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Feasibility of GHG emissions phase-out by mid-century

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Executive summary

Is it possible to phase out greenhouse gas emissions by 2050?

It *is* possible to almost entirely phase out net greenhouse gas (GHG) emissions[1] by the middle of the century.

While more research is needed, existing scenarios show that it is *technically and economically feasible* to reduce emissions to zero for roughly 90% of current sources of GHG emissions with technological options that are available today and in the near future. A nearly complete phase-out of net emissions by 2050 is possible with additional innovation and offsetting residual emissions by sinks. A net phase-out by 2050 would ensure a very high likelihood of meeting the agreed 2°C goal and a 50% chance of staying below 1.5°C by the end of the century.

Initial steps taken to decarbonise need to be amplified drastically. The longer we wait to act, the more expensive change becomes. Whether a phase-out is *politically* feasible will be determined in the coming years.

What are the major sources of greenhouse gas emissions?

Around two thirds of our greenhouse gas emissions originate in our use of fossil fuels in the energy system, in buildings, transport, industry and energy supply. The remaining third are primarily emissions from human use of land and livestock and from industrial processes. Reducing net emissions close to zero by mid-century means fundamentally restructuring all of our economic sectors in the coming decades.

What modelling analysis is available on a phase-out of global GHG emissions by mid-century?

Several low emissions scenarios have been modelled that result in (nearly) zero net GHG emissions by 2050. According to these, a phase-out is technically and economically feasible under certain conditions. Such studies can be broadly categorised as one of two types, reflecting two slightly different modelling approaches and resulting strategies:

- **Scenarios with (near) 100% renewable energy by 2050:** These scenarios aim, at the outset, at a certain emissions target as well as a certain contribution of renewables. They find that 100% renewable energy by 2050 is possible. Saving energy is a key strategy in these scenarios because high efficiency facilitates an energy supply based almost entirely on renewable sources.
- **Scenarios with less than 100% renewable energy but carbon capture and storage (CCS):** So-called integrated assessment models are commonly used to

[1] "Net" emissions denotes that negative emissions, i.e. GHG sinks, are used to offset residual emissions. For the remainder of this paper it is understood that we mean net emissions when discussing phase-out, even if the term 'net' is omitted for simplicity.

choose from different technological options to achieve a cost optimal global energy system within certain economic boundary conditions, e.g. very low emissions. Energy efficiency is modelled on a more generic level. Consequently, these scenarios result in a higher use of energy and a lower share of renewables. To still meet certain emissions targets, the models assume that carbon capture and storage (CCS), and possibly also nuclear power, are deployed on a large scale. The use of biomass with CCS enables these scenarios to sometimes reach net negative emissions in the second half of the century.

More research is underway for very low emissions scenarios to be published during the course of 2013 in preparation of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

What are the sectoral options of global phase-out of GHG emissions by mid-century?

Technological and non-technological options exist today or in the near future to reduce greenhouse gas emissions to zero for roughly 90% of current sources of global GHG emissions. The energy system presents the greatest potential for emission reductions through efficiency savings and fuel shift. Table 1 summarises key options and challenges for each sector.

On average, the global economy could cope with such a change. Cost estimates for low emissions scenarios require less than 5% of annual GDP until 2050. Many of these options include substantial cost savings, but also have other social benefits, primarily from avoided direct environmental water, air and soil pollution associated with traditional energy generation. These in turn have positive impacts on human health and ecosystem preservation.

What are the main issues of concern of global phase-out of GHG emissions by mid-century?

Global phase-out of greenhouse gas emissions is possible but not without some challenges, see Table 1.

A step change in global action in almost all countries is needed now. The speed of the transition would be unprecedented. Some countries may be less capable of achieving this transformation alone and may need help along the way.

All solutions require large changes to the infrastructure on which our energy systems are based. For example, a high share of renewables requires smart grids and storage to manage supply and demand patterns. The planned investment has to be diverted in a different direction.

For roughly 10% of current sources of global emissions, technological options are not yet available to reduce GHG emissions to zero, e.g. for some industrial process and in agriculture. Innovation programmes would need to support the development of such technologies. As a last resort exemptions for "essential uses" could be applied, as is current practice in the phase-out of ozone depleting substances under the Montreal Protocol.

