliable manner. Therefore, climate research analyses several climate scenarios spanning the field of possible developments.

The most widely used climate scenarios were based on the IPCC SRES Scenarios since 1995 and are now switching to the Representative Concentration Pathways (RCPs) approach.

THE IPCC SRES SCENARIOS

In 1990 and 1992 the Intergovernmental Panel on Climate Change (IPCC) published long-term emission scenarios that were widely used in climate change research, the IS92 scenarios. After an evaluation of these scenarios in 1995 a new set of scenarios was developed to be used as input for the Third IPCC Assessment Report in 2001 and the Fourth Assessment Report in 2007. This new set was published in the Special Report on Emission Scenarios (SRES) and contains in total 40 different scenarios which are grouped into four major scenario families (Figure 2), called the A1, A2, B1, and B2 families.

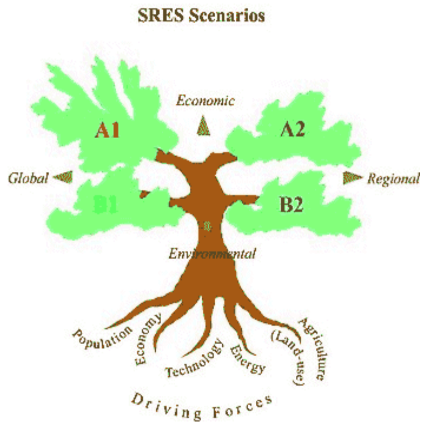


FIGURE 2: THE FOUR IPCC SCRES SCENARIO FAMILIES GROUPED INTO THE RELATIVE ORIENTATION OF THE DIFFERENT STORYLINES (ECONOMY, ENVIRONMENTAL CONCERNS) AND GLOBAL AND REGIONAL DEVELOPMENT PATTERNS (IPCC SRES, 2000).

The A1 storyline describes a future world with rapid introduction of new and efficient technologies, rapid economic growth and a global population that peaks in the mid-century and declines afterwards. Increasing mobility, the convergence between regions and increased cultural and social interactions (“rich” and “poor”) are major themes in this scenario family. Three sub-families describing alternative directions of future technologies exist: a fossil intensive (A1F1), a non-fossil energy sources (A1T), and a balanced (A1B) scenario.

The A2 family describes a heterogeneous world based on self-reliance and preservation of local and regional identities. Regional economic growth, more fragmented and slower technological change, and continuously increasing global population define this scenario.

The B1 storyline represents a convergent world. Growth of the global population resembles the A1 scenario family but economic structures change more rapidly towards a reduction in material intensity and cleaner and more efficient technologies. Global solutions are the major underlying theme of this family but no additional climate initiatives are introduced.

The B2 storyline is similar to the A2 family but global population growth rate is lower than in A2. Its emphasis lies on local economic, social, and environmental solutions with intermediate levels of economic development and diverse technological changes. Activities on local and regional levels are preferred.

THE REPRESENTATIVE CONCENTRATION PATHWAYS (RCPS)

A new set of scenarios, the representative concentration pathways (RCPs), was designed for the Fifth IPCC Assessment Report (AR5). The RCP mark a new approach that is no longer based on different story lines. Pathways of radiative forcings are normatively determined, and every pathway can result from a diverse range of socioeconomic and technological development scenarios. The pathways for the year 2100 span the range of radiative forcing values found in the open literature, i.e. from 2.6 to 8.5 W/m^2 and are closely related to greenhouse gas concentration rather than emissions trajectories.

The four scenarios were developed independently by four modelling teams (see (Van Vuuren et al., 2011) for more details). They are not forecasts and they do not represent boundaries for land-use changes or climate change. The four RCPs are:

- RCP 2.6: a peak of the radiative forcing of 2.6 W/m² and decline before 2100
- RCP 4.5: a peak of 4.5 W/m² without overshoot and stabilisation after 2100
- RCP 6: a peak of 6 W/m² without overshoot and stabilisation after 2100
- RCP 8.5: a continuously rising pathway with 8.5 W/m² in 2100

Comparison studies between the “old” scenarios and “new” scenarios abound (Ryu and Hayhoe, 2013; Dufresne et al., 2013, Bellenger et al., 2013; Haarsma et al., 2013; Jourdain et al., 2013 and numerous others). One significant difference between the two scenario sets is aerosol radiative forcing. In the RCP family the aerosol concentrations reach their maximum ~2020 and decrease afterwards whereas in the SRES storyline concentrations increasing until 2030/2050. Also, the RCP considers absorbing aerosols, while the SRES only scattering sulphate aerosols were taken into account.

Defresne et al. (2013) summarised the differences in radiative forcing until 2100 and van Vuuren et al. (2011) estimated the CO2 emissions and concentrations which lead to the radiative forcing (Figure 3). As can be seen, the RCP4.5 is close to the SRES B1, the RCP6.0 is between SRES B1 and SRES A1B, and the RCP 8.5 is higher than the SRES A2 scenario. The lowest RCP scenario, the RCP2.6, is lower that any of the SRES scenarios and satisfies the 2°C target.

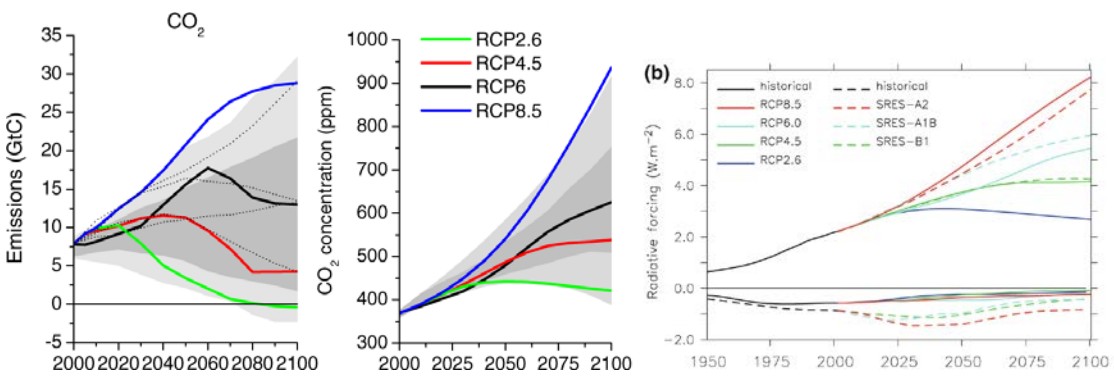


FIGURE 3: LEFT) CO2 EMISSIONS FOR THE FOUR RCP SCENARIOS AND THE SRES SCENARIOS (DOTTET LINES) AND THE 98TH AND 90TH PERCENTILE FOUND IN LITERATURE. MIDDLE) CO2 CONCENTRATIONS OF THE FOUR RCP SCENARIOS. RIGHT) LONG-LIVED GREENHOUSE GASES (CO2, CH4, N2O, CFC) (POSITIVE VALUES) AND AEROSOL (NEGATIVE VALUES) RADIATIVE FORCING IN W/M² FOR 1950 – 2100. THE HISTORICAL AND FUTURE SIMULATIONS WERE PERFORMED WITH THE IPSL-CM5A-LR MODEL USING THE RCP (SOLID) AND SRES (DASHED) SCENARIOS (FROM DEFRESNE ET AL., 2013).

To assess the possible contribution of nuclear energy to GHG mitigation, future development of energy needs must be understood. Energy scenarios describe the overall energy production and use over time and the energy mix associated with that specific development. Like climate scenarios, energy scenarios also are based on assumptions about driving forces, such as demographic development, availability of resources, build capacity limitations, etc.

Different approaches to treat future emission reductions with models exist. Top-down approaches focus on market interaction with little technological detail in the energy sector. Bottom-up approaches focus on substitution of individual energy technologies and their costs. Hybrid models try to combine the advantages of the two other perspectives by linking the macro-economic component and the technology component. Practically all internationally accepted models are rooted in mainstream economic theory, essentially assuming an infinite planet. More advanced models recognizing that the planet is finite and therefore potentially better suited to model situations of energy carrier scarcity (e.g. oil, gas, uranium), but also of scarcity of sinks (e.g. climate change) are still in the development stage.

Backbone for most projections of nuclear power build rates are either current rates, extrapolations of current trends with assumptions regarding other processes, or a mixture of both. (GEA, 2012) and the so-called “450” scenario of (IEA, 2012) chose a different approach – they represent normative rather than extrapolative scenarios: These scenarios describe possible pathways into the future that could satisfy some attributes of energy services considered desirable (availability, affordability, access, security, health, climate and environmental protection) that must be met concurrently.

The present study makes use of various scenarios for the future of the worldwide energy supply system to give an impression how various institutions see the future of the nuclear fleet. Each of those scenarios is then discussed to evaluate what contribution to climate protection realistically could be expected.

The projections used include the “IAEA-high” and “IAEA-low” scenario (IAEA, 2012), the “high” and “low”, the “WEO-current policy” and the “WEO-450” scenarios from (IEA, 2012), as well as the “GEA-high efficiency” scenario. The cited scenarios differ considerably, since the assumptions for each scenario are different. The goal of the various scenarios is to give an impression on how the future could be under the assumption that certain conditions become true.

It is therefore important to know which assumptions were made in each of the various scenarios. The present chapter will list the scenarios used, and summarize briefly the underlying assumptions. Later chapters will only refer to results of the scenarios, but the reader should keep in mind how the results were derived.

Most scenarios consider factors like

- Population growth;
- Economic growth;
- Correlation of economic growth and energy use;
- Technology performance and costs;
- Energy resource availability and future fuel prices;
- Energy policy and physical, environmental and economic constraints;
- Others.

Thus, the factors considered in energy scenarios are very similar to those in climate scenarios. When combining energy and climate scenarios this should be kept in mind, and consistency checks should be made.

SCENARIOS DEVELOPED BY IAEA

The IAEA publishes annually two projections for the development of nuclear electricity generation (e.g. (IAEA, 2012)). The report provides three main figures: current installed nuclear capacity and electricity generation, a projection of nuclear capacity and electricity generation for 2030, and a projection for 2050.

The IAEA estimates (see (IAEA, 2012)) use a country by country 'bottom up' approach to assess present and future generating capacity. A group of experts reviews nuclear power projects and programmes in each country on a yearly basis, including operating reactors, possible licence renewals, planned shutdowns and plausible construction projects for the next years. The plausibility of the projects is judged with an optimistic and a pessimistic approach, which leads to the "high" and "low" projections. Other factors, like economic growth, energy policies, future electricity demand and others are also evaluated on a country by country basis, one time biased to lead to low future power build rates, on time biased to lead to high build rates. The aggregated projections are compared and adjusted by comparison with other projections, like OECD/NEA studies on nuclear power programmes, development indicators published by the World Bank, and global and regional projections on energy and electricity made by other organisations.

SCENARIOS DEVELOPED BY IEA

In its annual World Energy Outlook the International Energy Agency publishes scenarios on future energy supply and demand. In the 2012 edition (IEA, 2012) four scenarios were published:

The "current policy" scenario;

the "new policy" scenario;

the "450" scenario;

and the "efficiency" scenario.

The projections for all four models were calculated using the IEA World Energy Model "WEM" (IEA, 2013) that is described as a "large-scale mathematical construct" (IEA, 2013) using a partial equilibrium model. The model requires assumptions on fuel prices, CO2 prices, energy policies, technological breakthroughs, as well as other socioeconomic drivers, and delivers energy flows, CO2 emissions, and needed investments for technologies. To simulate expected feedbacks (e.g. fuel prices may be a result of needed investments for a technology) the model is run iteratively. The model aims to be comprehensive. It generates detailed sector-by-sector and region-by region projections. It consists of six main modules: final energy demand, power generation and heat, refinery/petrochemicals and other transformations, fossil-fuel supply, CO2 emissions and investment.

The main scenario, the "new policies" scenario, takes into account energy related policy commitments and plans that have already been implemented as well as those that have been announced. New commitments include renewable energy and energy efficiency targets, programmes relating to nuclear phase-out or additions, national targets to reduce greenhouse-gas emissions communicated under the 2010 Cancun Agreements and the initiatives taken by G-20 and Asia-Pacific Economic Cooperation (APEC) economies to phase out inefficient fossil-fuel subsidies.

The "current policies" scenario on the other hand provides a baseline for all other scenarios. Only policies which have been implemented up to 2012 are considered with the aim to provide a reference against which to evaluate the effectiveness of the measures assumed in the other scenarios.

The “450” scenario uses a different method for setting the boundary conditions – instead of being a projection based on past trends, modified by known policy actions, it deliberately selects a plausible energy pathway that achieves the goal of limiting the global temperature rise to two degrees Celsius. As described above this corresponds to a concentration of greenhouse gases in the atmosphere of 450 ppm C02.

A fourth scenario, the “efficiency” scenario, evaluates especially the effect of energy efficiency measures.

The IEA model relies heavily on external databases that are described in detail in (IEA, 2013). Thus e.g. one of the key drivers for energy demand is population growth. Projections on population growth are not part of the model, but are taken as boundary condition from the United Nations Population Division report (UNEP, 2010).

An overview on input and output parameters of the IEA model is given in Figure 4.

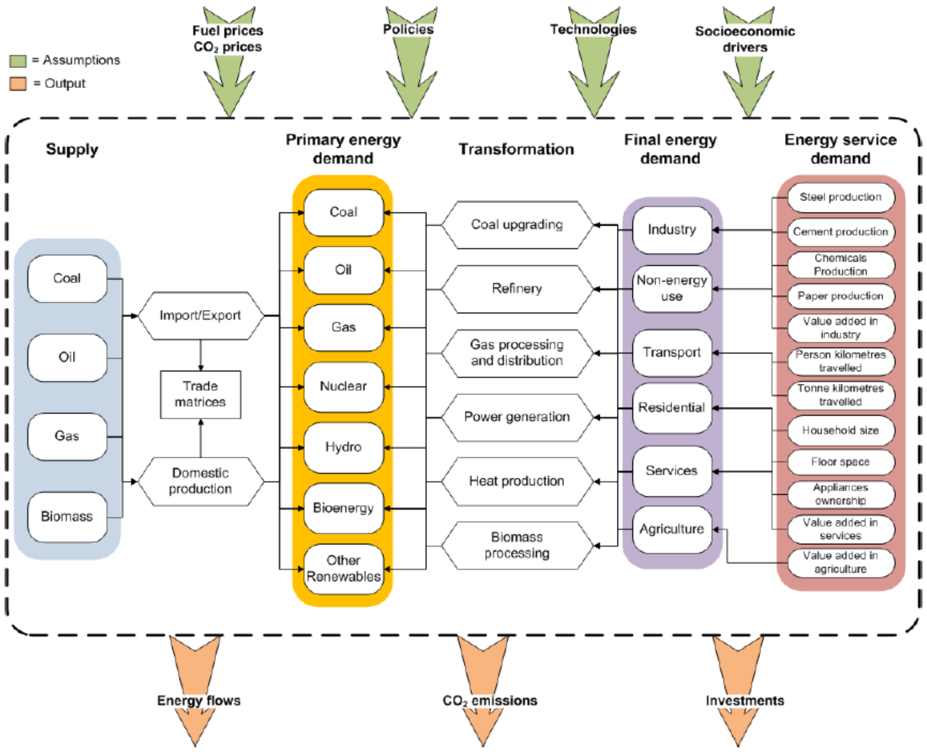


FIGURE 4: OVERVIEW – WORLD ENERGY MODEL USED IN (IEA, 2012), AS SHOWN IN (IEA, 2013).

SCENARIOS DEVELOPED IN GEA

While the main scenarios in (IEA, 2012) and (IAEA, 2012) start with “business as usual” and then assume measures which are likely to be implemented from a current point of view, the scenario development in (GEA, 2012) is “unashamedly normative” – which means that the authors prescribe targets which are to be met, and then analyse pathways to get there. The scenarios aim to fulfil the following goals:

- Stabilizing global temperature at 2°C above pre-industrial levels in the 21st century
- Enhancing energy security by diversification and resilience of energy supply (particularly the dependence on imported oil),
- Eliminating household and ambient air pollution, and
- Universal access to modern energy services by 2030.

Starting from this scenario, (GEA, 2012) investigates several possible “energy pathways” – i.e. choices of supply-side options, energy efficiency measures, behavioural changes of the end user that would satisfy the pre-set conditions.

Three branching points are assumed for each of the possible pathways. The first branching point differentiates between energy efficiency and supply side measures. The second branching point regards transportation technologies – either conventional transport technologies (i.e. a transport system based on liquid fuels) or advanced transport technologies (i.e. electric or hydrogen powered vehicles). The third branching point investigates which possible mix of energy supply could be deployed for the pathway (i.e. can one do without CSS, without nuclear energy, or without biomass?). A total forty-one pathways result from the process, as shown in Figure 5.

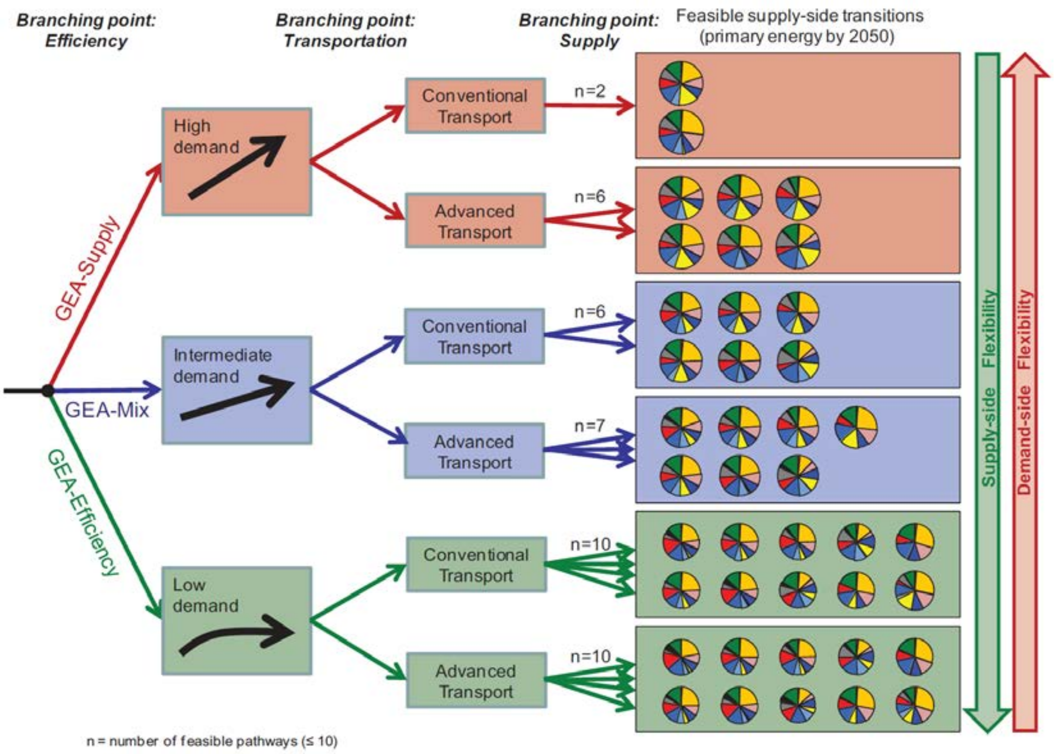


FIGURE 5: OVERVIEW – PATHWAYS AND BRANCHING POINTS FOR THE (GEA, 2012) SCENARIO.

Each pathway is evaluated using two different programs: one is MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact), which is described as “a systems engineering optimization model used for medium- to long-term energy system planning, energy policy analysis, and scenario development” (Messner, 1995). It provides a framework for representing an energy system with all its interdependencies from resource extraction, imports and exports, conversion, transport, and distribution to the provision of energy end-use services such as light, space heating and cooling, industrial production processes, and transportation. The framework covers all GHG-emitting sectors, including agriculture, forestry, energy, and industrial sources, for a full basket of greenhouse gases and other radiatively active gases: CO2 , methane, nitrous oxide, nitrogen oxides, volatile organic compounds, carbon monoxide, sulfur dioxide, black carbon and organic carbon, tetrafl uoromethane, hexafluoroethane, various hydrofl uorocarbons (HFC125, HFC134a, HFC143a, HFC227ea, HFC245ca), and sulfur hexafluoride.

The second program is IMAGE, “an integrated assessment modeling framework consisting of a set of linked and integrated models (Bouwman, 2006).

ANTHROPOGENIC CLIMATE CHANGE

THE CLIMATE SYSTEM

Various definitions of the climate system exist, depending on the time scale addressed. For the purposes of this study the climate system is centred on the atmosphere, but encompasses five interacting sub-systems: atmosphere, hydrosphere, cryosphere, biosphere and lithosphere (see Figure 6). It is driven by variable boundary conditions, by internal dynamics, feedbacks, and changes in external dynamics ("forcings"), including natural phenomena (volcanic eruptions, solar variations) and human-induced phenomena. Thus, change over varying time scales is an intrinsic characteristic of climate and the climate system.

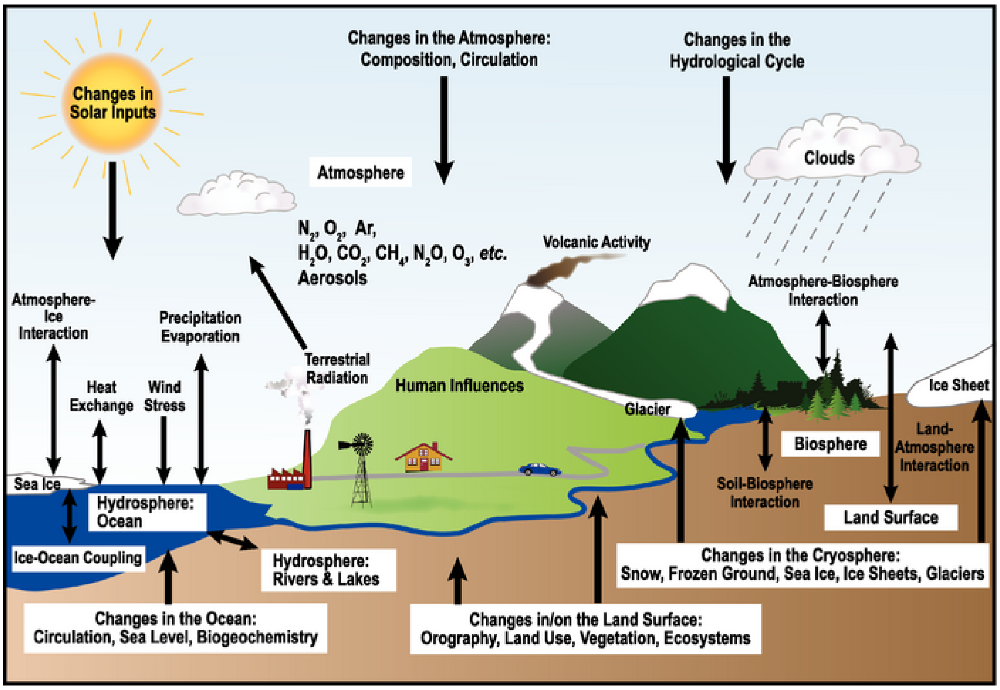


FIGURE 6: THE CLIMATE SYSTEM INCLUDING THE SUB-SYSTEMS, THEIR INTERACTIONS AND THEIR PROCESSES (SUMMERVILLE ET AL., 2007).

The climate system can be described by balances of energy, water and carbon dioxide and associated fluxes. Meteorological parameters like temperature, humidity, radiation or precipitation are part of the energy balance of the climate system. The reproduction of the energy budget and the energy fluxes within the climate system are at the core of climate models and therefore components of the energy budget are also used to validate results of climate models.

Water is an important agent in the climate system: every change of phase is associated with either release or uptake of energy, and thus by transporting water in any phase, energy is also transported. But water vapour is also a key greenhouse gas with a short residence time within the troposphere. Evaporation from water surfaces and plants and water the vapour content in the atmosphere increase, with increasing temperature, constituting a positive feedback mechanism enhancing the green house effect (see below).

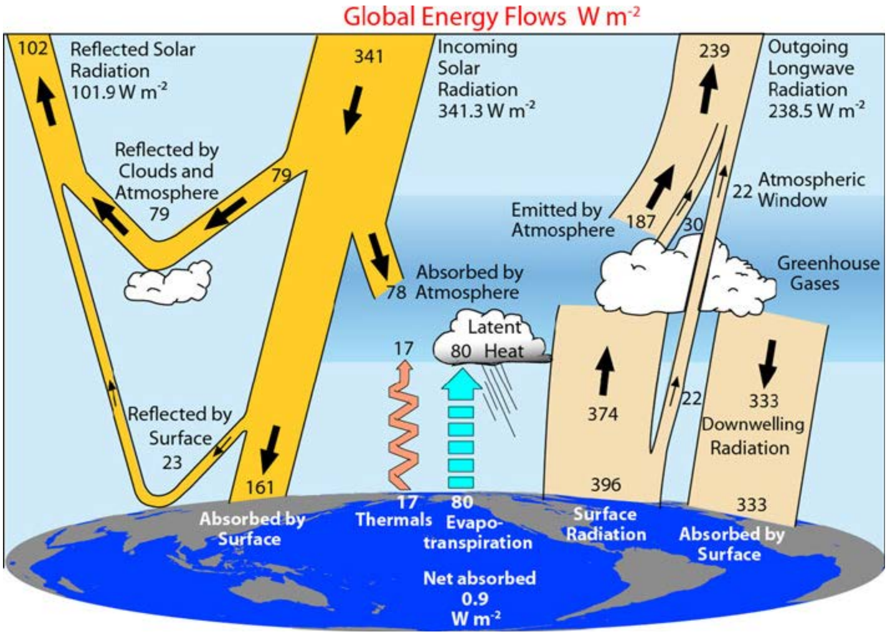


FIGURE 7: GLOBAL ANNUAL MEAN ENERGY BUDGET OF THE EARTH FOR 2000 – 2005 IN W M-2. BROAD ARROWS INDICATE THE FLOW OF ENERGY IN PROPORTION TO THEIR IMPORTANCE (TRENBERTH AND FASULLO, 2012).

The global energy budget of the earth (Figure 7) describes how the energy received from the sun is distributed within the climate system. About one third of solar energy is reflected and scattered back to space without energy impact on the atmosphere or the earth´s surface. A considerable part of the solar energy is absorbed at the earths surface and converted to latent heat, sensible heat and kinetic energy and distributed within the atmosphere-ocean system. Another part is absorbed within the atmosphere and radiated in all directions (see greenhouse effect). Over the past 10.000 years the outgoing terrestrial radiation and the incoming solar radiation were roughly in balance on a multi-year average.

The radiative balance and therefore the radiative equilibrium temperature of the earth depend on three factors: 1) the solar constant, 2) planetary albedo, and 3) the greenhouse effect. Solar constant is the term used for the incoming solar energy per unit area at the top of the atmosphere. It´s yearly mean at present is about 1365 Wm^{-2}. It is influenced by the intensity of solar radiation that is e.g. affected by sun spots, and the earth’s orbit. The planetary albedo (mean global albedo) describes the ratio between outgoing and incoming shortwave radiation at the top of the atmosphere. The planetary albedo is mainly influenced by the amount and type of clouds, but also by sea-ice distribution, glaciated regions, snow cover, carbon particulate matter and other aerosols in the atmosphere and by land use (e.g. forested areas vs. agricultural areas). A change in planetary albedo of 1% would increase radiative forcing by 3.4 Wm^{-2} and would change the radiation temperature of the Earth by 2 K..

Changes in the climate system can be imposed by a number external driving forces, such as a change in incoming radiation as described above, but even with unchanging external conditions, variations in climate would occur due to non-linear interactions leading to internal oscillations.

Externally forced changes in the climate system are related to continental drift, changes in the Earth’s orbit and the rotational parameters, volcanic activities or changes in solar irradiation. They affect the energy balance of the Earth through a change in the radiation balance. The radiation balance can be changed in three basic ways: 1) changing the amount of incoming solar radiation by e.g. changing the sun´s intensity or the earth´s orbit (eccentricity, axial tilt, precession); 2) changing the fraction of the reflected solar radiation, thus the albedo, by e.g. changing ice cover, vegetation, clouds, atmospheric particles,…; and 3) by modifying the outgoing long-wave radiation e.g. by changing the greenhouse gas concentrations. Responses of the climate system can be either direct or indirect, e.g. through feedback mechanisms.

Boundary conditions causing changes within the climate system are e.g. due to changing plate tectonics influencing the position of the continents, the character of ocean basins, or the heaving of mountains. Especially high-altitude Mountains, their location and shape, can alter climate and weather, e.g. depending on their orientation relative to dominant flow directions. Continental drift, e.g. of Antarctica, and the heave of the Tibetan plateau improved the conditions for glaciation and thereby changed the surface albedo (reflectivity for sun light).

Such changes in boundary conditions dominated climate until about 2 million years ago. During the past 600.000 years a sequence of glacial and interglacial periods, the so called Milankovich cycles, has dominated the climate. It is triggered by the oscillation of the Earth's orbit and its parameters, the eccentricity, the axial tilt (obliquity) and the precession. The precession completes one full cycle in 26,000 years, the obliquity, ranging between 22.1° and 24.5° tilt, has a cycle of appr. 41,000 years. The eccentricity with an approximately 100.000 years cycle dominates the other two. Important though these cycles are in triggering and timing climate changes, they cannot explain the observed amplitude of temperature change. Positive feedback-mechanism enhances external forcing, namely the ice-albedo feedback and the green house gas (GHG) feedback. The first refers to the fact that in a warming world, ice cover shrinks reducing the reflectivity of earths surface and thus increasing absorption an warming that in turn leads to more melting. The GHG feedback describes the increase of water vapour, CO2 and methane concentrations in the atmosphere with rising temperatures due to releases from the warming ocean or thawing permafrost regions.

Solar variability is also influenced – on a much shorter time scale – by the sun spot cycle. The intensity of solar radiation at earths surface varies between ±0.08% over the course of the 11-year sun spot cycle.

Volcanic eruptions can also be considered external forces, though not all eruptions affect climate. Only if eruptions are energetic enough to transport particulate matter into the stratosphere do they influence climate. Sulfur dioxide emitted reacts with water vapour and oxygen to form sulphate particulates. These particulates and other volcanic particles reflect the incoming solar radiation and therefore cool the atmosphere. The Mount Pinatubo eruption in 1991 and the Krakatau eruption in 1883 are examples of eruptions influencing climate. The combined effect of multiple volcanic eruptions within four years, the 1812 Mount Soufriere St. Vincent, in 1814 the Mount Mayon and in 1815 Mount Tamora, caused the well known year-without-summer in 1816. Monthly summer temperatures in Central Europe were 2.3 – 4.6 °C below average (Fagan, B. 2000).

Internal variations in the climate system occur even under constant boundary and external conditions (see Wagner in Jacobeit (2002)) and affect the spatial distribution of meteorological conditions as well as global averages. They are a consequence of the chaotic nature of the (non-linear) climate system and of feedback mechanisms between components of the climate system. Three types of ensuing variability are generally distinguished: 1) variability due to non-linear feedback loops within the climate system, 2) variations associated with random fluctuations and 3) variability driven by a periodic external force. The time scales of internal variability vary between hours and several hundred years; they are generally of a shorter time scale than the long-term external forcings. One example for a relevant internal variability is the Atmosphere-Ocean feedback that manifests itself in the El Nino – Southern Oscillation (ENSO) or the Atlantic Ocean Meridional Overturning Circulation (MOC). The ENSO) has a recurring time scale of 2 – 8 years whereas the NAO has a time scale of 60 – 80 years. Atmospheric oscillations act on different and overlapping timescales and thus can reinforce or counteract each other. Internal feedback mechanism can also enhance external forcings e.g. the increase of water vapour and other greenhouse gases with increasing temperatures or the loss of glaciated or snow covered surfaces and albedo. Some of the internal factors influence the climate system at the same time scale as the anthropogenic climate forcing; their quantification is of special interest, but also represents a special challenge.

The chaotic nature of the climate system and the wide range of time scales of internal variations limit the predictive capacity. To reduce the level of uncertainty a better understanding of other types of variability, the periodical and feedback types, is needed.

GREENHOUSE EFFECT

Life on Earth would not be possible without the so-called greenhouse effect. The Earth receives energy of the sun through radiation (Figure 8), mostly as visible light and nearby wavelengths (UV, near infrared). This radiation passes through the atmosphere to the Earths' surface where ~ 50% are absorbed and thus warm the surface to ~ 254 K (see the Stefan-Boltzmann law). The remaining 50% are reflected or absorbed by the atmosphere. The heated surface emits thermal radiation in the wavelength range of 4 – 100 µm. This thermal radiation is absorbed by greenhouse gases and aerosols in the atmosphere and re-emitted in all directions, als towards the earth (back radiation). This results in more radiative energy within the lower layers and the surface and leads to a higher equilibrium temperature (287 K in a norm atmosphere) than the earth would have without atmosphere (~ 254 K). Any change in concentration of greenhouse gases and aerosols within the atmosphere also changes the equilibrium temperature.

Greenhouse gases are gases that absorb radiation in the thermal infrared range. Of special interest are gases that absorb in the so-called "atmospheric window" of 8 – 14 µm wavelength, where the main green house gas of the atmosphere, water vapour (H_2O), does not absorb (Figure 8). Anthropogenic greenhouse gases as e.g. carbon dioxide (CO_2), methane (CH_4), ozone (O_3) and others absorb within this window.

The effect of aerosols on the energy balance of the Earth is twofold. On the one hand light scattering aerosols, as e.g. sulphates, cool the earth whereas aerosols containing black carbon absorb the incoming shortwave radiation and thus warm the atmosphere.

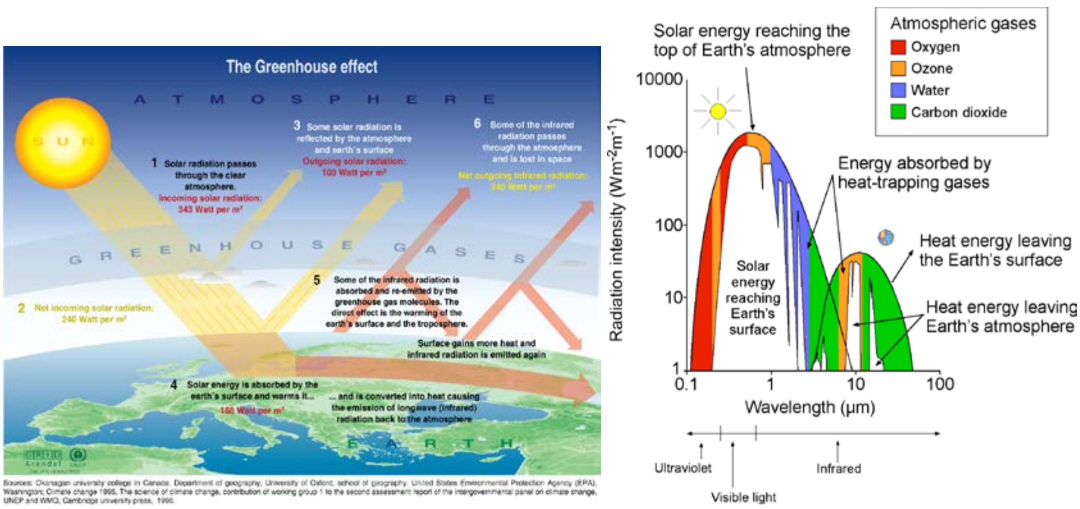


FIGURE 8: LEFT: GRAPHICAL SUMMARY OF THE GREENHOUSE EFFECT INCLUDING THE WATTS / M² OF INCOMING, ABSORBED, AND OUTGOING RADIATION (IPCC AR2, OKANAGAN UNIVERSITY COLLEGE, CANADA, DEPARTMENT OF GEOGRAPHY, UNIVERSITY OF OXFORD, SCHOOL OF GEOGRAPHY, UNITED STATES ENVIRONMENTAL PROTECTION AGENCY (EPA), WASHINGTON; CLIMATE CHANGE 1995, THE SCIENCE OF CLIMATE CHANGE, CONTRIBUTION OF WORKING GROUP I TO THE SECOND ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC), UNEP AND WMO (WORLD METEOROLOGICAL ORGANIZATION, CAMBRIDGE UNIVERSITY PRESS, 1996). RIGHT: ATMOSPHERIC TRACE GASES TRAPPING THE SOLAR ENERGY REACHING THE ATMOSPHERE (LEFT CURVE) AND LEAVING THE EARTH'S SURFACE (RIGHT

CURVE). WHITE PEAKS DENOTE THE ENERGY THAT FULLY PASS THE ATMOSPHERE, ABSORPTION BY GREENHOUSE GASES IS GIVEN BY COLOR (CREATED BY JILL TAYLOR AND CAROL GORANSON FOR THE BOSTON AREA CLIMATE EXPERIMENT. THIS POSTER WAS DESIGNED DURING THE CLASS "CLIMATE CHANGE: MECHANISMS AND BIOLOGICAL IMPACTS," AT THE UNIVERSITY OF MASSACHUSETTS BOSTON, FALL 2006).

PAST CLIMATE

According to changes in the internal and external climate forcings, variations and oscillations of the earth climate occurred at different time scales. Figure 9 gives an overview on climate change over the past 500 million years using different data sets. Oxygen isotope measurements of (δ18O) on benthic foraminifera are the basis for the top right graph (Zachos et al., 2001). Isotope ratios are highly correlated to temperature changes (Petit et al, 1999). The top left shows a somewhat longer reconstruction based on a similar method but using fossils (Veizer et al., 1999). The bottom figure shows the shorter time slice of 5 million years of climate records (Lisiecki and Raymo, 2005) constructed using deep sea sediment cores. Peaks and lows are time consistent with results of orbitally driven glaciation models based on the Milankovitch cycles.

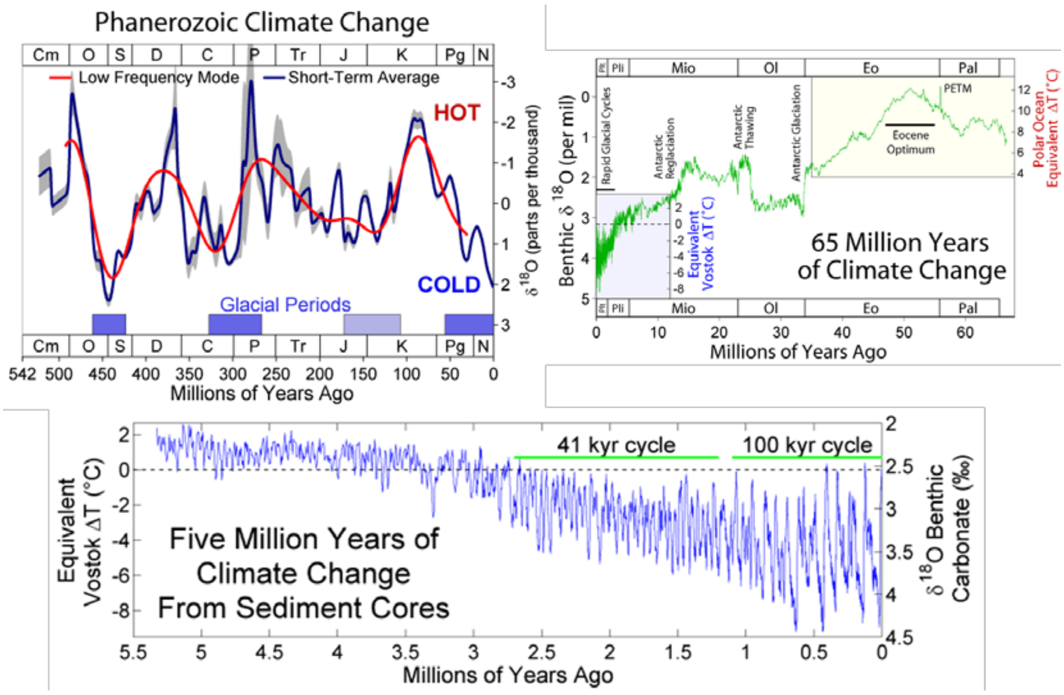


FIGURE 9: HISTORIC CLIMATE CHANGE BASED ON ICE CORE DATA, FOSSILS, AND SEDIMENT CORES AND SHOW THE CLIMATE EVOLUTION STARTING FROM 540 MILLION YEARS AGO. PLOTS WERE CREATED BY ROBERT A. ROHDE FROM PUBLISHED AND PUBLICLY AVAILABLE DATA (SEE REFERENCES IN THE TEXT) AND ARE AVAILABLE ON HTTP://WWW.GLOBALWARMINGART.COM/.

A long discussion evolved around what has become known as the hockey stick curve (IPCC 2001; Figure 10) showing that after a period of roughly 2000 years of rather constant global average temperature only modified by shorter term fluctuations attributed essentially to internal variabilities of the climate system, volcanic eruptions and the sun spot cycle, a rapid temperature increase occurred within the last about 150 years that significantly exceeded all former changes in this time period. Critics claimed that the statistical model integrating the different proxy data did not capture former variations correctly and therefore gave recent temperature rise undue significance. Although minor modifications were made to the hockey stick curve, its main conclusions withstood the scientific debate that must now be considered resolved and closed.

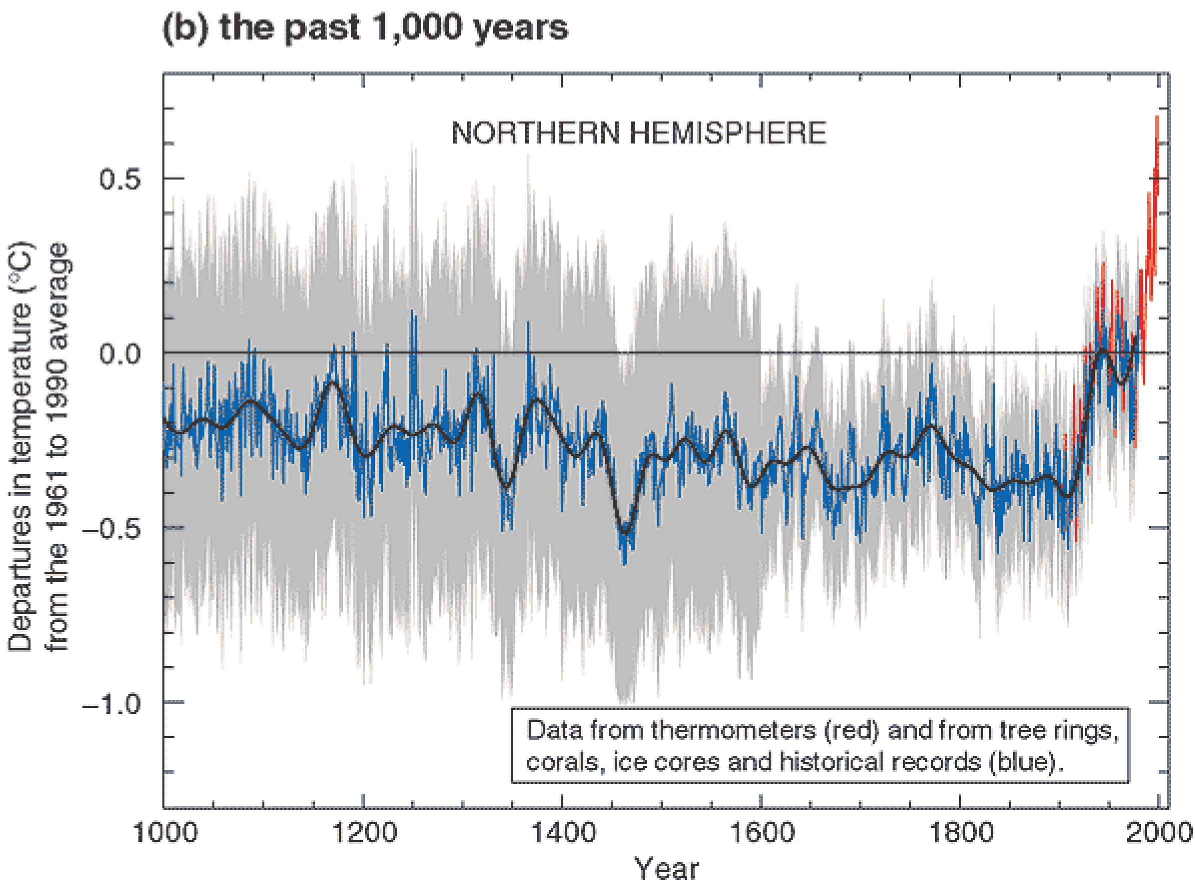


FIGURE 10: THE HOKEY STICK CURVE YEAR BY YEAR (BLUE CURVE) AND 50 YEAR AVERAGE (BLACK CURVE) VARIATIONS OF THE AVERAGE SURFACE TEMPERATURE OF THE NORTHERN HEMISPHERE FOR THE PAST 1000 YEARS HAVE BEEN RECONSTRUCTED FROM "PROXY" DATA CALIBRATED AGAINST THERMOMETER DATA (IPCC 2001)

ANTHROPOGENIC INTERVENTIONS

The human influence on the climate system is highly complex but can be traced back to three main activities: 1) release of climate influencing trace gases, 2) particle emission, and 3) land-use and land-cover changes that can result either in gaseous or particulate emissions or changes in surface albedo. All three components release approx. 10 Gt C per year worldwide (La Quere 2009, Peters et al. 2011), about half of which remains in the atmosphere. The ocean and the land-biosphere system act as carbon sinks, but cannot compensate the anthropogenic emissions (IPCC 2007) (Figure 12 f). In balance, only 2.4±0.5 Gt/year and 2.6±1 Gt/year are absorbed by the ocean and the biosphere, respectively.

Carbon is an essential element in the biogeochemical cycles of the earth. Most of the carbon on earth is stored in the lithosphere (rocks) and in the oceans. Natural processes release carbon into the atmosphere, e.g. through gassing of the oceans and volcanism, and take up carbon mainly into the oceans and the biosphere. The natural fluxes are small compared to reservoir sizes, but considerably larger than the input through human interventions. Thus the emissions of C from fossil fuel burning amount to about 7 GT of C per year, while the flux from the oceans is calculated to be 70 Gt of C per year. Antrophgenic GHG emissions are treated in more detail in the Section “Greenhouse Gas Emission Development”.

Increased CO2 concentrations (Figure 13) in the atmosphere resulting from antropogenic emission affect the radiation balance of the atmosphere, enhance radiative forcing which in turn leads to warming and climate change.

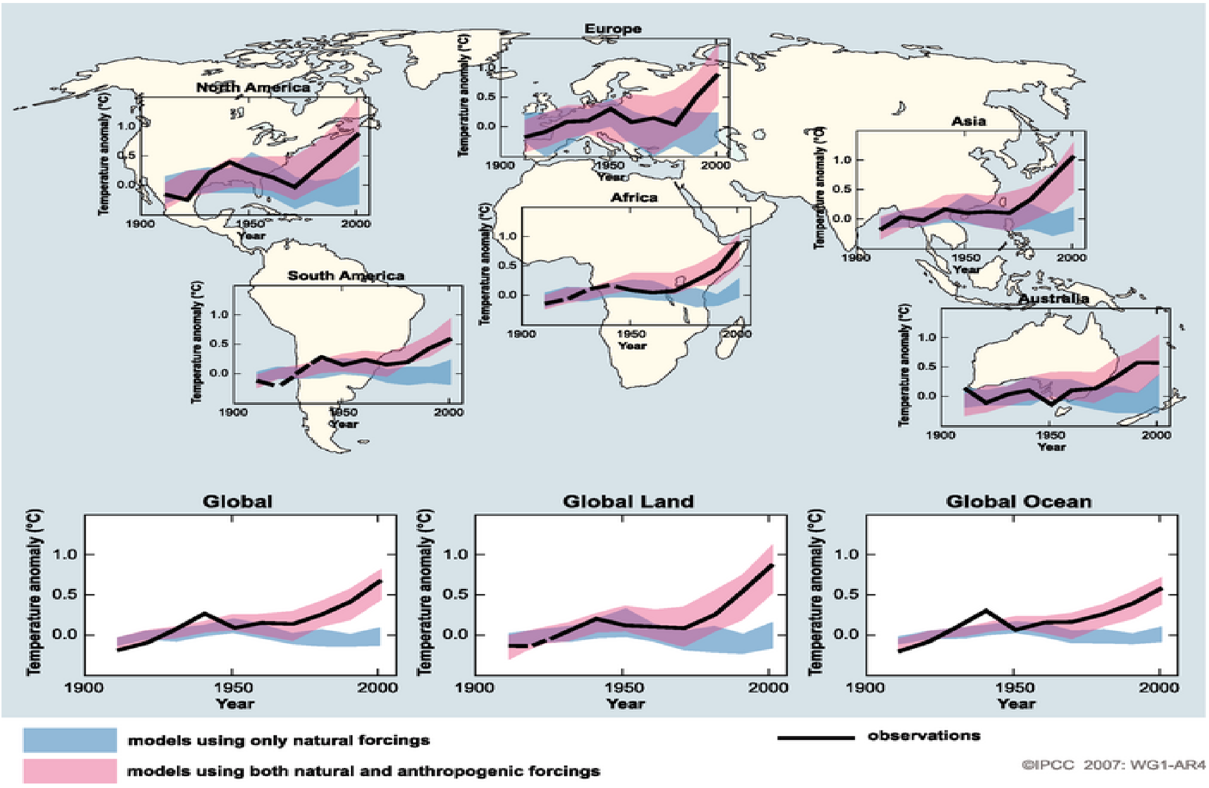


FIGURE 11: LEFT: RIGHT: THE GLOBAL MEAN CARBON FLUXES IN GT C/YEAR AND THE RESERVOIRS IN GT (SARMIENTE AND GRUBER, 2006). DASHED ARROWS INDICATE THE MEAN ANTHROPOGENIC FLUXES FOR 1980-1999, SOLID THE PRE-INDUSTRIAL FLUXES. PRE-INDUSTRIAL RESERVOIR STORAGE IS WRITTEN IN NORMAL FONT, THE CHANGES ARE SHOWN IN ITALICS.

Land-use and land-cover change also affect the global radiation and energy balance through modifications of the surface albedo and the near surface exchange processes of energy and moisture. Particle erosion from the surface can also be affected (Arora and Boer 2010, Canadell et al. 2007, Houghton 2003, Pongratz et al. 2009, Houghton et al. 2012), and others for more information). Deforestation, desertification, transformation of natural vegetation for human use (forestry, agriculture,…) and/or (small-scale) changes in cultivation (e.g. from food to fuel) are the most common human-caused land surface changes.

Anthropogenic aerosols affecting the climate system are mainly produced by: 1) biomass burning (slash and burn deforestation) - primarily black carbon, 2) land-use and land-cover changes producing dust particles, and 3) industrial air pollution such as soot, sulfates or ammonium. They affect the climate system through scattering and absorption of solar radiation directly and indirectly through modification of cloud properties. Aerosols serve as cloud condensation nuclei where an increase of nucleis reduces the size of the droplets and thus brighten the cloud and change the cloud's albedo. This last effect also leads to an increase cloud cover but decreases the precipitation efficiency (Albrecht, 1989).

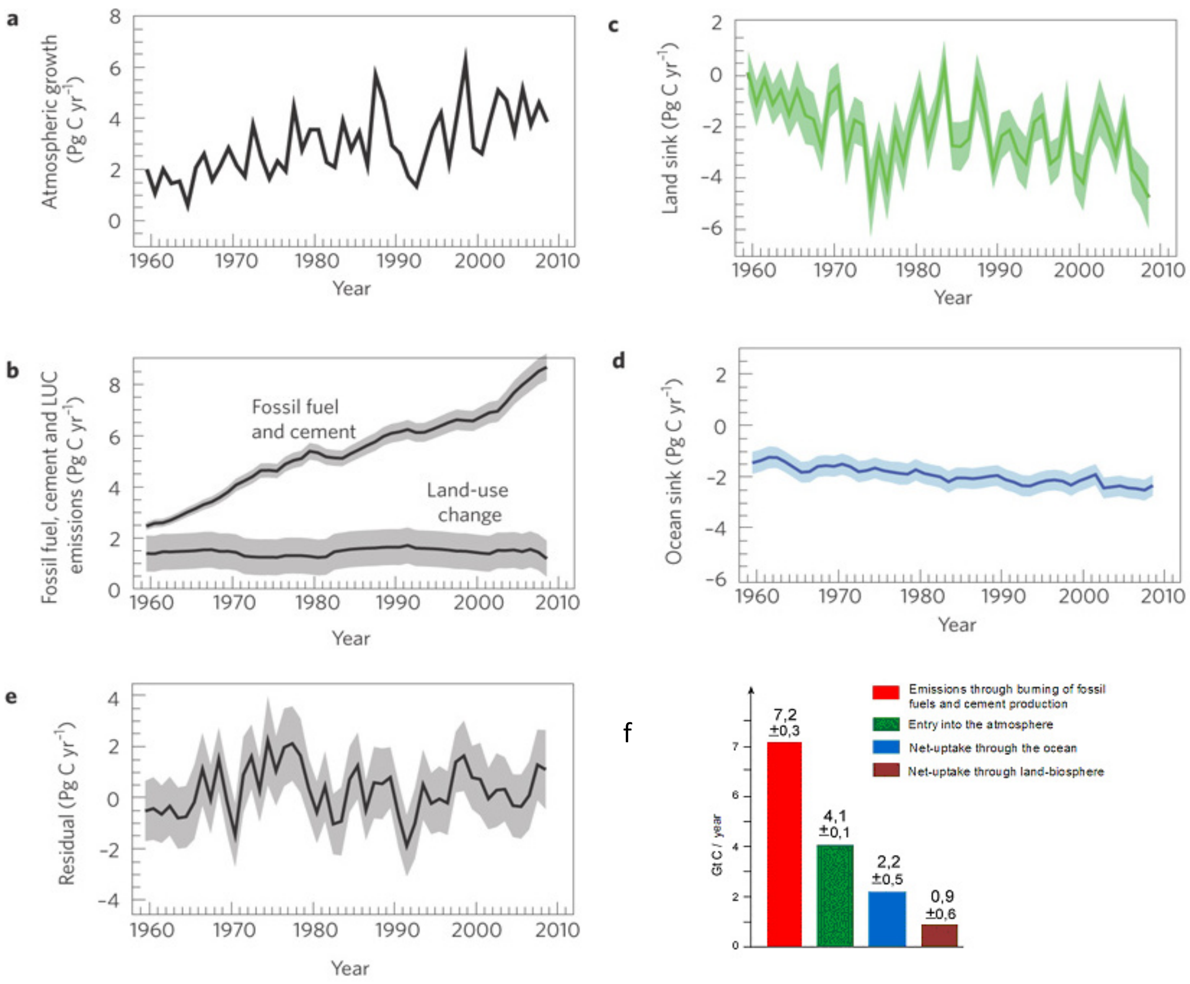


FIGURE 12: TIME SERIES OF (A) THE ATMOSPHERIC CO_2 GROWTH RATE, (B) CO_2 EMISSIONS FROM FOSSIL FUEL COMBUSTION AND CEMENT PRODUCTION, AND FROM LUC. (C) LAND CO_2 SINK (NEGATIVE VALUES REPRESENT LAND UPTAKE) AND (D) OCEAN CO_2 SINK (NEGATIVE VALUES CORRESPOND TO OCEAN UPTAKE). IN (E) THE RESIDUAL SUM OF ALL SOURCES AND SINKS IS SHOWN. SHADED AREAS ARE UNCERTAINTIES ASSOCIATED WITH EACH COMPONENT (A – E TAKEN FROM LE QUERE ET A., 2009). IN (F) A SUMMARY OF THE CARBON EMISSIONS AND ITS SINKS OF THE EPISODE 2000 – 2005 IS SHOWN (MODIFIED AFTER JACOBEIT, 2007).

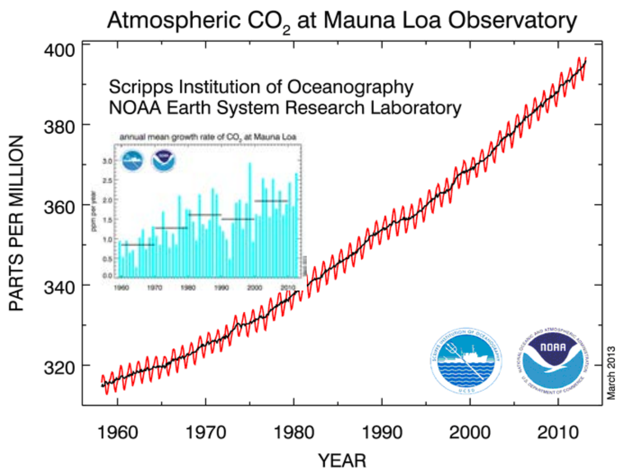


FIGURE 13: TIME SERIES OF THE CO2 CONCENTRATIONS AT THE MAUNA LOA OBSERVATORY AND THE YEARLY CHANGE IN PERCENTAGE (SMALL IMAGE). TAKEN FROM DR. PIETER TANS, NOAA/ESRL (WWW.ESRL.NOAA.GOV/GMD/CCGG/TRENDS/) AND DR. RALPH KEELING, SCRIPPS INSTITUTION OF OCEANOGRAPHY (SCRIPPSCO2.UCSD.EDU/). DOWNLOAD AM 31.3.2013.

The ongoing increase in greenhouse gas concentrations in the atmosphere lead to a decrease of outgoing radiation and an increase of energy in the climate system. According to Fasullo and Trenberth (2008) this increase is currently 0.9 Wm^{-2} which agrees with the 0.5 ± 0.43 Wm^{-2} since the beginning of the industrial period according to Loeb et al. (2012). This extra energy is partly stored in deeper layers of the ocean and cryosphere but it is used mainly to heat the surface. Once GHG concentrations stabilise, a new radiative equilibrium corresponding to the higher surface temperature will evolve.

Anthropogenic radiative forcing is a measure for the pertubance of the radiation balance by human activity. Each atmospheric component altered by humans contributes to the anthropogenic radiative forcing (Figure 14).

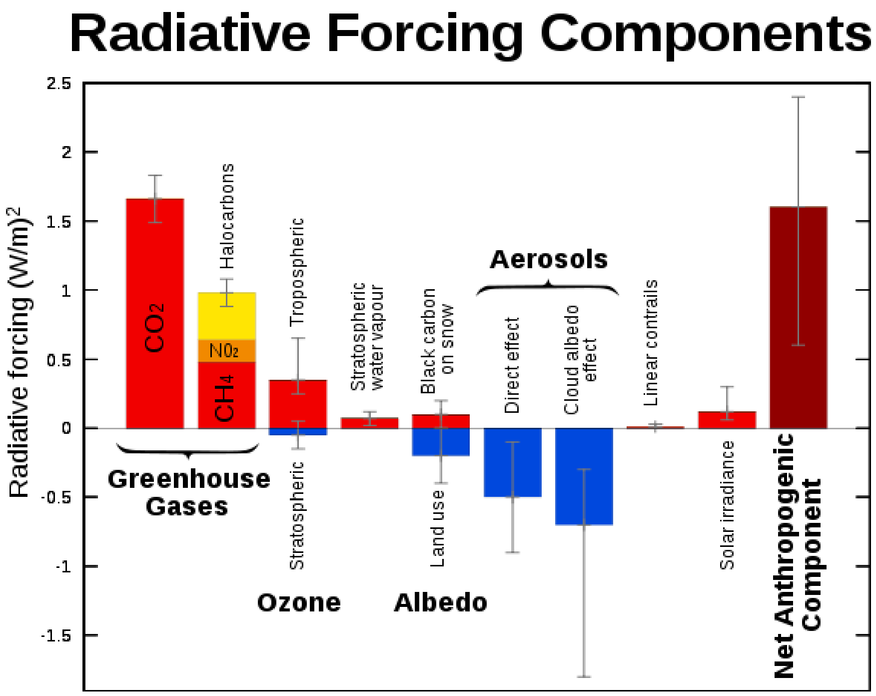


Figure 14: Global radiative forcing change distributed into the components for the year 2005 (Forster et al., 2007) difference to the pre-industrial radiative forcing in 1750. Here the warming at the Earth's surface is not considered.

CLIMATE CHANGE SCENARIOS FOR THE 21ST CENTURY

CHANGES IN AVERAGE CONDITIONS

All climate model scenarios indicate a warming within the next decades. The climate change signals of the newest climate model generation forced by the RCP emission scenarios are similar to the findings of previous studies and highly depend on the radiative forcing scenario. A comparison of the expected global surface warming between the SRES and the RCP scenarios is given in Figure 15 (Knutti and Sedlacek, 2012) showing that the range of the RCPs scenarios is much larger than the range of the SRES scenarios. The RCP 8.5 scenarios represents an even stronger warming than the SRES-A2 scenario indicating a more extreme future whereas the RCP 2.6 shows a stabilisation of the global mean surface temperature starting 2050. This is not represented by any of the former SRES scenarios.

Under all RCP scenarios long-term temperatures are expected to rise exceeding the 2°C warming compared to pre-industrial temperatures by 2100 except the RCP2.6 scenario (2°-target, see Chapter

3). Rogelj et al. (2012) also show that the RCP4.5 scenarios yield a temperature increase which is close to the SRES B1 scenario whereas the RCP8.5 is close to the extreme SRES A1F1 scenario.

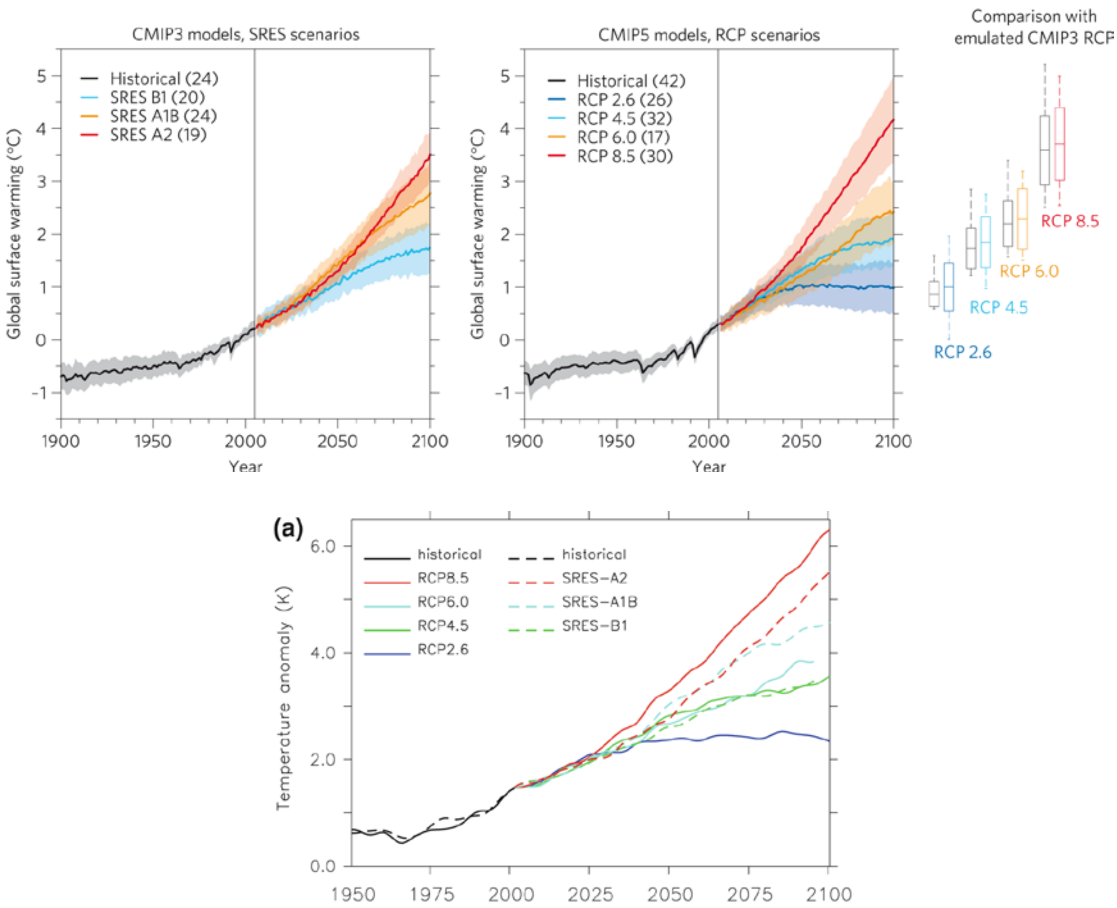


FIGURE 15: HISTORIC AND FUTURE GLOBAL TEMPERATURE CHANGE, MEAN AND STANDARD DEVIATION (SHADED) RELATIVE TO 1986 – 2005 OF THE SRES/CMIP3 SCENARIOS (LEFT) AND THE RCP/CMIP5 SCENARIOS (RIGHT). IN BRACKETS THE NUMBER OF MODELS PERFORMING THE SIMULATIONS IS GIVEN. THE BOX PLOTS ON THE VERY RIGHT (MEAN, STANDART DEVIATION, MINIMUM AND MAXIMUM RANGE) FOR THE 2080-2099 PERIOD FOR THE CMIP5 (COLOURED) AND THE MAGICC MODEL WHICH WAS CALIBRATED TO THE CMIP3 MODELS (GRAY) RUN FOR THE RCP SCENARIOS (TAKEN FROM KNUTTI AND SEDLACEK, 2012). BOTTOM) EVOLUTION OF THE GLOBAL MEAN AIR SURFACE TEMPERATURE ANOMALIES SIMULATED USING THE IPSL-CM5A-LR FOR HISTORICAL AND FUTURE USING RCP AND SRES FORCINGS - FROM (DEFRESNE ET AL., 2013).

But not only the global mean temperature is comparable between the newest GCM generation and former model runs. Also the spatial pattern of the mean temperature (Figure 16) and pattern of annual precipitation (Figure 17) for a multi-model mean of two time slices and two seasons for the RCP8.5 and the SRES A2 scenario show clear similarities. Warming will be more pronounced in high northern latitudes and on continents and less in the tropics and over the sea. This indicates the robustness of the large-scale features and consistency with the results of the 4th IPCC Assessment reports.

Precipitation projections indicate that for the next few decades the mean precipitation will increase especially in regions where the mean precipitation is already relatively high (e.g. tropics) and decrease in regions where mean precipitation is low (e.g. subtropics). Also a strong increase of precipitation occurs in the polar region. These findings confirm the results of the IPCC AR4. An increase of frequency and intensity of heavy precipitation events is expected at the global scale (Chou et al., 2009).

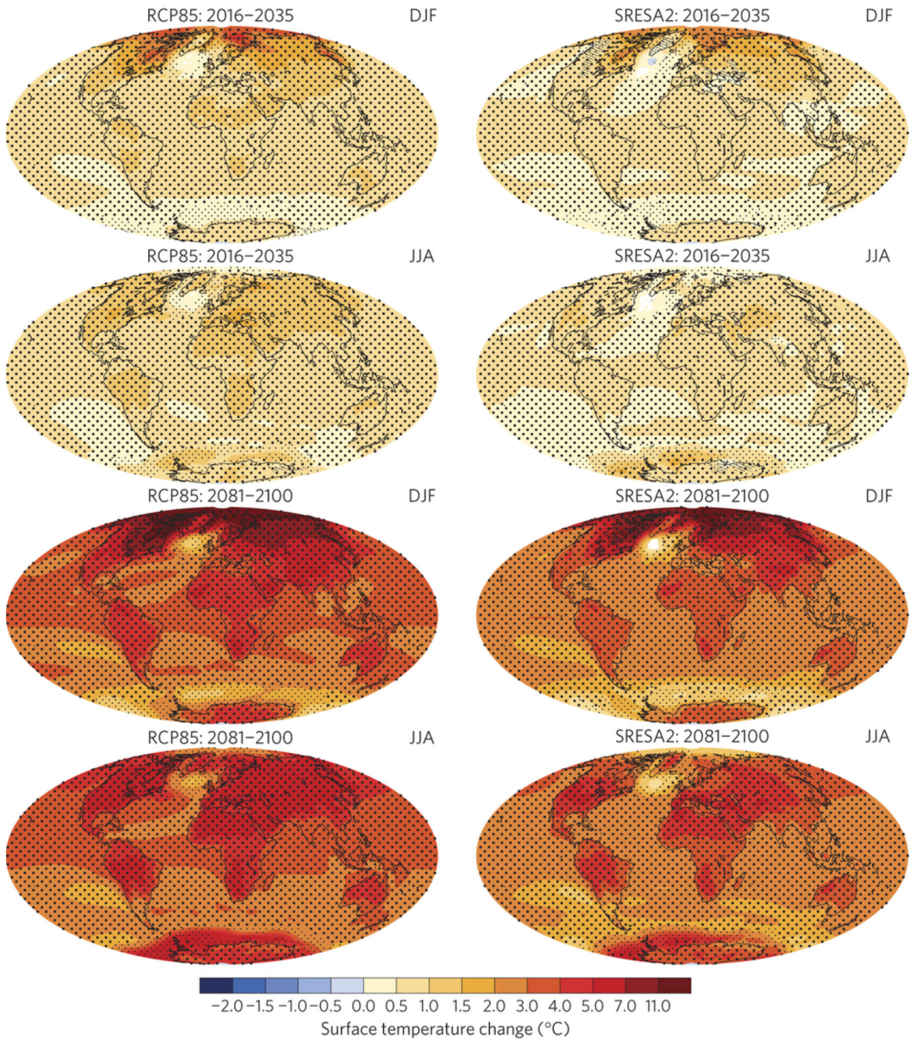


FIGURE 16: MEAN SURFACE TEMPERATURE CHANGE (°C) AND A MULTI-MODEL MEAN FOR DJF AND JJA OF THE TWO INVESTIGATION EPISODES RELATIVE TO 1986-2005 FOR THE CMIP5 (LEFT) AND CMIP3(RIGHT) MODELS. THE WHITE AREAS DENOTE INCONSISTENT MODEL RESPONSES, THE HATCHES NO SIGNIFICANT CHANGES, AND THE STIPPLING MARKS SHOW A HIGH ROBUSTNESS (KNUTTI AND SEDLACEK, 2012).

A direct consequence of the temperature increase is the frequency of extreme warm temperatures and sea level rise. Figure 18 (World Bank, 2013) highlights the effect of different emissions scenarios on both phenomena. In the RCP2.6 scenario the sea level rise stays below 70 cm in all parts of the world till the end of the 21st century. In the RCP8.5 the sea level rise exceeds 1 m in most tropical regions and reaches 1.25 m in some. To indicate extreme warm anomalies the monthly temperature anomalies of more than 3 standard deviations (σ) for the north hemisphere summer (JJA) were analysed. Without climate change and assuming a normal distribution of monthly temperature anomalies, an anomaly of more than 3 σ would occur once in 740 years, which means that there is a 0,1 ‰ chance of exceedance per month. In Figure 18 a value of 50 indicates that a 3 σ event occurs every second month (50% chance per month). Even under the moderate RCP2.6 scenario the extreme warm months increase rapidly in the tropic region. Under the RCP8.5 scenario nearly all months exceed the 3 σ threshold in the tropical region, but also in Western Europe and the USA values of 80 % are reached. This means that 4 out of 5 summer months are warmer than a 3 σ anomaly.

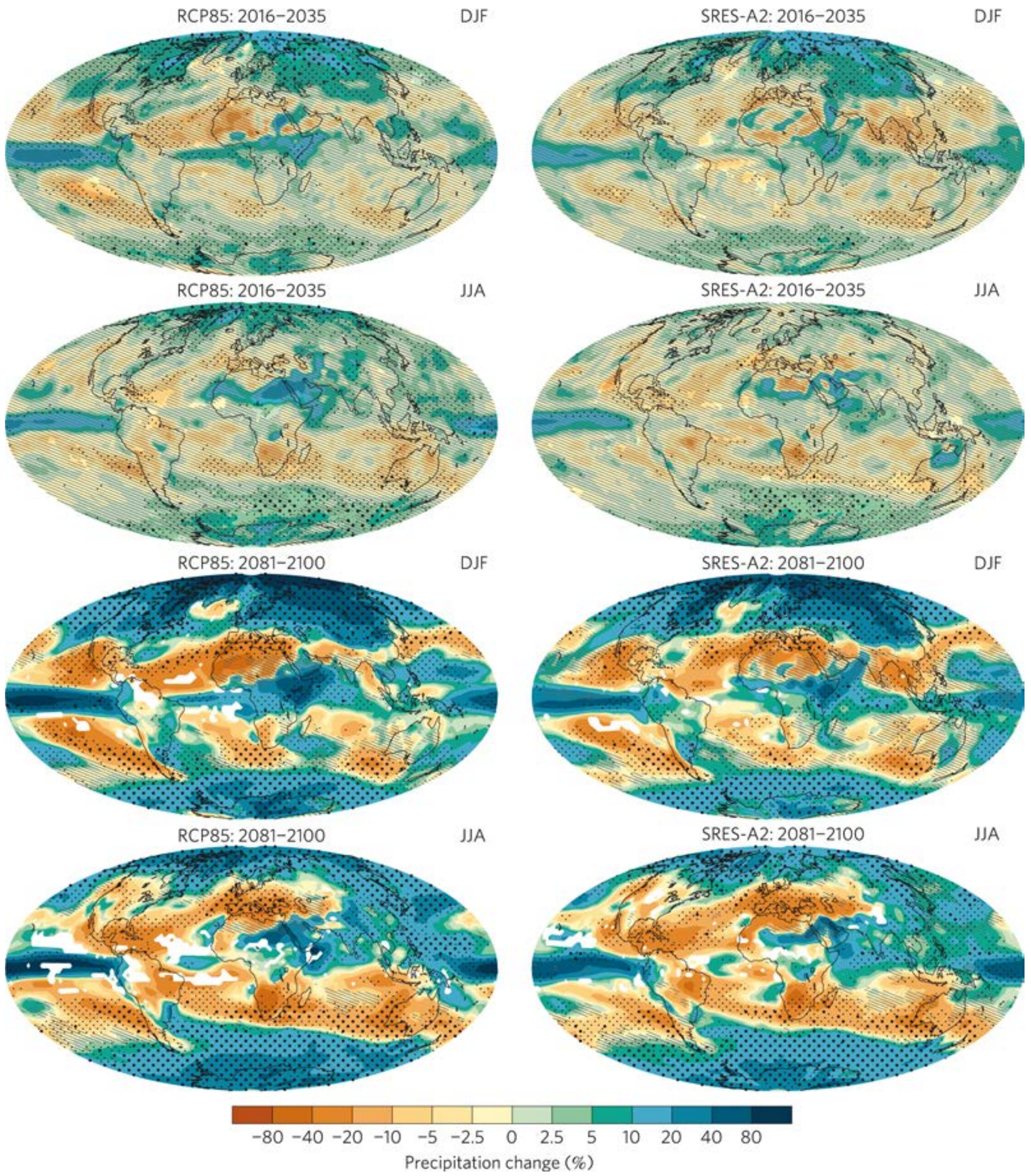


FIGURE 17: PATTERNS OF PRECIPITATION CHANGE FOR A MULTI-MODEL MEAN RELATIVE PRECIPITATION DJF AND JJA OF THE TWO INVESTIGATION EPISODES RELATIVE TO 1986-2005 FOR THE CMIP5 (LEFT) AND CMIP3(RIGHT) MODELS. THE WHITE AREAS DENOTE INCONSISTENT MODEL RESPONSES, THE HATCHES NO SIGNIFICANT CHANGES, AND THE STIPPLING MARKS SHOW A HIGH ROBUSTNESS (KNUTTI AND SEDLACEK, 2012).

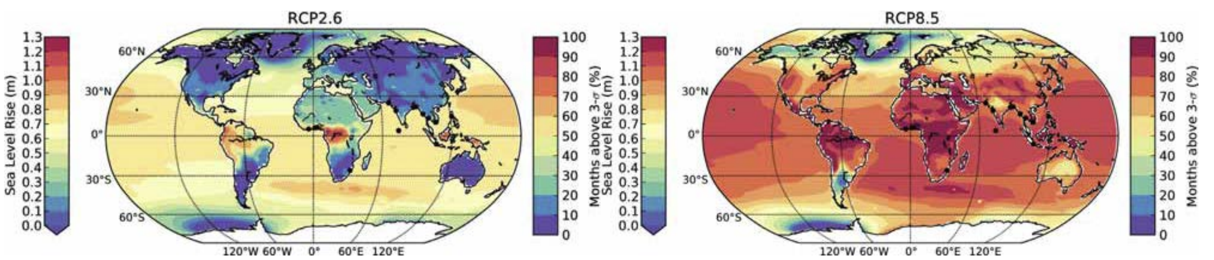


FIGURE 18: SEA LEVEL RISE (ON OCEANS; METERS) AND NORTHERN HEMISPHERE SUMMER EXTREME TEMPERATURE ANOMALIES (ON CONDINENTS; FREQUENCY OF MONTHS WITH A WARM TEMPERATURE ANOMALY HIGHER THAN 3 STANDARD DEVIATIONS) FOR THE RCP2.6 EMISSION SZENARIO (LEFT SIDE) AND THE RCP8.5 (RIGHT SIDE) TILL THE END OF THE 21ST CENTURY. (WORLD BANK 2013)

EXTREME EVENTS

In 2011 the IPCC published a special report on “MANAGING THE RISKS OF EXTREME EVENTS AND DISASTERS TO ADVANCE CLIMATE CHANGE ADAPTATION” (SREX, 2011). The key finding concerning extreme events in this report are:

- It is very likely that there has been an overall decrease in the number of cold days and nights and an overall increase in the number of warm days and nights at the global scale, that is, for most land areas with sufficient data.
- There have been statistically significant trends in the number of heavy precipitation events in some regions.
- There is medium confidence that some regions of the world have experienced more intense and longer droughts,
- There is limited to medium evidence available to assess climate-driven observed changes in the magnitude and frequency of floods at regional scales

Figure 19 and Figure 20 highlight the finding of this report concerning the climate change signal of the return period of extreme high maximum daily temperature (Figure 19) and daily precipitation rates (Figure 20). In both figures the results of three different climate change emission scenarios and the changes for the time frame 2046-2065 and 2081-2100 relative to the base period 1981-2000 are shown. Events with a return period of 20 years within the base period constitute the reference scenario. A decrease in return period indicates an increase in frequency.

All regions of the world show an increase in frequency of high daily maximum temperatures. In Europe 20 year events turns into 5 year events in mid-century and into 2 years events at the end of the century. In the tropics the frequencies are even higher.

For daily precipitation also most regions show an increase of frequency. Here the changes are higher in high latitudes and the subtropics and less pronounced in the tropics.

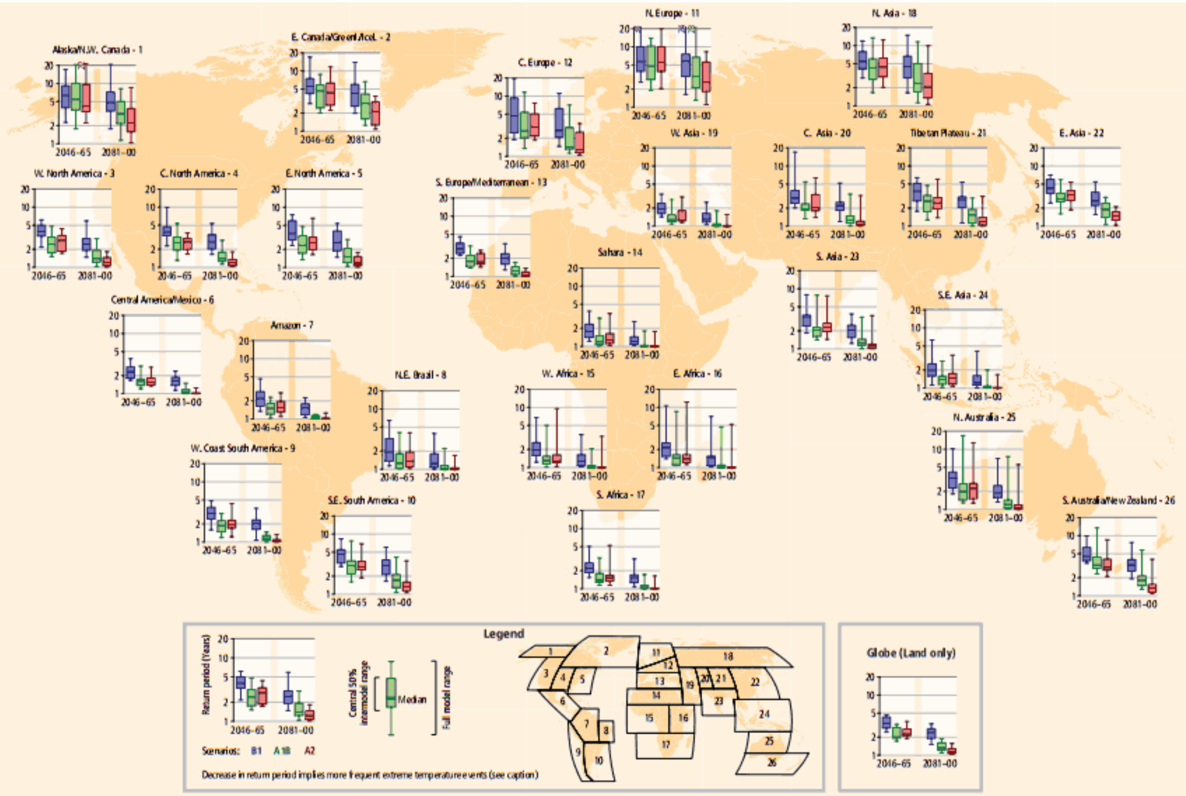


Figure 19: Projected return periods for the maximum daily temperature that was exceeded on average once during a 20-year period in the late 20th century (1981–2000). A decrease in return

period implies more frequent extreme temperature events (i.e., less time between events on average). The box plots show results for regionally averaged projections for two time horizons, 2046 to 2065 and 2081 to 2100, as compared to the late 20th century, and for three different SRES emissions scenarios (B1, A1B, A2) (IPCC, 2011)

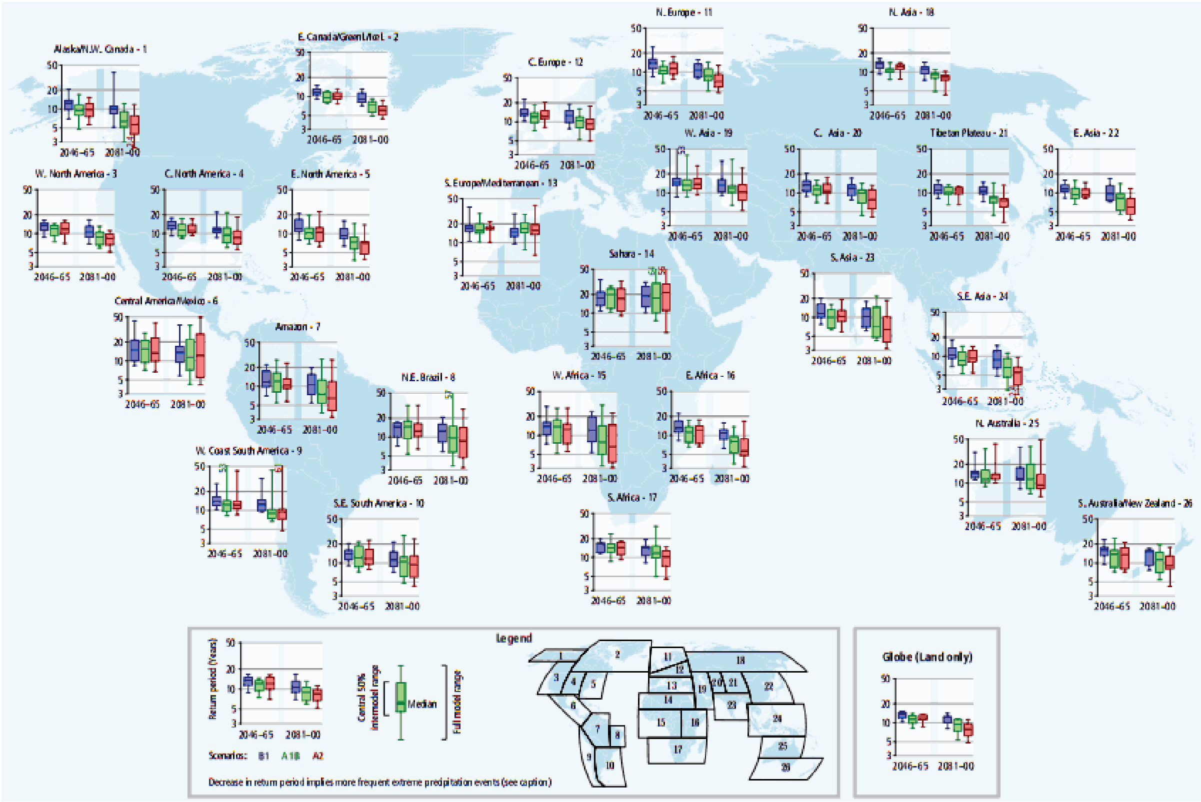


Figure 20: Projected return periods for a daily precipitation event that was exceeded in the late 20th century on average once during a 20-year period (1981–2000). A decrease in return period implies more frequent extreme precipitation events (i.e., less time between events on average). The box plots show results for regionally averaged projections for two time horizons, 2046 to 2065 and 2081 to 2100, as compared to the late 20th century, and for three different SRES emissions scenarios (B1, A1B, A2) (IPCC, 2011)

TIPPING POINTS

The term ‘‘tipping point’’ commonly refers to a critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system (Lenton et al., 2008). In the case of the climate system it means a threshold, the crossing of which triggers a transition to a new climatic state at a rate determined by the climate system itself. Tipping points occur because of amplifying feedbacks in the climate system (Hanson, 2009). Human activities may have the potential to push components of the Earth system past critical states into qualitatively different modes of operation, implying large-scale impacts on human and ecological systems. Lenton et al. (2008) introduce the term ‘‘tipping element’’ to describe large-scale components of the Earth system, including non-climatic variables, that may pass a tipping point with severe long term consequences.

Policy relevant tipping elements in the climate system are (Figure 21: Arctic sea ice, Greenland and West Antarctic ice sheet, glaciers and ice caps, biosphere reaction (Amazon rainforest, boreal forest,…), atmospheric and ocean-atmospheric regimes (MOC, thermohaline circulation, ENSO, Indian summer monsoon, Sahara and West African monsoon,…), and permafrost thawing. Arctic sea ice is one of the most well-known tipping elements. Melting sea ice exposes the darker ocean surface which absorbs more radiation than sea ice. This amplifies the warming and increases the ocean heat content. This positive ice-albedo feedback can also introduce other changes in the climate system as e.g. shift in the large scale pressure distribution. At present, both, arctic summer and -winter sea ice area is declining with its strongest trend in September. The IPCC (2007) projections indicate that the September sea ice minimum will further decrease and winter sea ice thickness will decrease.

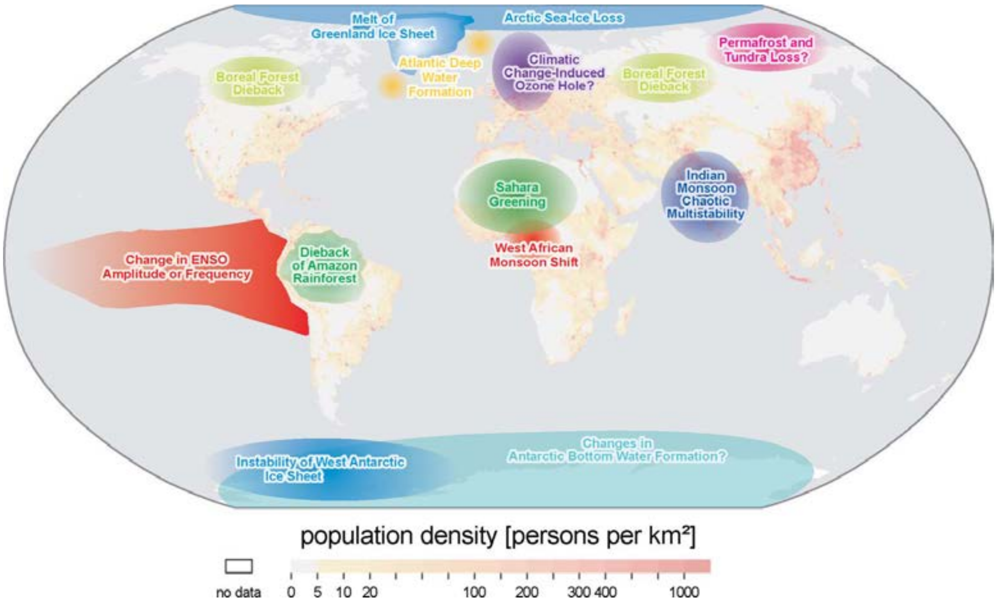


FIGURE 21: FIHUREPOTENTIAL POLICY-RELEVANT GLOBAL TIPPING POINTS IN THE CLIMATE SYSTEM (LENTON ET AL., 2008). THE GLOBAL POPULATION DENSITY IS SHOWN ASWELL. SUBSYSTEMS INDICATED CAN EXHIBIT THRESHOLD-TYPE BEHAVIOR IN RESPONSE TO ANTHROPOGENIC CLIMATE FORCING. SMALL PERTURBATIONS CAN QUALITATIVELY ALTER THE FUTURE FATE OF THE SYSTEM AND CAN BE TRIGGERED IN THIS CENTURY

REACHING THE TWO DEGREE TARGET

TWO DEGREE TARGET

The 2°C target describes the international political agreement to limit global temperature rise to less than 2°C compared to the pre-industrial level. This limit was first suggested by W.D. Nordhaus (1975, 1977) to kept the temperature increase within the amplitude of natural long-term climate variations. In 1995 this target was brought into the political debate by the „Wissenschaftlicher Beirat für Globale Umweltfragen“ of the German Bundestag (WBGU, 1995) as a limit above which climate tipping points might be crossed. During the Kyoto negotiations it was officially adopted as a target by European Council in 1996 and 2005 (Randalls, 2010). It makes the second article of the UN Framework Convention on Climate Change (UNFCCC) – preventing dangerous anthropogenic perturbances of the climate system - operational. In 2010 the 2°C target was officially accepted at the 16th UN Conference of the Parties under the UNFCCC in Cancún. To fulfil the 2°C target with a probability of 50% respectively 70% the greenhouse gas concentrations must not exceed 450 ppm resp. 400 ppm CO2 eq. for any prolonged period of time. Figure 22 shows the probability of exceeding the 2°C threshold for different GHG stabilisation levels as calculated in various studies. As can be seen, uncertainties are rather large, and stabilisation levels with a (very) good chance of not exceeding the 2°C target are those below 350 ppm CO2eq. Above 550 ppm CO2eq it is unlikely that the 2°C target can be maintained (IPCC, 2007).

GREENHOUSE GAS EMISSION DEVELOPMENT

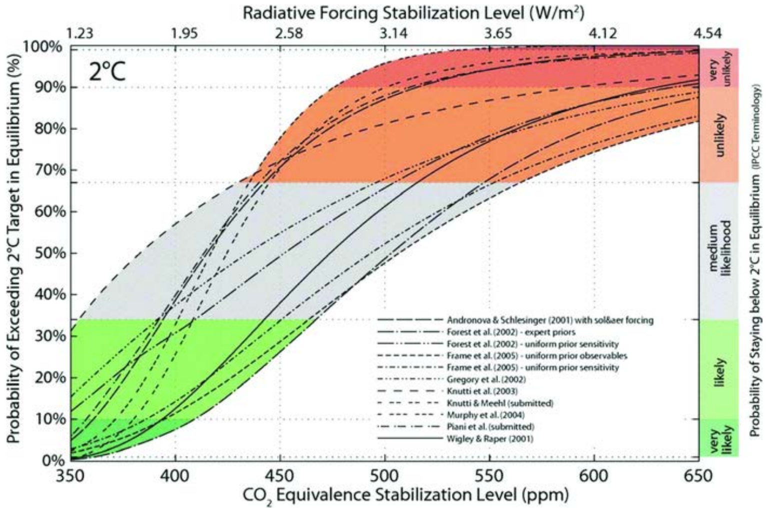
The Kyoto-protocol addressed several greenhouse gases and limited national emissions during the period 2008 to 2012 in relation to the emissions of the year 1990. Other metrics besides annual emission on a national basis have been introduced into the political discussion, such as cumulative emissions, per-capita emissions, emission intensities, e.g. based on GDP, etc.. Whatever metric is used, uncertainties regarding the submitted data abound and comparing the procedures applied by different countries and organisations is problematic. Problems include:

- Assessment: Data can be based on either direct measurements or estimations. Methods differ in accuracy, usability, and cost.
- Attribution: emissions can be attributed to the geographic area where they are emitted.
- Sectors: Economic sectors are partially ill defined, not well documented or suffer from the lack of data availability.
- Time horizon: greenhouse gases have different absorption capacities and times of residence in the atmosphere; they are therefore frequently reported as CO2 equivalents. There are some uncertainties regarding these calculations that need to be taken into account.

Although much progress has been made regarding unified procedures through the IPCC and other international processes, careful scrutiny of any data used is still advisable.

Greenhouse gases emitted by humans and their primary sources are:

- Methane (Ch4): waste management, agriculture, energy
- Carbon dioxide (CO2): fossil fuel, land-use, de-/reforestation, soil erosion,…
- Nitrous oxide (N2O): agriculture (e.g. fertilizer)
- Fluorinated gases: industrial processes, refrigeration,…



-

FIGURE 22: PROBABILITY OF EXCEEDING THE 2°C ABOVE PRE-INDUSTRIAL (1.4°C ABOVE 1990 LEVELS) TARGET SHOWN FOR A RANGE OF CO2-EQUIVALENT STABILISATION LEVELS. TAKEN FROM IPCC (2007,SOURCE: HARE AND MEINSHAUSEN (2005)).

According to the AR4 IPCC (2007) economic activities producing the emissions (numbers in parentheses show percentage of 2004 global greenhouse gas emissions, highest ranked first) were:

- Energy supply (26%): coal burning, natural gas and oil, ...
- Industry (19%): burning of fossil fuels for energy and emissions from transformation processes not associated with energy consumption
- Land-use/Land-cover/Forestry (17%): deforestation, land clearing, fires
- Agriculture (14%): management of agricultural soils, livestock, biomass burning, ...
- Transportation (13%): burning of fossil fuels for road, air, rail, marine transportation
- Commercial and residential buildings (8%): on-site energy generation and burning of fuels for heat or cooking
- Waste, wastewater (3%): landfill methane, wastewater methane and nitrous oxide

Thus, energy related emissions constituted some 66% of total global GHG emissions (in CO2 equivalents) in 2004.

Annual emissions of anthropogenic greenhouse gases have continuously increased, especially in the energy sector, mainly due to increased production (Figure 23). In the year 2010 emissions reached 50.1 Gt CO2 eq. (UNEP, 2012). Compared to the base year 1990 global emissions increased by 30% (land-use and land-cover related CO2 emissions included), and by 20% in the period 2000-2010 (UNEP, 2012). In 2009 global CO2 emissions from fossil fuels and cement production declined (recession) but increased in 2010 and 2011 (Olivier et al., 2012) reaching 34 Gt CO2. Forestry and land-use emissions decreased in 2010 by 15%, whereas CH4 and N2O emissions increased by 0.5%. Values at the country level have to be interpreted with care as every country and region calculates the shares and trends slightly differently (see UNEP, 2012 for more information).

The shares of main economic sector for individual GHG emissions in the year 2010 are shown in Figure 24, also for selected nations.

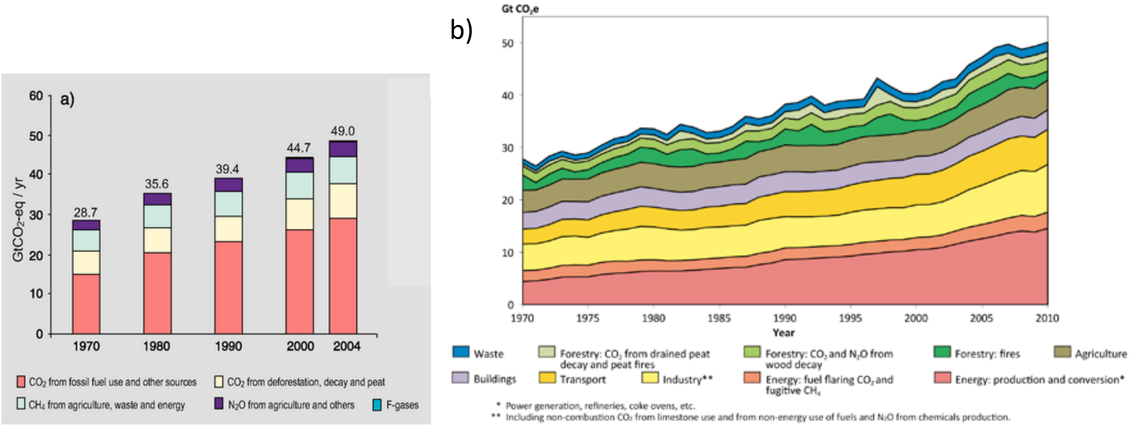


FIGURE 23: A) GLOBAL ANNUAL EMISSIONS OF ANTHROPOGENIC GHG IN GTCO2-EQU. / YR FOR 1970 – 2004 (SOURCE: IPCC, 2007). IN B) SIMILAR TO A) BUT BY SECTOR FOR GLOBAL GREENHOUSE GAS EMISSIONS 1970-2010. FOR 2010 EMISSIONS OF 50.1 GTCO2E WERE CALCULATED FROM BOTTOM-UP EMISSION INVENTORIES (UNEP 2012, *SOURCE: JRC/PBL (2012) (EDGAR 4.2 FT2010).*

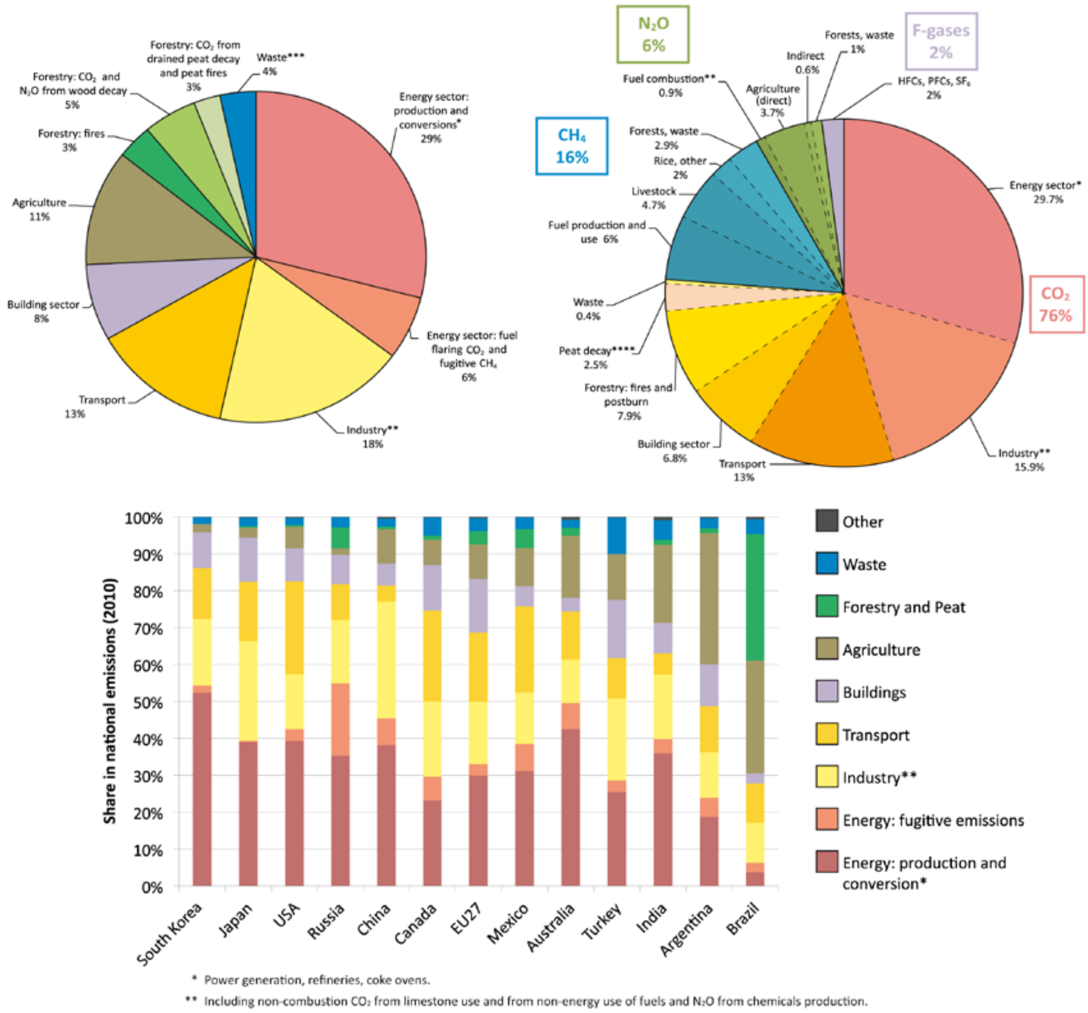


FIGURE 24: SOURCES OF GLOBAL GREENHOUSE GAS EMISSIONS IN 2010 BY (LEFT) MAIN SECTOR AND BY (RIGHT) MAIN SECTOR AND GAS TYPE (IN CO2E USING GWP VALUES AS USED FOR UNFCCC/KYOTO PROTOCOL REPORTING, UNEP 2012, *SOURCE: JRC/PBL (2012) (EDGAR 4.2 FT2010).* THE BOTTOM GRAPH SHOWS THE SHARE OF EACH SECTOR IN THE NATIONAL EMISSIONS, NOTE THAT THE EU COUNTRIES ARE COUNTED IN ONE AS THE EU27 (UNEP, 2012).

FUTURE EMISSION PATHWAYS BASED ON ECONOMIC PROJECTIONS (IEA, GEA, …; 2020, 2050, 2100)

Limiting global warming to 2°C compared to pre-industrial levels requires very stringent emission reductions, but there are different ways to achieve this goal. International organisations such as the International Energy Agency (IEA) and the United Nations Environment Programme (UNEP), as well as joint international efforts such as the Global Energy Assessment (GEA) have developed (energy) pathways, some of which lead to the necessary reduction of global greenhouse gas emissions.

PATHWAYS DEFINED BY THE GEA

GEA defined several goals to be met by all their pathways:

- Energy systems must be able to support the expected economic and demographic developments (e.g. population growth) until 2050.
- Modern energy and end-use conversion (e.g. cleaner cooking) has to be accessible to all humans until 2030.
- Energy security must be enhanced for all regions (i.e. resilience of the energy system)
- Health and environment must be improved to reduce deaths and illness due to energy related pollution
- Global temperature rise must be kept below the 2°-target

In total, 60 different pathways of energy transformations that meet the above goals were defined by the GEA (GEA, 2012). These can be grouped into three major pathways, the GEA-Supply, the GEA-Mix, and the GEA-Efficiency, for each of them two subgroups are defined accounting for transport (advanced transport system, using electricity and hydrogen, or classic transport, using hydrocarbons). In a next step GEA (2012) investigates which of its ten supply-options are viable for each of the six branches. GEA (2012) concludes that 41 out of the 60 pathways support the transformation towards a sustainable economy. For example, if the society chooses an energy pathway with high energy demand (the “supply” branch), CSS technologies must be deployed – supply options without CSS will necessarily violate one or more of the above requirements. On the other hand, investing in energy efficiency permits to avoid CSS, while the objectives can still be met. Eleven world regions, grouped into five GEA regions, were defined. Included into the pathways are energy sectors (supply and demand) and social, environmental, economic, and technological developments resulting in radically changed human behaviour towards an increased usage of renewable energies.

The three GEA scenario groups (Figure 25) share common socioeconomic assumptions but differ radically in the structure of the energy systems:

GEA-Efficiency: energy intensity improvements are doubled compared to the historical average. This can be achieved e.g. by improving building sector efficiency by a factor of four by 2050, adoption of best-available technologies in the energy system, e.g. enhanced recycling, improvement of the life-cycle of a product, reducing energy demand through efficiency standards. Emphasis is laid on the demand-side. The primary energy demand level should not exceed 700 EJ in 2050, compared to 490 EJ in 2005. The share of renewable energy should reach 75% in 2050, increasing to 90% by 2100. The focus is on increase of renewable energy across all pathways.Some pathways assume a phase out of nuclear power by end of lifetime of the existing power plants, some provide optional bridges for a medium-term transition toward renewable energies. Unconventional oil resources remain largely untapped reducing the GHG and air pollution emissions.

GEA-Supply: focus here is on up-scaling of supply-side options with a modest emphasis on efficiency. The energy demand reaches 1050 EJ in 2050 with a massive up-scaling of energy supply with new infrastructures and fuels as e.g. hydrogen and electric vehicles. Renewable energies are expected to contribute 50% by 2050. Fossil Carbon Capture and Storage (CCS) becomes essential in the medium term, in the long term it declines as zero-carbon options prevail. Nuclear power plants on the other hand increase after 2030 in some pathways presuming that issues as nuclear waste are resolved. Some pathways include nuclear phase-out as alternative energy sources increase. Here, CCS is a must.

GEA-Mix: these pathways are intermediate with respect to efficiency and up-scaling of cleaner supply-side technologies. Energy demand level reaches 920 EJ in 2050 with the main emphasis on the diversity of the system enhancing resilience against innovation failures or technology shocks. Local and regional implementation strategies are emphasised and co-evolution of multiple fuels is forced.

Being normative pathways, all GEA pathways sustain the 2°C target.

THE IEA PATHWAYS

The IEA pathways defined four scenarios/pathways of energy trends starting in 2010 until 2035, taking energy security, environment and economy into account, differing mainly regarding the underlying governmental policies. Not all these pathways are compatible with the 2°C target.

Current Policies Scenario (CPS): only measures and policies that are/were adopted by mid-2012 are considered, only very few future policies are taken into account as e.g. energy and climate targets of China's Five-Year plan and feed-in tariff for renewable sources in Japan. Advanced biofuels are assumed to reach full commercialisation by 2025. The aim of this scenario is to show how the World would evolve if energy policies remain unchanged.

New policies scenario (NPS): policy commitments and plans to address energy related challenges already implemented or announced regarding renewable energy, energy efficiency, nuclear phase-out or additions, national greenhouse gas emissions reduction targets, phasing out of inefficient fossil fuels etc. are considered to be implemented. The aim is to assess the impact of the above actions compared to the *current policies scenario*. These pathways are not a-priori compatible with the 2°C target.

450 Scenario (450S): plausible energy pathway scenario including actions that lead to a 50% chance of reaching the 2°-target. Policy actions implementing the commitments of the Cancun Agreement by 2020 are assumed. Further emission targets for 2035 and beyond ensure a consistent emission trajectory where the greenhouse gas concentrations stabilise at 450 ppm CO_2-equ. Further, abatement measures in non-OECD countries are supported by OECD countries with $100 billion per year from 2020 onwards. Advanced biofuels are assumed to reach full commercialisation by 2015. The aim of this pathway is to test whether it is plausible that the 2°-target is achieved.

Efficient World Scenario: a large step change in energy efficiency is assumed and implications for environment, economy and energy security are quantified. All future investments improve energy efficiency and are economically viable. Market barriers are removed. Technological potential of energy efficiency is determined by sector and regions. Additionally, payback periods of investments are be calculated. The aim is to depict economically viable energy efficiency focussed pathways. These pathways are also not a-priori compatible with the 2°C target, but much closer that the *new policies scenario*.

The increase in world primary energy demand of the NPS is in the order of 1.2% per year, for the CPS it reaches 1.5% per year. Even the 450S assumes a rise of energy demand between 2010 and 2035 of 0.6% per year (Table 1 and Figure 26). Future CO_2 emissions differ by a factor of two in 2035 between the different scenarios. The emission increase in the NPS is consistent with a long-term temperature increase of 3.6°C, in CPS with 5.3°C.

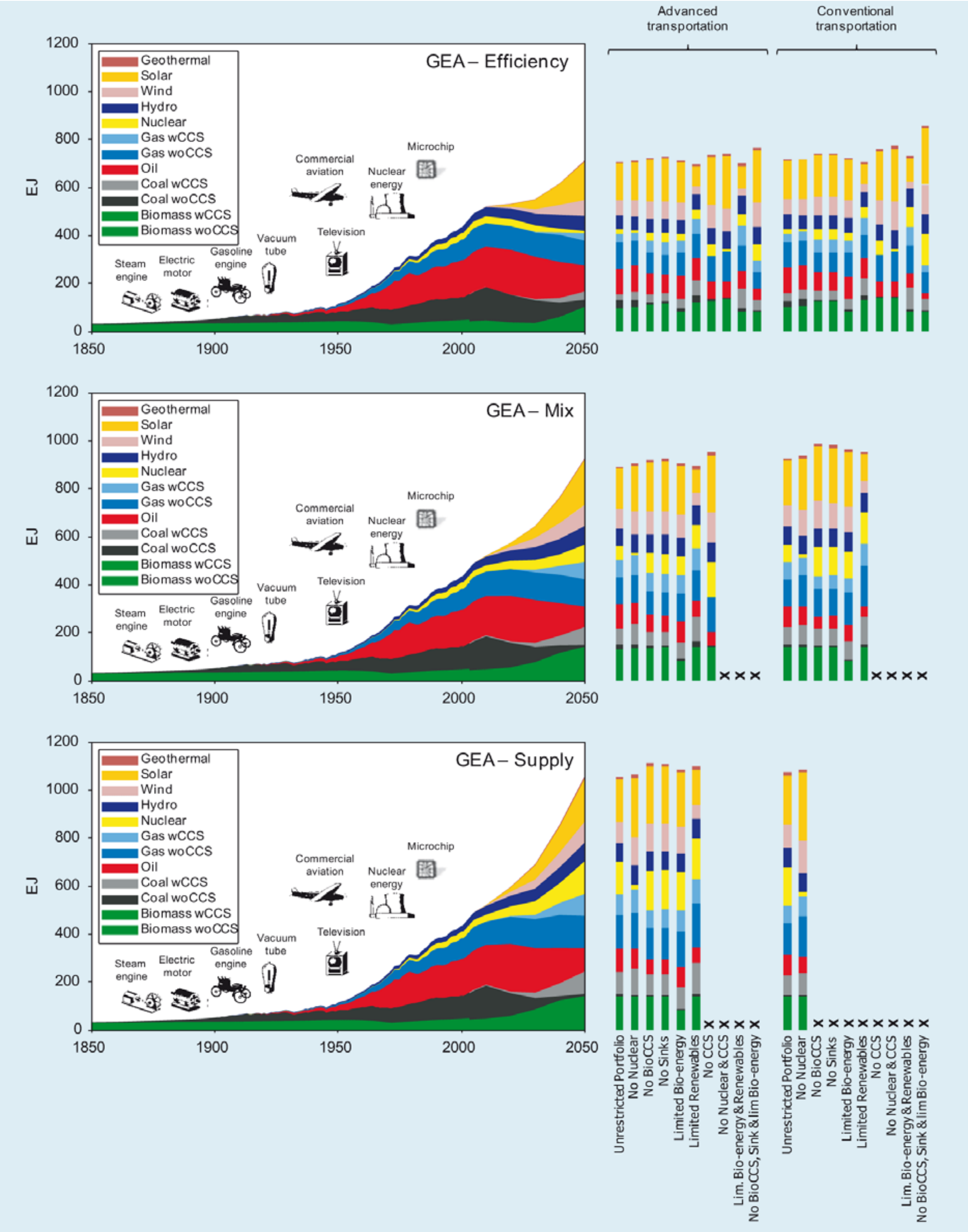


FIGURE 25: FUTURE DEVELOPMENT OF THE ENERGY IN THE THREE GEA PATHWAY FAMILIES. LEFT: THE ILLUSTRATIVE PATHWAYS. RIGHT: THE 2050 ENERGY MIX OF ALL 60 PATHWAYS. CONVENTIONAL TRANSPORTATION ARE PATHWAYS ASSUMING THE CONTINUATION OF A LIQUID-BASED TRANSPORTATION SYSTEM. ADVANCED TRANSPORTATION ARE PATHWAYS ALLOWING FOR FUNDAMENTAL CHANGES IN INFRASTRUCTURES. PATHWAYS MARKED "X" ARE THE 19 CASES WHERE THE GEA NORMATIVE GOALS COULD NOT BE REACHED (GEA, 2012).

THE UNEP PATHWAYS

For all 64 scenrios the UNEP considers, temperature stays below an increase of 1.5° or 2° compared to the pre-industrial levels (Figure 27). Of the diverse possible pathways least cost scenarios, i.e. the cheapest combination of policies and measures, are studied. Actions begin immediately and each of the scenarios has a particular emission trajectory through time but all stay within an acceptable limit of cumulative emissions.

“likely” pathway: emission scenarios that are likely (66% probability or more) to meet the 2°-target and do not exceed 44 GtCO2equ/year ± 2GtCO2equ/year in 2020. Emissions decrease thereafter and do not exceed 37 GtCO2equ/year (range: 33-44) in 2030 and 21 GtCO2equ/year (range: 18-25) in 2050.

TABLE 1: WORLD PRIMARY ENERGY DEMAND AND ENERGY-RELATED C02 EMISSIONS BY SCENARIO (MTOE). * INCLUDES TRADITIONAL AND MODERN BIOMASS USES. ** EXCLUDES INTERNATIONAL BUNKERS. NOTE:TPED =TOTAL PRIMARY ENERGY DEMAND; MTOE = MILLION TONNES OF OIL EQUIVALENT;GT = GIGATONNES. TAKEN FROM IEA, 2012.

			New Policies		Current Policies		450 Scenario	
	2000	2010	2020	2035	2020	2035	2020	2035
Total	10 097	12 730	14 922	17197	15 332	18 676	14176	14 793
Coal	2 378	3 474	4 082	4 218	4417	5 523	3 569	2 337
Oil	3 659	4113	4 457	4 656	4 542	5 053	4 282	3 682
Gas	2 073	2 740	3 266	4106	3 341	4 380	3 078	3 293
Nuclear	676	719	898	1138	886	1019	939	1556
Hydro	226	295	388	488	377	460	401	539
Bioenergy*	1027	1277	1532	1881	1504	1741	1568	2 235
Other renewables	60	112	299	710	265	501	340	1151
Fossil fue/ shore in TPED	80%	81%	79%	75%	80%	80%	77%	63%
Non-OECD shore of TPED**	45%	55%	60%	65%	61%	66%	60%	63%
C02 emissions (Gt)	23.7	30.2	34.6	37.0	36.3	44.1	31.4	22.1

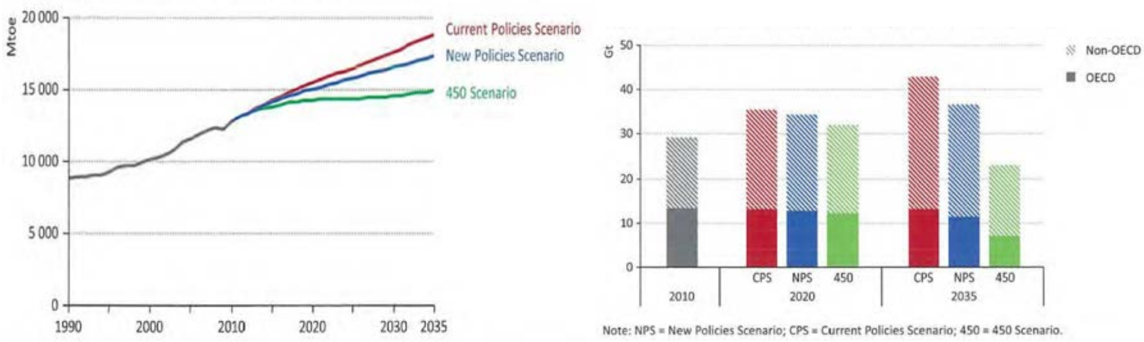


FIGURE 26: LEFT: WORLD PRIMARY ENERGY DEMAND FOR THREE OF THE FOUR SCENARIOS AND RIGHT) THE GLOBAL ENERGY-RELATED CO2 EMISSIONS IN EACH OF THE THREE SCENARIOS COMPARED TO THE 2010 VALUES (IEA, 2012).

“medium”: emission scenarios that have a 50-66% chance of meeting the 2°-target and reaching the 46GtCO2equ/year ± 2GtCO2equ/year in 2020. Beyond 2020 emissions decrease and emission do not exceed 41 GtCO2equ/year (range: 39-46) in 2030 and 27 GtCO2equ/year (range: 24-29) in 2050.

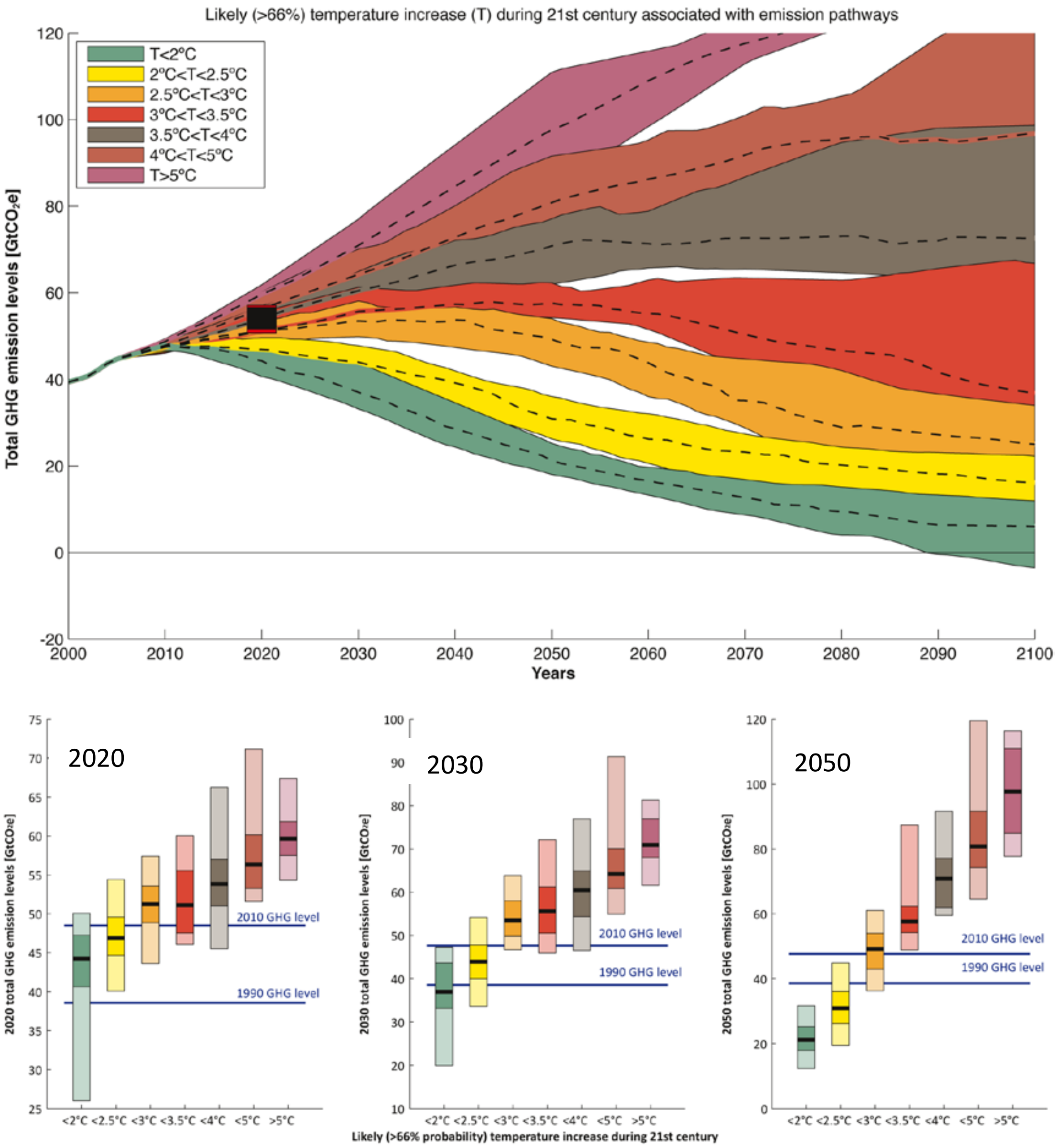


FIGURE 27: PATHWAYS LIMITING THE TEMPERATURE INCREASE WITHIN THE "LIKELY" (>66%) CHANCE OF STAYING BELOW DIFFERENT TEMPERATURE LIMITS (TOP), THE SMALL BOX DENOTES THE EMISSION LEVELS WHICH ARE CONSISTENT WITH THE CURRENT PLEDGES. BELOW: TIME SLICES OF GLOBAL TOTAL EMISSIONS FOR 2020, 2030, AND 2050 (TAKEN FROM UNEP, 2012).

To avoid the excess emissions until 2020 the business as usual emission levels would need to be reduced by 14 GtCO2equ/year. UNEP defined 4 pledge cases which have a "likely" chance of staying within the 2°C target (44 GtCO2equ/year). Their gaps to the 2020 emissions would be:

- Case 1: "Unconditional pledges, lenient rules", 13 Gt CO2 eq./year (range 9–16 Gt CO2 eq./year)
- Case 2: "Unconditional pledges, strict rules", 10 Gt CO2 eq./year (range 7-14 Gt CO2 eq./year)
- Case 3: "Conditional pledges, lenient rules", 11 Gt CO2 eq./year (range 7-15 Gt CO2 eq./year)
- Case 4: "Conditional pledges, strict rules", 8 Gt CO2 eq./year (range 4-11 Gt CO2 eq./year)

UNEP (2012) also identified important findings from a literature study. The most critical factor is limiting energy demand. Increasing renewable energies and enhancing energy efficiency reduce the need for other technologies, especially nuclear and CCS. The possibilities of biological CCS are explored.

UNFCC AND GREENHOUSE GAS EMISSION REDUCTIONS

The United Nations Framework Convention on Climate Change (UNFCCC), adopted in 1992 and ratified so far by 194 countries and the EU, has the ultimate objective to achieve "... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate sytem." As a framework convention, additional agreements and protocols are required to make this aim operational in internationally coordinated actions.

The Kyoto Protocol was the first legally binding agreement to reduce the greenhouse gas emission by defined quantities within a given period of time. Although these reductions were only a very small first step and by no means sufficient to reach the 2°C target, they marked what was then greeted as a good beginning for expected further steps that were to follow. The ratification process for the Kyoto Protocol was slow and it therefore only entered into effect in 2005, eight years after its adoption at the COP in Kyoto.

The Kyoto protocol to the UNFCC sets binding reduction targets for the period 2008-2012 compared to 1990 for industrialised countries and non-binding reduction targets for developing countries. 190 countries and the European Union signed the protocol in 1997, but not all ratified it, and Canada withdrew in 2011. All countries committed to the protocol report their measures and achievements in reducing greenhouse gases to the UNFCCC.

In the context of the Kyoto protocol emission trading was introduced as one of the “flexible mechanisms” to control and reduce the emissions. By introducing individual upper limits of GHG emissions through emission certificates for industrial units and by putting a price on these certificates emissions can be traded - between companies or countries. An emission trading scheme with the necessary administrative support was operationally installed within the EU in 2005 after a period of testing.

Two project based measures defined in the Kyoto Protokol were the Clean Development Mechanism (CDM) and Joint Implementation (JI). JI enables industrialized countries to carry out joint implementation projects with other developed countries, while the CDM involves investment in sustainable development projects that reduce emissions in developing countries. (http://unfccc.int/kyoto_protocol/mechanisms/items/1673.php - accessed 2013.0705). Other international support actions include capacity building in developing countries mainly towards renewable energies and improved energy efficiency.

Although not all data are yet analysed, it is clear that the emission reductions aimed for in the Kyoto Protocol (5% for the emissions of Annex I countries) were overachieved. Between 1990 and 2011 the countries listed in Annex I of the UNFCCC including the USA and Canada have reduced their overall emissions (without land use change emissions) by 1.8 Gt CO2 eq. or 9.3 %. Most countries fulfilled their individual obligations, although in some cases this was not due to GHG reduction measures but to other political or economic developments. Austria is one of the countries that did not meet its targets that were among the most ambitious in the EU. In fact GHG emissions in Austria were higher in the first commitment period than in the reference year 1990.

A follow-up agreement at global level has not yet been reached – the international community has not agreed on the type of agreement needed to reduce greenhouse gas emissions. Negotiations are so tedious that even the commitment to a follow-up agreement and a time schedule was considered a success at the COP in Durban.

One aspect merits mention in this context: At the Cancun COP in 2010 it was agreed that by 2015 a review should be made on whether the 2°C objective needs to be strengthened in future, including the consideration of a 1.5°C goal, on the basis of the best scientific knowledge available. This indicates that the 2°C target might prove insufficient and a more stringent target necessary.

GLOBAL EMISSION REDUCTION FOR THE TWO DEGREE PATHWAY

None of the follow-up agreements to the Kyoto Protocol in discussion on the global level so far achieves reductions near those needed to meet the 2°C target. There seems to be agreement that the potential to reach the 2°C-target is in place, but there is danger that “lock in” effects of high emission technologies, structures and processes could jeopardize success. This is an issue e.g. in view of the rapid increase in gas production in the USA.

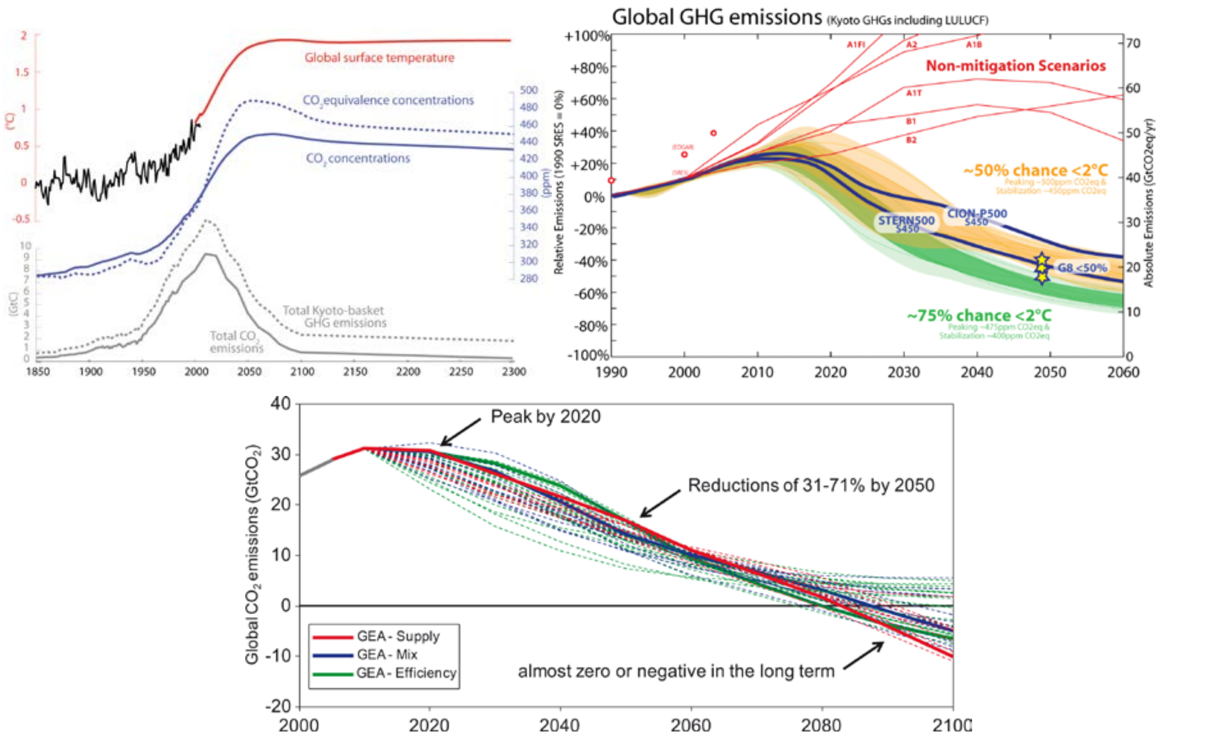


FIGURE 28: TOP LEFT) HISTORICAL CO2 EMISSIONS (GREY), CONCENTRATIONS (BLUE) AND GLOBAL MEAN TEMPERATURE (BLACK) AND TIME SERIES FOR FUTURE EVOLUTIONS (TEMPERATURE ON RED). TOP RIGHT) GLOBAL GREENHOUSE GAS EMISSIONS UNDER DIFFERENT SCENARIOS. IN RED THE NON-MITIGATION SCENARIOS, IN BLUE TWO MITIGATION SCENARIOS OF THE STERN REPORT (STERN, 2006) AND THE EUROPEAN COMMISSION (2007). PEAK CONCENTRATIONS ARE REACHED AT ~500 PPM CO2-EQU. AND STABILISE AT 450 PPM CO2-EQU. G8 INDICATES LONG-TERM GOALS AGREED ON IN HEILIGENDAMM IN 2007. RED CIRCLES INDICATE GLOBAL EMISSIONS OF THE EDGAR DATABASE. TAKEN FROM EU (2008). BOTTOM SHOWS THE THREE GEA PATHWAYS AND THEIR SUB-SCENARIO TIME SERIES DEVELOPMENT OF THE CO_2 EMISSIONS. THEY ALL PEAK BY 2020 WITH REDUCTIONS OF 31-71% BY 2050 TO BE ABLE TO REACH THE 2°-TARGET IN 2100 (GEA, 2012). NEGATIVE EMISSIONS ARE DUE TO CCS IN COMBINATION WITH THE USE OF SUSTAINABLE BIOMASS.

To stabilize temperature at 2°C by 2100 GHG concentrations should not exceed 450 ppm CO2eq. for any prolonged time. This can only be achieved if the overall GHG emissions are capped and emission pathways therefore reach an early maximum followed by a rapid decrease (e.g. Figure 25, top left). The GHG emission cap and the rate of decrease determine the probability of staying within the 2°C target (e.g. Figure 25, top right). Pathways with a late peak, a large cap or a slow decrease require negative emissions towards the end of this century to achieve the 2°C target (e.g. Figure 25, bottom). Negative emissions are achieved by combining sustainable biomass use with CCS.

Typically emission pathways assume a global emission peak around 2020 (IEA, GEA, UNEP, EU,…) and reductions compared to 1990 between 35 – 55 % by 2050. Taking 2005 as a references year, emissions would need to be reduced by 60% in order to reach the 50% reduction with the base year of 1990 as global emissions increased by 20% between 1990 and 2005. Scenarios with later peaks in concentrations require a larger effort in reducing the annual emissions to stay within the 2°-target.

Van Vuuren et al. (2007) e.g. used the IPCC B2 scenario as a baseline scenario, corresponding to the World Energy Outlook of 2004. With this baseline the worldwide primary energy use would double between 2000 and 2050 and grow by additional 35% until the end of the century. The most important energy carriers would be oil until 2050, and natural gas till 2030 being repaced thereafter with coal. The CO2 emissions of the energy sector would peak at 18 GtC (1 GtCO2 = 3.66*GtC) in 2080. They selected three emissions scenarios leading to a stabilisation at 650, 550 and 450 ppm CO2-equ. Compared to the baseline scenarios this implies a reduction of 65%, 80%, and 90% respectively (Figure 29).

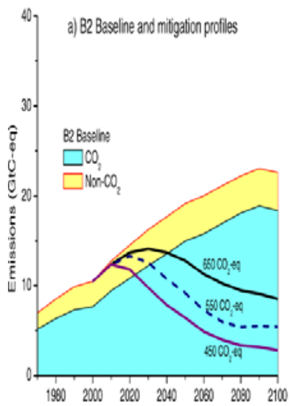


FIGURE 29: CO2-EQU. EMISSIONS OF ALL SOURCES OF THE B2 BASELINE PATHWAY AND THE THREE EMISSION SCENARIOS. (VAN VUUREN ET AL., 2007).

The uncertainties in all pathways lie especially in the carbon cycle: Carbon uptake by the oceans, biomass and the soil depend on atmospheric and oceanic concentrations, on surface and ocean temperatures, ocean dynamics and climate parameters influencing biomass production.

Emission reductions foreseen in the different pathways generally are most stringent in energy production, and here especially in coal. Use is significantly reduced and remaining coal consumption is attached to power stations using CCS. CCS accounts for a large proportion of the emission reductions resulting in large amounts of CO2 storage (650 ppm: 160 GtC, 550 ppm: 250 GtC, 450 ppm: 300 GtC; van Vuuren et al., 2007). Renewable energy carriers such as solar, wind and modern biomass, as well as nuclear-based electricity are generally assumed to increase their share in the energy market. Usage of bio-energy e.g. increases in the stringent scenario of van Vuuren et al., 2007 from 200 EJ up to 350 EJ, produced by a mixture of crops. Land used for bio-energy crop growth would be regrowing natural vegetation in the baseline scenario. This increase is limited in some cases for renewables due doubts regarding their ability to contribute sufficiently reliably to the power system (MIT 2003; Sims et al. 2003) and in the case of nuclear e.g. due to the depletion of uranium after 2050 (Edenhofer et al., 2010). In general the option of using nuclear power is less important than renewables or CCS. Only when biomass potential is assumed to be low in scenarios does nuclear power become more important. Costs of nuclear energy are assumed to increase moderately, but e.g. cost for the storage of nuclear waste or of future accidents is not included in the models used for future energy scenarios.

Emission reductions can be achieved by switching to lower-carbon technologies for power, heat and transport and thus replacing fossil fuels, by increasing efficiency and by reducing demand for emissions-intensive goods and services. Action can also be taken on non-energy emissions, such as avoiding deforestation, changing to organic farming, producing less meat (Stern, 2006). Most of the scenarios and emission reduction pathways focus on low-carbon technologies and – increasingly in the last years – on efficiency gains. In the context of nuclear energy, replacing fossil fuels mainly for power, possibly for heat and transport, are the measures generally considered.

However, non-energy related emissions and demand reductions also have very large potentials that tend to be overlooked, as they do not lend themselves as readily to model calculations and because life style changes are politically more delicate to address. However, research and practical experiments on the community and region scales on the transition to a low carbon society are evolving, and it is to be expected that within the next decade these issues will receive far more attention than at present. This could lead to serious revisions of all scenarios and pathways, with the main difference being the reduced energy demand.

REGIONAL AND SECTORAL REDUCTION NEEDS FOR THE TWO DEGREE PATHWAY

It is not sufficient to address global reduction needs – international agreement would be easy to achieve at this level. It is the specifications regarding the reduction needs per sector and country or country group that make negotiations difficult. Looking at different metrics illustrates the wide variation in starting conditions. In 2010 energy intensity varied by more than a factor 4 within the leading world powers and energy demand per capita by a factor of more than 7 (Figure 30). While the IEA projects considerable decrease in energy intensity in the countries with low efficiency, it also expects an increase in per capita energy demand till 2035.

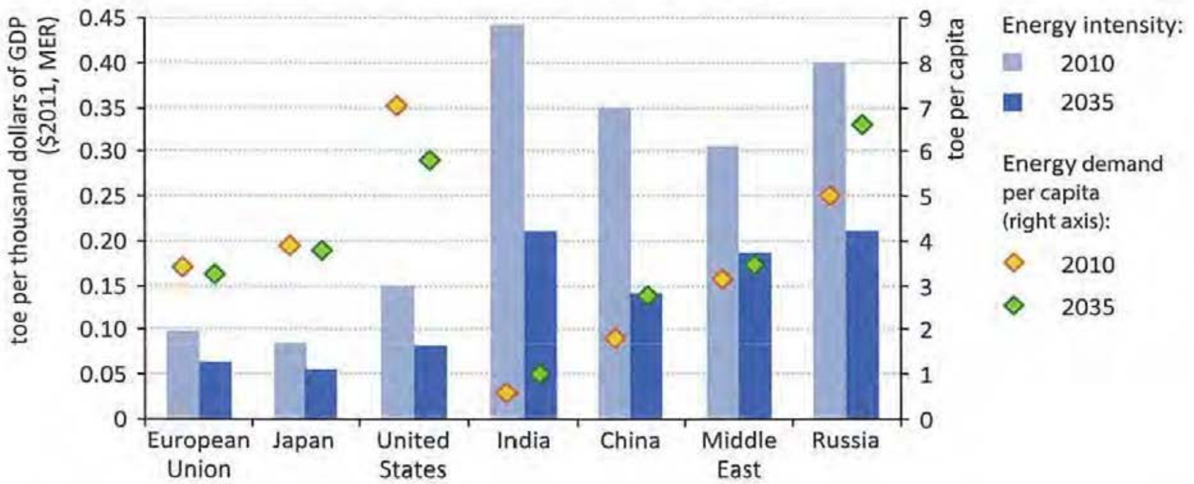


FIGURE 30: WORLD PRIMARY ENERGY DEMAND PER UNIT OF GOP AND PER CAPITA FOR 2010 AND THE NEW POLICIES SCENARIO (IEA, 2012).

Figure 31 summarizes past and projected greenhouse gas emissions per capita for selected countries. On the whole per capita emissions have sunk and are projected to continue to decrease, however this is more than compensated by the growth of the world population and increases in developing countries. Inspite of its comparatively low per capita emissions, due to its large and growing population China has now overtaken the USA as the country with the highest emissions.

It is also clear that the greatest energy need will occur in developing countries and countries in transition, while industrialized countries will need increasingly less energy. This means that new production units will primarily be build in those countries. This should be taken account of, as technology decisions are taken.

Anderson and Bows (2011) analysed CO2 emission pathways for Annex I and Non-Annex I countries, assuming that a total of 750 Gt of C represents the cap for CO2 emissions that corresponds to the 2°C target, with a 40% chance of exceeding it. They assumed that Non-Annex I countries would follow a very challenging pathway with an increase in CO2-emissions of 3,5% per year till 2025, when emissions peak, and then a decrease of 7% per year leading to near zero emissions towards the end of the century. Under these assumptions, CO2 emissions of the industrial countries should have peaked in the year 2010 and then dropped to zero at once. These calculations show more clearly than the global averages how large a challenge the 2°C target is in terms of emission reductions.

The European Union is one of the world leaders in the political drive to reduce GHG emissions and has taken considerable steps towards mitigation in its own domain. In 2007 it launched the European Climate Change Programme (ECCP), which consists of a range of measures (renewable energy, energy efficiency,..) and has led to the implementation of dozens of new policies and measures.

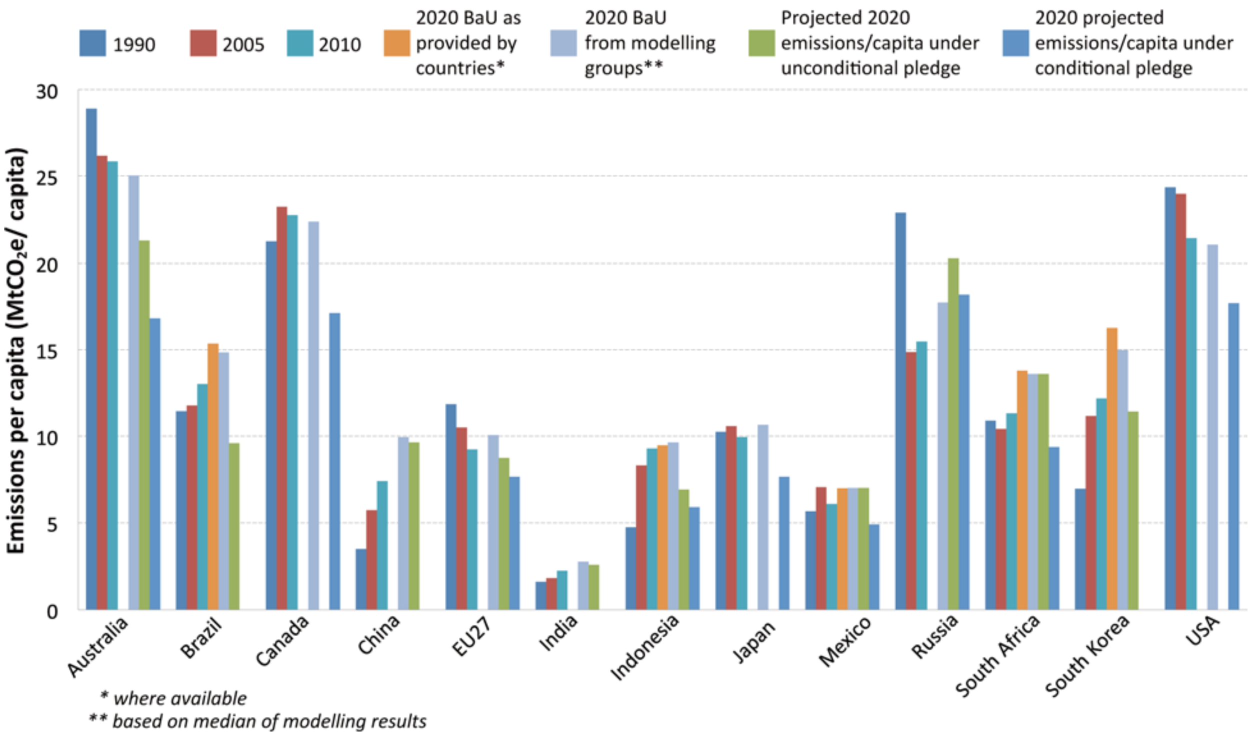


FIGURE 31: PAST AND PROJECTED GREENHOUSE GAS EMISSION PER CAPITA FOR THE G20 COUNTRIES (UNEP, 2012)..

The plan defining the so-called “20-20-20 targets” was adopted by the European Parliament in December 2008 (Energy and climate change – Elements of the final compromise, Council of the European Union, http://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/104672.pdf). Its aims are to reduce emissions of greenhouse gases by 20% by 2020 by adopting legislation to raise the share of energy consumption produced by renewable energy sources, such as wind, solar and biomass, to 20% by 2020 and by setting a target to increase Europe's energy efficiency by 20% by 2020 by improving the energy efficiency of buildings and of a wide array of equipment and household appliances (http://ec.europa.eu/clima/policies/brief/eu/index_en.htm). For some countries however, among them Austria, the specific requirements for GHG emissions resulting from this plan fall short of those they committed themselves to in the Kyoto protocol.

Europe has developed a “Roadmap for moving to a competitive low carbon economy in 2050” (EU, 2008) and has also implanted binding targets to reduce CO2 emissions from new cars and vans and is strongly supporting the development of carbon capture and storage (CCS) technologies to trap and store CO2 emitted by power stations and other major industrial installations. On CCS, as well as on the nuclear option, member states are divided.

In Europe, the potential for reduction of emissions in transportation, energy, buildings, industry and agriculture is relatively high. All these sectors have in common that immediate action is needed to avoid the lock-in of invested capital (e.g. shale gas extraction could be one of the lock-in cases). Clapp et al. (2009) compared several projections of mitigation models for the European Union and other regions and identified the sector emission and mitigation potentials:

- Energy: electricity use will sink to 36-39% of the present level in 2050. An increase of renewable energies and carbon dioxide low electricity generation are projected requiring new investments and innovations in production, efficiency, and storage technologies as well as in the energy and electricity infrastructure to be able to transfer, distribute, and store electricity and to connect local energy resources with the larger systems. Energy efficiency has significant potential in all sectors but to reach the 20% efficiency target further measures are needed. Investments in technologies and research are required from the governmental side as well as private sectors.
- Transport: sustainable transport policies vary amongst countries but they all have at least one of the three fundamental strategies in common: to reduce or avoid the need to travel, to move to more sustainable and lower carbon modes of transport and/or to improve the efficiency modes of transport. Investments in basic and fundamental research. To enhance the efficiency of transportation new materials, design, and more environmental friendly energy use are required as well as moving to new fuel strategies. Further, to enhance the performance in the transportation sector a common (EU) system in rail, air and other traffic would be of advantage. Investigations of fuel switch and fuel cells and batteries and or a second generation of biofuels and reduction of pricing of these alternative path would further enhance the emission reduction options.
- Industry: resource and energy friendly technologies and processes and more recycling of materials can contribute to the emission reductions.
- Buildings: more energy efficient buildings (heating, cooling) and alternative constructions (low energy buildings,…) as well as thermally upgrading old buildings towards more energy efficiency are possible mitigation measures. In May 2010 the EU adopted a Directive requiring Member States to ensure that by 2021 all new buildings are so-called 'nearly zero-energy buildings'.
- Agriculture: one possibility of reducing agricultural emissions is through more efficient combustion and fertilizers to be able to enhance the productivity of agriculture and animal breeding. Further efficiency can be gained using biogas produced of organic waste or more usage of local products.

Even though there is general agreement through all energy and emission scenarios and pathways that renewable energy carriers will needed to grow fast to meet the energy demand and to reduce GHG emissions, government subsidies for fossil fuels and fossil fuel based technology in 2011 amounted 523 billion US$, an increase of 30% compared to 2010, and only 88 billion US$ for renewables with a 24% increase (IAE 2012). And while efficiency will cumulatively account for about 60% of GHG emission reductions in this century in Europe, only about 10% of research and development funds are at present directed towards efficiency, while about 40% are invested in nuclear (GEA 2012).

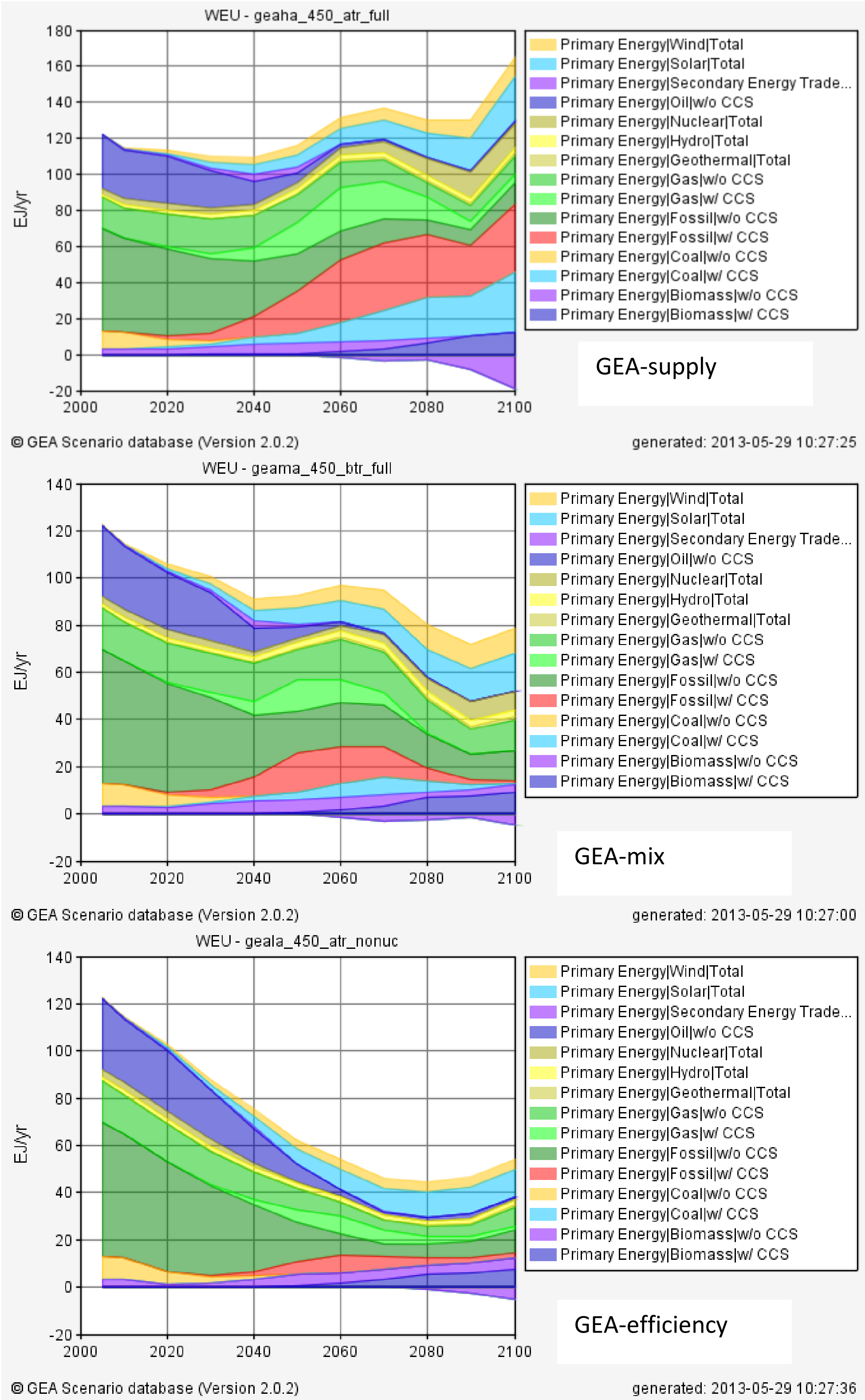


FIGURE 32: GEA-PRIMARY ENERGY PROJECTIONS FOR THE THREE PATHWAYS, SUPPLY, MIX AND EFFICIENCY FOR WESTERN EUROPE. ALL THREE PATHWAYS SEE A DEACREASE IN FOSSIL FUELS WITHOUT CCS BUT A (LIGHT) INCREASE OF FOSSIL FUELS WITH CCS. DATA USED FOR THESE PLOTS ARE AVAILABLE ON THE IIASA WEBPAGE[3].

[3] http://www.iiasa.ac.at/web-apps/ene/geadb/

REQUIREMENTS FOR ENERGY SUPPLY OPTIONS

Energy demand will rise if universal access to modern energy services is aimed for and the growing world population is taken account of. Any technology that is to minister to these new demands in a world reaching limits in many respects must have a few intrinsic characteristics to safeguard against further deterioration of the global ecosystem. Different authors list different characteristics, but basically they imply similar values. Based on (GEA, 2012, Muehe, 2001 and Weish, 2007) a list of such characteristics of the energy technology was developed and then discussed for the nuclear option:

- The energy source must be sustainable: any energy carrier that either does not regenerate or regenerates at a rate significantly below the rate of depletion cannot be considered to be a long term solution once about half of the known resource is used up.
- The energy system must be CO2 neutral or at least low in carbon: an increase in average global temperature above two degree Celsius would endanger a large number of ecosystems that might be unable to adapt to climate change, and therefore disappear. Also, it might not be possible to stabilize climate at higher temperatures. Therefore, in the long term, the economy must be CO2-neutral, meaning that anthropogenic GHG emission and absorption must balance.
- The energy system must not cause ambient pollution: to maintain clean and healthy environments, deployed technologies must keep the environment intact and be operational without undue use of land, water or other resources. Nuclear power (as will be explained more in detail further on in the chapter) has to be looked at in detail in respect to this point due to the risk of catastrophic accidents.
- The technology must not cause catastrophic accidents: the accident potential of energy systems strongly influences the acceptance of a technology by the general public. Accidents also have environmental and economic implications that need to be taken into account when evaluating a technology. Of special interest is the number of people an the size of the area affected and the time it takes the affected communities and environments to recover.

While the above points regard the energy system as a whole, single energy production technologies have to fulfil additional requirements, which are:

- The technology must be technically available: if a technology is intended to contribute to energy production in the period up to 2050, it has to be either already commercially proven, or available in the close future.
- The technology must be economically feasible: unless a technology can be classified as “infant technology” (i.e. a relatively new technology where large increases in productivity are to be expected in the close future) it should be able to compete against other technologies without a special environment of state subsidies or the like.
- the technology must be diverse and complementary to the other sources of energy in the overall energy supply system.

Energy technologies over the complete fuel cycle and life time must require less energy input than they can produce during their lifetime to be useful in the energy sense. Although for economic or (temporal or spacial) availability reasons energy supply technologies with a negative energy balance might be of interest, this can only be valid for a very small portion of any energy system. Problems of this type might e.g. arise in biomass plants and they have arisen in nuclear plants that were forced to shut down earlier than the expected life time.

CLIMATE CHANGE MITIGATION POTENTIAL OF NUCLEAR POWER

What is the contribution of nuclear power to mitigation today, how is the need for energy going to develop, and what could be the contribution in the future assuming different build rates of nuclear power plants? While these questions seem straight forward, there are several inherent problems in the estimation of the possible contribution of nuclear power to climate protection that will be addressed in the following.

CONTRIBUTION OF NUCLEAR POWER TO CLIMATE PROTECTION TODAY

CO2 EMISSIONS FROM NUCLEAR POWER

Even though the GHG emissions from NPPs are lower than emissions from fossil fired power plants, they are not zero. The direct emissions from the operation of nuclear power plants are very low, but considering the whole fuel cycle, emissions cannot be neglected. The main continuous contributors are emissions during mining of Uranium and the enrichment process. To compared to emissions from different technologies ideally emissions from plant construction, the whole fuel cycle and the dismanteling are added and divided by the overall electricity supplied, resulting in a value of grams of CO_2 eq. per kWh. The emissions per kWh found for nuclear show an enormous spread. Depending on the assumptions regarding the location of the mine, methods for mining, grade of uranium ore in the mined rock, enrichment technology, source of energy for mining and enrichment one can find numbers ranging from 2 g CO_2 eq./kWh to 800 g CO_2 eq./kWh. Van Leeuwen (2005), who published very high numbers for CO2 emissions from the nuclear fuel cycle was criticized for assumptions biased towards high emissions. Sovacool (2008) compared various sources and suggested a mean value of about 60 g CO_2 eq. / kWh. Beertens (2009) followed the same approach, but suggested 30 g CO_2 eq / kWh claiming that some of the sources Sovacool used trace back the work of Van Leeuwen and should therefore not be included. Neither Beertens (2009) nor Sovacool (2008) had data on a wide or representative spread of fuel cycle facilities in the world, so neither value is robust. They rather show the spread of numbers one can find in the literature.

As the purpose of the present study is to give an upper limit of what nuclear power could contribute (the real contribution will be lower), it is consistent to assume that nuclear power plants are emission free, even though the authors are aware that nuclear power is not emission free.

NUCLEAR POWER CLIMATE CHANGE MITIGATION POTENTIAL TODAY

To evaluate the mitigation potential of nuclear power additional assumptions have to be made – most importantly regarding the emissions of the substitute. In case of energy efficiency measures emissions would actually be reduced compared to any supply side measure. On the other hand, if a coal fired power plant that retired from operation 30 years ago replaces the NPP in question the mitigation potential is large.

One possible assumption is that the electricity from any NPP is substituted by the mix of all other sources available on the grid, increasing their respective shares. This value corresponds to the CO_2 intensity of electricity generation, 530 g CO_2 eq / kWh in 2010 (IEA 2012). OECD/NEA (2012) made three different assumptions: substitution of coal with roughly 1000 g CO_2 eq/kWh, of gas with roughly 500 g CO_2 eq/kWh (very close to the IEA 2012 value) or a nuclear-free mix such as that of a country like Denmark with approximately 300 g CO_2 eq/ kWh. In 2009 Denmark produced 36.4 TWh from a mix consisting of 18.5% renewables, essentially wind, 70.3% fossil – coal and gas, and 11% biofuel and waste with CO_2 emissions of 303 tonnes CO_2 eq./GWh (IEA, 2011a, 2011b).

The roughly 2500 TWh of electricity produced by nuclear in 2011 worldwide (IAEA, 2012), would - assuming further that nuclear power is emission free and that the electricity would have been generated by coal, gas, or a mix - have caused additional emissions of 2.5, 1.25 or 0.75 Gt CO_2 eq respectively (Table 2). This represents 5%, 2.5% and 1.5% of global emissions respectively, and 14%, 7% or 4.2% of the energy sector emissions worldwide. (Data for 2011 are not yet available, but these figures result assuming roughly 50 Gt CO_2 eq. total emissions and 17.5 Gt CO_2 eq. emissions from the power sector, which is close to the value of 2010).

TABLE 2: NUCLEAR POWER – CONTRIBUTION TO CLIMATE PROTECTION IN 2011.

Nuclear power replaced by	**Emissions per kWh (g CO2 eq. / kWh) OECD/NEA 2012**	**Emissions "avoided" in 2011 by nuclear power(1) Gt of CO2 eq.**	**Emissions avoided as % of the overall emissions in 2011 (2)**	**Emissions avoided as % of the emissions in 2011 from the energy sector (3)**
coal	1000	2.50	5.0%	14%
gas	500	1.25	2.5%	7%
mix	300	0.75	1.5%	4.2%

(1) Nuclear power generated 2500 TWh of electricity worldwide in 2011 (IAEA, 2012)

(2) Emissions from 2011 are not yet available but are considered to be close to the values from 2011, i.e. 50Gt of CO2 eq. (UNEP, 2012)

(3) Emissions from the energy sector (energy supply and fugitive emissions) amounted to 35% in 2011, see *JRC/PBL (2012)*

NUCLEAR POWER FUTURE CLIMATE CHANGE MITIGATION POTENTIAL

There are three crucial assumptions to be made to estimate the future potential of nuclear power to mitigate GHG emissions:

1.) Will nuclear energy be used almost exclusively for electricity production as today, or will non-electrical applications of nuclear power like hydrogen production, desalination, supply of process heat (refer to WP7 for more details) be deployed?

2.) How much energy / electricity per year will be needed in the future?

3.) What are the GHG emissions of the technologies that would replace nuclear power or would that would be replaced by nuclear power?

The accuracy of past forecasts does not inspire much confidence in any projection (see WP3 for details). It is, however, clear that extrapolating current emission trends will not be the most likely future, as the consequences of climate change could become catastrophic. Hopefully changes in the worldwide energy policies will avoid that course of events, but since there is no clear indication of an agreement worldwide on how to tackle the issue of climate protection, the future remains uncertain.

Forecasts for the close future (up to 2030) can be made based on governmental programmes (see WP3). Projections beyond this date necessarily include arbitrary assumptions.

Therefore the numbers that are provided in the following are not to be interpreted as a forecasts – rather they should raise sensibility for the possible role of nuclear power, assuming different scenarios.

CLIMATE CHANGE MITIGATION POTENTIAL ASSUMING CURRENT POLICIES

The first baseline on what nuclear power could contribute it based on the “current policy” scenario (IEA 2012). It is projected up to 2035, it assumes that nuclear power will contribute only to electricity generation and provides the following information:

1.) Total growth of electricity supply
2.) TWh from Nuclear power electricity generation in the year 2035
3.) CO2 intensity of generated electricity, i.e. an estimation of the g CO2 eq. per kWh generated from the electricity supply system in 2035

The scenario does not predict total GHG emissions by 2035. This number is gained by extrapolation of the UNEP (2012) “business as usual” scenario total GHG emissions for the years 2010 and 2020.

The resulting contribution from nuclear power is low compared to predictions of IAEA (2012). Therefore, in Table 3 values for assumes build rates of nuclear power plants and electricity production following IAEA (2012). The projections in IAEA (2012) are made for the years 2030 and 2050 – to be able to fit the numbers in the scenario of IEA (2012) linear interpolation has been used[4]. WP3 of the EHNUR project looks in detail at nuclear expansion scenarios, and confirmes the IAEA (2012) trends up to 2025, but predicts a decrease of installed capacity thereafter.

TABLE 3: NUCLEAR POWER – CONTRIBUTION TO CLIMATE PROTECTION IN 2035.

	IEA cur.pol.	**IAEA low**	**IAEA high**
Total generated electricity (TWh)	40400	43300	49500
Nuclear generated electricity (TWh)	3900	4100	6900
Nuclear share of electricity production	9.7 %	9.8 %	13.8 %
CO2 intensity of electricity generation (g CO2 eq. / kWh)	530	530	530
Nuclear CO2 prevention potential for the year 2035 (Gt CO2 eq.)	2.07	2.17	3.66
Extrapolated total emissions in the year 2035 (Gt CO2 eq.)	71.5	71.5	71.5
Nuclear contribution (“prevented” emissions)	2.9 %	3.0 %	5.1 %

Table 3 summarizes key figures. Assuming a “business as usual” scenario, without further policy changes, the nuclear operating fleet in the year 2035 could prevent the emission of 2.07, 2.17 and 3.66 Gt CO2 eq. according to the “current policy scenario” of IEA (2012), the “low” and the “high” scenario of IAEA (2012) respectively. Considering that the emissions from a “business as usual scenario” would amount to 71.5 Gt CO2 eq. in the year 2035, the nuclear CO2 emission prevention potential would be 2.9%, 3.0% and 5.1% of the total emissions in the respective scenarios. Thus, while the future contribution of nuclear to the mitigation of GHG emissions would increase in absolute numbers, its share would not increase. The nuclear contribution would remain rather marginal.

[4] The report IAEA (2012) provides for the “low” scenario, total electricity production, values for 2020, 2030 and 2050, while for the “high” scenario only values for 2020 and 2030 are given. Therefore to derive values for 2035, in case of the “low” scenario linear interpolation has been used, in case of the “high” scenario linear extrapolation.

UPPER BOUND FOR NUCLEAR CO2 EMISSION PREVENTION POTENTIAL

The next evaluation aims to establish an upper bound for what nuclear power could contribute to preventing GHG emissions. As in the last section the overall setup is a "business as usual" scenario, policies that are in place 2012 stay in place, but no further changes in energy policies are assumed to happen. The projection period is to 2035, total needed electricity is again taken from the "current policies" scenario from IEA (2012), the total global CO2 emissions in the year 2035 are as above. The use of nuclear power is again restricted to electricity generation, as it seems unlikely that nuclear power will be deployed for non-electrical applications before 2035 (see Weimann (2013)).

To provide an upper bound it is assumed that by 2035 all CO2 emitting sources of electricity are substituted by nuclear power plants. The share of electricity from fossil-fuel plants, nuclear and renewable sources is again taken from the "current policies" scenario from IEA (2012), see Table 4. The CO2 intensity of the fossil fuelled electricity generation is assumed to be 750 g CO2 eq. / kWh, which corresponds to a mix of 50% coal-fired and 50% gas-fired plants.

TABLE 4: ELECTRICITY GENERATION IN 2035, "CURRENT POLICIES", IEA (2012)

Total generated electricity (TWh)	40400
From fossil fuels (TWh)	26800
Nuclear (TWh)	3900
Hydro (TWh)	5400
Other renewable (TWh)	4300

TABLE 5: NUCLEAR POWER – UPPER BOUND FOR CO2 EMISSION PREVENTION IN 2035.

Fossil fuels substituted by nuclear (TWh)	26800
CO2 intensity of electricity generation (g CO2 eq. / kWh)	750
Nuclear CO2 prevention potential for the year 2035 (Gt CO2 eq.)	20.1
Extrapolated total emissions in the year 2035 (Gt CO2 eq.)	71.5
Nuclear share of "prevented" emissions	28.1 %

As Table 5 shows, with this assumption an upper bound of 28.1 % of the overall emissions could be prevented, which corresponds to 20.1 Gt CO2 eq. In spite of the considerable contribution of the assumed carbon free nuclear energy in this scenario, overall emissions are still at 50 Gt CO2 eq in 2035 and therefore exceed the values needed to meet the 2°C target. Thus, the business-as-usual scenario is no solution to the climate problem, even if all fossil fuels in electricity production were replaced by nuclear.

The overall electricity generation from nuclear power in the year 2035 in this scenario would need to be 30700 TWh. Making the unlikely assumption that all nuclear power plants that were in operation in 2010 are still in operation in 2035, 2600 TWh would be accounted for (IAEA, 2012). Assuming further that the worldwide overall average load factor remaining constant at 80% (IAEA, 2012), additional nuclear power plants with, roughly, an overall installed capacity of 4000 GWe need to be built. Considering that a typical size of currently offered designs is 1 GWe per unit, this means that 4000 additional units would have to be built by 2035, without retiring any units from the currently operating nuclear fleet.

HORIZON TO 2050 – NORMATIVE SCENARIO

Considering the complexity of worldwide society, and the fact that the future energy system is highly dependent on societal choices, uncertainties connected to any projection up to 2050 are so large that the predictive value of the projection is low. For this reason the scenarios in (IEA, 2012) are limited to 2035. Nevertheless the time frame to 2050 is very important, since the climate policy requirements to meet the 2° target will not be fully in place by 2035. Also, potential technological advances such as hydrogen based economy or carbon capture and storage are not expected to be available on a shorter term. Finally, due to the inertia of the system, larger policy changes cannot be expected to show short term results.

The present study chose to follow (GEA, 2012) for the time frame up to 2050. Instead of presenting projections to demonstrate a single effect or single measure (which was the purpose of the two previous sections), the present section adopts the normative approach taken in (GEA, 2012).

GEA (2012) defines three branching points

1.) degree of use of energy (i.e. increased supply of energy or increased saving of energy),
2.) future of the transport system (i.e. vehicles based on liquid fuels, or hydrogen/electric powered vehicles),
3.) restrictions on the energy supply mix (i.e. instead of using all possible options for energy supply, one tries a pathway where technologies like nuclear power, biomass or CSS, are not available).

For the present study the most important result from GEA (2012) is the evaluation of the “no-nuclear” branching point – i.e. the answer to the question if there are conditions which necessitate the use of nuclear energy in order to reach the climate goals. The “no-nuclear” option assumes that nuclear power plants are constructed up to 2020, and from there on phased out (with the last plants taken from the grid in 2060). The result of the evaluation is that the “no-nuclear” option, i.e. an energy supply mix without nuclear energy, is feasible under all levels of energy demand, and with all transportation system alternatives. The fact that even high levels of energy demand can be met without the “nuclear option” means alternatives can substitute nuclear energy at a global scale without endangering a successful energy transition, at the same time meeting climate and health targets. The “nuclear option” is thus seen by GEA (2012) really as an option and not as a necessity.

CONCLUSIONS

Anthropogenic climate change requires a rapid shift towards a CO_2 neutral economy, if the global average temperature increase is to be kept below 2°C. Such a shift would strongly influence the energy (and electricity) supply system, which is currently based to a larger part on fossil fuels.

The EHNUR project addresses the question whether nuclear power could significantly contribute, or even be the backbone of a new, sustainable and CO_2 neutral energy system. To be a desirable source of energy nuclear power should

- guarantee sustainable availability;
- be CO2 neutral (low carbon);
- not cause ambient pollution;
- not cause catastrophic accidents;

- be proliferation resistant;
- be technologically feasible;
- be economically feasible, and
- be diverse and complementary to the other sources of energy in the overall energy supply system.

The present chapter assessed the (potential) contribution of nuclear energy to Green House Gas mitigation by

a) the current nuclear fleet;

b) a possible future nuclear fleet with nuclear power build rates as expected by institutions like IAEA and IEA, and

c) a hypothetical nuclear fleet that substitutes coal-fired and gas-fired power plants.

The analysis showed that the current contribution of nuclear power to GHG mitigation is rather low – depending on the assumption which technology is substituted by nuclear power, the avoided emissions range from 1.5 % to 5% of total energy emission (a value of 2.5% corresponds to the assumption that the nuclear power plants would be substituted by the current world-wide mix of electricity generation options).

“Business as usual” scenarios with nuclear energy build rates as expected by institutions like IEA and IAEA, show that in the year 2035 nuclear power could help to avoid between 3% and 5% of the total overall emissions, depending on optimistic or pessimistic assumptions regarding nuclear plant build rates. Thus, while the future contribution of nuclear to the mitigation of GHG emissions would increase in absolute numbers, its share would not increase.

The third scenario aimed to establish an upper limit by assuming that all coal-fired and gas-fired power stations are substituted by nuclear energy – but apart from this with the scenario is “business as usual”. The analysis showed that in this upper bound case 28% of the expected emissions would be avoided.

However, in spite of this considerable contribution by nuclear, 51.4 Gt of CO_2 eq. would still be emitted in the year 2035. This is not compatible with the two degree target (see Figure 27). This means that nuclear power, even with this extreme assumption, cannot turn a business-as-usual scenario into a solution for the climate problem.

A second observation to be made is that the scenario would require 4000 new 1 GWe units by 2035 . As is shown in other WPs of the EHNUR project such build rates are not feasible. In fact, it is doubtful that even the comparatively (modest) expectations of IAEA (2012) will be put into practice.

These results, i.e. the fact that the potential for prevention of CO_2 emissions by nuclear power plants is small if build rates remain at levels projected by IEA (2012) and IAEA (2012), and that even with extreme assumptions nuclear power cannot solve the climate problem, are in line with the outcome of the GEA scenario studies presented in the last section. GEA scenarios envisage no situation which would make it impossible to abandon nuclear power. Even assuming an increase in demand for energy, nuclear power can be substituted by alternatives.

As stated in GEA (2012) - even if nuclear energy can contribute modestly to climate stabilization, it is a controversial option. The reasons include the unresolved problem of long-term waste disposal, the risk of catastrophic accidents and the associated liabilities, economic considerations, other issues, like bottlenecks and doubts on the long term availability of uranium resources and the possible proliferation of weapons-grade fissile material. These issues are addressed in detail in other EHNUR WPs.

REFERENCES

Albrecht, B. (1989) Aerosols, cloud microphysics, and fractional cloudiness, Science, 245, 1227, doi:10.1126/science.245.4923. 1227

Allen, M. R., Stott, P. A., Mitchell, J. F. B., Schnur, R., and Delworth, T. L., (2000) Quantifying the uncertainty in forecasts of anthropogenic climate change. Nature, 407, p617-620.

Anderson, K. and Bows, A., (2011) Beyond 'dangerous' climate change: emission scenarios for a new world. Royal Society's Philosophical Transactions 369, pp. 20–44; doi:10.1098/rsta.2010.0290

Arora, V. K., and Boer, G. J., (2010) Uncertainties in the 20th century carbon budget associated with land use change. Global Change Biology, 16,3327-3348.

Balunias, S.L., (2005) The Impact of Solar Variability on the Earth's Climate, in : Michaels, P., ed 2005: Shattered Consensus: The true State of Global Warming. Lanham, MD: Rowan and Littlefield, pp. 146-178

Bellenger, H., Guilyardi, , Leloup, J., Lengaigne M., Vialard, J., (2013) ENSO representation in climate models: from CMIP3 to CMIP5. Climate Dynamics
Online publication date: 30-Apr-2013.

Beerten, J., Laes, E., Meskens, G., D'haeseleer, W., (2009) Greenhouse gas emissions in the nuclear life cycle: A balanced appraisal, Energy Policy 37

Bouwman, L., Kram, T., and Klein-Goldewijk, K., (2006) Integrated Modelling of Global Environmental Change. An Overview of IMAGE 2.4, Netherlands Environmental Assessment Agency, Bilthoven

Canadell, J. G., et al., (2007) Contributions to accelerating atmospheric CO(2) growth from economic activity, carbon intensity, and efficiency of natural sinks. Proceedings of the National Academy of Sciences of the United States of America, 104, 18866-18870.

Cantelaube, P., and Terres, J.-M., (2005) Seasonal weather forecasts for crop yield modelling in Europe.Tellus A 57, 476–487. (doi:10.1111/j.1600-0870.2005.00125.x)

Chou, C., Neelin, J. D., Chen, C. A., and Tu, J. Y., (2009) Evaluating the "Rich-Get-Richer'' Mechanism in Tropical Precipitation Change under Global Warming. J Climate, 22, p1982-2005.

Christensen, J.H., Carter, T.R., Rummukainenm M. (2007) Evaluating the performance and utility of regional climate models: the PRUDENCE Project. Clim Change, doi:10.1007/s10584-006-9211-6

Clapp, C., Karousakis, K., Buchner, B. , Chateau, J., (2009) National and Sectoral Mitigation Potential: A Comparison Across Models. OECD/IEA Information Paper.
COM/ENV/EPOC/IEA/SLT(2009)7, Paris.

Collins, M., Chandler, R.E., Cox, P.M., Huthnance, J.M., Rougier, J., Stephenson, D.B. (2012) Quantifying future climate change. Nat. Clim Change 2:403–409.

Dufresne, J.-L., M.-A. Foujols, S. Denvil, A. Caubel, O. Marti, O. Aumont, Y. Balkanski, S. Bekki, H. Bellenger, R. Benshila, S. Bony, L. Bopp, P. Braconnot, P. Brockmann, P. Cadule, F. Cheruy, F. Codron, A. Cozic, D. Cugnet, N. Noblet, J.-P. Duvel, C. Ethé, L. Fairhead, T. Fichefet, S. Flavoni, P. Friedlingstein, J.-Y. Grandpeix, L. Guez, E. Guilyardi, D. Hauglustaine, F. Hourdin, A. Idelkadi, J. Ghattas, S. Joussaume, M. Kageyama, G. Krinner, S. Labetoulle, A. Lahellec, M.-P. Lefebvre, F. Lefevre, C. Levy, Z. X. Li, J. Lloyd, F. Lott, G. Madec, M. Mancip, M. Marchand, S.

Masson, Y. Meurdesoif, J. Mignot, I. Musat, S. Parouty, J. Polcher, C. Rio, M. Schulz, D. Swingedouw, S. Szopa, C. Talandier, P. Terray, N. Viovy, N. Vuichard, (2013) Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5. Climate Dynamics 40:9-10, 2123-2165
Online publication date: 1-May-2013.

Edenhofer, O., Knopf, B., Barker, T., Baumstark, L., Bellevrat, E., Chateau, B., Criqui, P., Isaac, M., Kitous, A., Kypreos, S., Leimbach, M., Lessmann, K., Magné, B., Scrieciu, S., Turton, H., and Van Vuuren, D. P., (2010) The economics of low stabilization: model comparison of mitigation strategies and costs. The Energy Journal, 31(1), 11-48.

EU, (2008) The 2°C target - Background on Impacts, Emission Pathways, Mitigation Options and Costs, Information Reference Document Prepared and adopted by EU Climate Change Expert Group 'EG Science' th July 2008

Fagan, B. (2000) The Little Ice Age: How climate made history – 1300-1850. New York: Basic Books, pp 169-177

Fasullo, J. T., and Trenberth, K.E., (2008) The Annual Cycle of the Energy Budget. Part {II:} Meridional Structures and Poleward Transports. J. of Climate 21, 2313-2325.

Forster, P., Ramaswamy, V. ., P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. Van Dorland, (2007) Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

GEA, (2012) Global Energy Assessment - Toward a Sustainable Future, Cambridge University Press, ISBN:9781107005198

Haarsma, R.J., Selten, F., Oldenborgh, G.J., (2013) Anthropogenic changes of the thermal and zonal flow structure over Western Europe and Eastern North Atlantic in CMIP3 and CMIP5 models. Climate Dynamics Online publication date: 22-Mar-2013.

Hanson, J. (2009): Storms of my grandchildren. Blommsbury London, Berlin, new York, pp316, ISBN 9781408807453

Hewitt, C. and Griggs, D., (2004) Ensembles-based predictions of climate changes and their impacts (ENSEMBLES). Eos 85, 566

Houghton, R. A., (2003) Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000. Tellus Series B - Chemical and Physical Meteorology, 55,378-390.

Houghton, R. A., et al. (2012) Chapter G2 Carbon emissions from land use and land-cover change. Biogeosciences Discuss., 9,835-878

IAEA, (2012) REFERENCE DATA SERIES No. 1, 2012 Edition Energy, Electricity and Nuclear Power Estimates for the Period up to 2050, International Atomic Energy Agency, Vienna, 2012

IEA, (2011a), CO2 Emissions from Fuel Combustion, IEA Statistics, International Energy Agency, OECD, Paris, France.

IEA, (2011b), Electricity Information 2011, IEA Statistics, International Energy Agency, OECD, Paris, France.

WP2 - Requirements from climate protection and security of supply- the nuclear contribution EHNUR

IEA, (2012), “World Energy Outlook 2012”, Paris, France, International Energy Agency, ISBN 978-92-64-18084-0

IEA, (2013), “World Energy Model Documentation”, http://www.worldenergyoutlook.org/docs/weo2011/other/WEO_methodology/WEM_Methodology_WEO2011.pdf, retrieved June 2013

IPCC, (2007), Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., and Miller, H.L., (Hrsg.), Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, ISBN 978-0-521-88009-1 (pb: 978-0-521-70596-7).

IPCC SRES, (2000) in Nakićenović, N., and Swart, R., Special Report on Emissions Scenarios: A special report of Working Group III of the Intergovernmental Panel on Climate Change (book), Cambridge University Press, ISBN 0-521-80081-1, 978-052180081-5 (pb: 0-521-80493-0, 978-052180493-6).

IPCC, (2011), IPCC. Summary for Policymakers. In: Intergovernmental Panel on Climate Change Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (Field CB, et al., eds). New York, NY:Cambridge University Press (2011). Available: http://ipcc-wg2.gov/SREX/ [accessed 2 Dec 2011

IPCC, (2013), http://www.ipcc-data.org/ddc_definitions.html, retrieved June 2013

Jacobeit J., (2002) Klimawandel – natürlich bedingt, vom Menschen beeinflusst. In: Löffler, G. & H. Voßmerbäumer (Eds.): Mit unserer Erde leben. Würzburg, 165-184

Jacobeit, J., (2007) Zusammenhänge und Wechselwirkungen im Klimasystem. In: Endlicher, W. & F-W. Gerstengarbe (Eds): Der Klimawandel – Einblicke, Rückblicke und Ausblicke. Potsdam 2007, 1-16pp

Jourdain, N.C., Gupta, A.S., Taschetto, A.S., Ummenhofer, C.C., Moise, A.F., Ashok, K., (2013) The Indo-Australian monsoon and its relationship to ENSO and IOD in reanalysis data and the CMIP3/CMIP5 simulations. Climate Dynamics Online publication date: 5-Feb-2013.

Knutti, R. and Sedlacek, J., (2012) Robustness and uncertainties in the new CMIP5 climate model projections, Nature Climate Change, published online, doi:10.1038/nclimate1716

Koch, D., and Del Genio, A. D., (2010) Black carbon semi-direct effects on cloud cover: review and synthesis, Atmos. Chem. Phys., 10,7685–7696,doi:10.5194/acp-10-7685-2010

Kromp-Kolb, H., and Molin A., (2007): Nuclear Power, Climate Policy and Sustainability. An Assessment by the Austrian Nuclear Advisory Board, 292 S., BMLFUW, Vienna

Leggett, J., Pepper, W.J., Swart, R.J., Edmonds, J., Meira Filho, L.G., Mintzer, I., Wang, M.X., and Watson J., (1992) Emissions Scenarios for the IPCC: an Update, Climate Change 1992: The Supplementary Report to The IPCC Scientific Assessment, Cambridge University Press, UK, pp. 68-95

Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W. and Rahmstorf, S., (2008) Tipping elements in the Earth’s climate system. PNAS, 105,6, pp. 1786-1793

Le Quéré C, Raupach MR, Canadell JG, Marland G et al. (2009) Trends in the sources and sinks of carbon dioxide. Nature geosciences, doi: 10.1038/ngeo689. http://www.nature.com/ngeo/journal/v2/n12/full/ngeo689.html

Lisiecki, L. E., and M. E. Raymo (2005) A Pliocene-Pleistocene stack of 57 globally distributed benthic δ18O records, Paleoceanography 20: PA1003

Loeb, N. E., Lyman, J. M., Johnson, G. C., Allan, R. P., Doelling, D. R., Wong, R., Sonden, B. J. and Stephens, G. L., (2012) Observed changes in top of the atmosphere radiation and upper-ocean heating consistent within uncertainty. Nature geoscience, doi:10.1038/ngeo1375

Meehl, G. A. et al., (2007) The WCRP CMIP3 multimodel dataset—A new era in climate change research. Bull. Am. Meteorol. Soc. 88, 1383–1394

Messner , S. and Strubegger M., (1995) User's guide for MESSAGE III", IIASA, Laxenburg, Austria

MIT (2003) The future of nuclear power – an interdisciplinary MIT study. Massachusetts Institute of Technology, Cambridge, USA

Mühle, H., (2001) Der Syndrom-Ansatz – eine Möglichkeit für die Entwicklung von Nachhaltigkeitsindikatoren, [Online],
Available: http://www.itas.fzk.de/deu/tadn/tadn002/mueh00a.htm [14 Nov 2001]

Nordhaus, W.D., (1975) Can we control carbon dioxide? IIASA, Laxenburg

Nordhaus, W.D., (1977) Strategies for the control of carbon dioxide. Cowles Foundation for Research in Economics at Yale Univer-sity, Connecticut

OECD-NEA/IAEA, (2010) Uranium 2009: resources, production, and demand. OECD Publishing, Paris, France.

OECD/NEA (2012) The Role of Nuclear Energy in a Low-carbon Energy Future, NEA No. 6887, Paris

Olivier, J.G.J., Janssens-Maenhout, G. and Peters, J.A.H.W., (2012) Trends in global CO2 emissions; 2012 report. PBL Netherlands Environmental Assessment Agency, Institute for Environment and Sustainability (IES) of the European The Emissions Gap Report 2012 – References Commission's Joint Research Centre (JRC)—Report No. 500114022. The Hague/Bilthoven, Netherlands: PBL Netherlands Environmental Assessment Agency. Available at: http://www.pbl.nl/sites/default/files/cms/publicaties/PBL_2012_Trends_in_global_CO2_emissions_500114022.pdf

PBL, (2009) Meeting the 2 °C target From climate objective to emission reduction measures, Netherlands Environmental Assessment Agency (PBL), Bilthoven, December 2009, PBL publication number 500114012, ISBN: 978-90-78645-28-3

Pongratz, JReick, ., C. H., Raddatz, T., and Claussen, M., (2009) Effects of anthropogenic land cover change on the carbon cycle of the last millennium. Global Biogeochemical Cycles, 23

Rogelj, J., Meinshausen, M., and Knutti, R., (2012) Global warming under old and new scenarios using IPCC climate sensitivity range estimates, Nature Clim. Change, 2, 4, pp 248-253, doi: 10.1038/nclimate1385

Ryu, J.H., and Hayhoe, K., (2013) Understanding the sources of Caribbean precipitation biases in CMIP3 and CMIP5 simulations. Climate Dynamics Online publication date: 15-May-2013.

Randalls, S., (2010) History of the 2 ° C climate target. In: WIREs Climate Change, Vol. 1 Issue 4, doi:DOI: 10.1002/wcc.62

Sarmiento, and Gruber, N. (2006) Ocean Biogeochemical dynamics. Princeton University Press

Sillmann, J., Kharin, V.V., Zwiers, F.W., Zhang, X., and D. Bronaugh, (2013a) Climate extreme indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate, J Geo Res, 118, 1716-1733, doi:10.1002/jgrd.50203

Sillmann, J., Kharin, V.V., Zwiers, F.W., Zhang, X., and Bronaugh, D., (2013b) Climate extreme indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections, J Geo Res, 118, 2473-2493,doi:10.1002/jgrd.50188

Sims REH, Rogner HH, Gregory, K., (2003) Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation. Energy Policy 31:1315–1326

Somerville, R., Le Treut, H., Cubasch, U., Ding, Y., Mauritzen, C., Mokssit, A., Peterson, T., and Prather, M., (2007) Historical Overview of Climate Change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Sovacool, B. (2008) Valuing the greenhouse gas emissions from nuclear power: A critical survey, Energy Policy 36, p2940–2953

Stott, P. A., and Kettleborough, J. A., (2002) Origins and estimates of uncertainty in predictions of twenty-first century temperature rise. Nature, 416, 723-726.

Stott, P. A., and Jones, G., (2012) Observed 21st century temperatures further constrain decadal predictions of future warming. Atmos Science Letters, 13, 3, p 151–156

Stott,P., Good, P., Jones, G., Gillett, N., and Hawkins, E., (2013) The upper end of climate model temperature projections is inconsistent with past warming, Environ. Res. Lett. 014024 doi:10.1088/1748-9326/8IEA (2012)014024

Taylor, K. E., Stouffer, R. J. and Meehl, G. A. (2012) Summary of the CMIP5 Experiment Design. Bull. Am. Meteorol. Soc. 93, 485–498.

Tebaldi, C. and Knutti, R., (2007) The use of the multi-model ensemble in probabilistic climate projections. Phil. Tran. R. Soc. A 365, 2053–2075.

Trenberth, K. E., and Fasullo, J. T. (2012) Tracking Earth's energy: from El Nino to global warming. Surv. Geophys. 33; 413-426.

Trenberth, K. E., Fasullo, J. T., and J. Mackaro, (2011) Atmospheric Moisture Transports from Ocean to Land and Global Energy Flows in Reanalyses. J. Climate 24, 4907-4924

UNPD (2010) World Urbanization Prospects: The 2009 Revision Population Database, UNPD (United Nations Population Division), New York, 2012

UNEP (2010) How Close Are We to the Two Degree Limit? Information Note, 2010

UNEP (2012) The Emissions Gap Report 2012, A UNEP Synthesis Report, November 2012, available at http://www.unep.org/pdf/2012gapreport.pdf [July 2013]

van Leeuwen, S. and Smith, J.W., (2005) Nuclear power — the energy balance.(The Netherlands), available at http://www.stormsmith.nl [July 2005]

van Vuuren, D. P., den Elzen, M. G. J., Lucas, P. L., Eickhout, B., Strengers, B. J., Van Ruijven, B., Wonink, S. and Van Houdt, R., (2007) Stabilizing greenhouse gas concentrations at low levels: An assessment of reduction strategies and costs. Climatic Change 81 (2), pp. 119-159.

van Vuuren DP, JA Edmonds, M Kainuma, K Riahi, AM Thomson, K Hibbard, GC Hurtt, T Kram, V Krey, J-F Lamarque, T Masui, M Meinshausen, N Nakicenovic, SJ Smith, and S Rose (2011a) The representative concentration pathways: an overview Climatic Change, 109: 5-31. DOI: 10.1007/s10584-011-0148-z. Available at: http://www.springerlink.com/content/f296645337804p75/. [July 2013]

Veizer, J., Ala, D., Azmy, K., Bruckschen, P., Buhl, D., Bruhn, F., Carden, G.A.F., Diener, A., Ebneth, S., Godderis, Y., Jasper, T., Korte, C., Pawellek, F., Podlaha, O. and Strauss, H. (1999). "87Sr/86Sr, δ13C and δ18O evolution of Phanerozoic seawater". Chemical Geology 161: 59-88

WBGU (1995) Scenario for the derivation of global CO2 reduction targets and implementation strategies. Statement on the occasion of the first conference of the parties to the framework convention on climate change in Berlin. WBGU—German Advisory Council on Global Change, Bremerhaven

Weaver, A. J., Zickfeld, K., Montenegro, A., and Eby, M., (2007) Long term climate implications of 2050 emission reduction targets, in: Geophysical Research Letters

Weimann, G., and Kromp-Kolb, H. (2007) Timeliness of the Nuclear Energy Option. In: Kromp-Kolb, Helga and Andreas Molin (Eds.), Nuclear Power, Climate Policy and Sustainability 1, 292; BMLFUW, Vienna

Weimann, G., Giersch, M., Cerveny, M., Baumgarten, D., (2013) EHNUR Annex 6: Non electrical use of nuclear power.

Weish, P., (2007) Atomkraft und Nachhaltigkeit, Zeitschrift Humanwirtschaft, April

WNA (2013), The Nuclear Renaissance (by the World Nuclear Association), available at http://www.world-nuclear.org/info/inf104.html, [June 2013]

Wyngaard, J. C. 2004: Toward numerical modeling in the “Terra Incognita”, J. Atmos. Sci., 61, 1816-1826

Zachos, James, Mark Pagani, Lisa Sloan, Ellen Thomas, and Katharina Billups (2001) Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present, Science 292 (5517): 686–693.