We also need to explore combinations of technologies that can produce net negative GHG emissions, such as bioenergy carbon capture and storage or afforestation, to balance out areas where it is not possible to reduce emissions to zero. For CCS, a significant effort would have to be made to achieve technical maturity and social acceptance of the required technologies. CCS would also require significant infrastructure investments for both transport and storage facilities.

Some scenarios foresee a stronger role for nuclear power in a low GHG emission world while others do not see it as essential. The political feasibility of such scenarios with a high share of nuclear energy remains uncertain given public concerns about safety.

Bioenergy and changed land use demands are essential for a global phase-out. The sustainability of the biomass, the link to food security and other demands for land have to be carefully managed.

Most scenarios model emission reductions assuming that at the same time demand for energy services and food, in particular meat consumption, will *increase*, primarily in regions with comparatively low consumption levels today. Changes in lifestyles of those parts of our population with high per capita income and high per-capita emissions could provide additional levers for phasing out emissions.

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Table 1. Key technical options, and challenges, for phasing out net GHG emissions[2]

Sector	Current emissions (% of global total)	Main areas where technological options are available today or in the near future to reduce net GHG emissions	Remaining technical challenges
Industry	29%	Material and energy efficiency, fuel switch to electrification and sustainably sourced biofuels, CCS, no HFCs	No technological option currently available for some production processes (currently 6% of global emissions)
Buildings	18%	Zero emissions buildings (new and renovated), efficient appliances	Energy efficient renovation of existing building stock
Transport	15%	Smart urban areas, energy efficiency, modal shift to public transport and electric rail, electric and hybrid vehicles, sustainably sourced biofuels	Shifting to 100% biofuel use in air, water and freight road transport, extending range of electric vehicles
Energy supply	13%[3]	Renewable energy, nuclear, CCS Methane capture and reuse in fossil fuel production	Dependency on viability and infrastructure needs of CCS (some scenarios) Integration of renewables in the electricity grid
Land use change	15%	Stopping deforestation/ degradation Afforestation and reforestation	Conflicting demands for land (alternative land uses are often more profitable)
Agriculture	7%	Adoption of improved livestock and agricultural land management technologies Reduction of demand: food waste and loss, dietary changes	Reduction options provide some reductions but not to zero
Waste	3%	Stopping landfilling of organic waste Treating waste water	-

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[2] The list of technical options in this table reflects an array of options for climate mitigation and should not be viewed as a recommendation from the authors or from GCCA

[3] This value does not include electricity and district heat used in the industry / buildings / transport sectors. These emissions are included in those sectors.

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1 The need for action: Current emissions

Our global economic system is built on processes and infrastructure which emit around 49 $GtCO_2$-eq of greenhouse gases (GHG) per year with a steadily increasing trend over the last decades (Figure 1). These emissions increase the trapping of heat in the Earth's atmosphere leading to changes in a multitude of critical ecosystem processes on which human life depends [Parry, 2007].

To reduce the risks related to climate change, we need to dramatically reduce GHG emissions, aiming for a complete phase-out of net emissions as soon as possible.

This paper will examine the possibilities for, and impacts of, a phase-out of all GHG emissions by the middle of the century [Haites, 2013]. "Phase out" in this report denotes that either all greenhouse gas emissions are reduced to zero, or where not possible, remaining emissions are compensated by sinks of those gases, i.e. negative emissions.

Figure 1 sets out the different sources of GHGs and their associated activities. Around two thirds of our emissions originate in our use of fossil fuels in the energy system. Fossil fuels are used in all the energy using sectors: Buildings, Transport, Industry, Agriculture and Heat and Power generation. The energy system thus presents the greatest potential for emission reductions through efficiency savings and fuel shift (e.g. using electricity instead of oil).

The remaining third of emissions are direct emissions, primarily from land use and livestock, but also from industrial process emissions. Additional mitigation options exist here, e.g. phasing out deforestation.

Reducing emissions therefore means fundamentally restructuring all of our economic sectors in the coming decades. This seems like a daunting task until we remember the technical revolutions we have seen in the last fifty years – our capacity for innovation and change is enormous. We will lay out the main technical levers for each sector in the following chapters.

This study surveys existing scenarios which show how a zero or near-zero GHG emissions level can be reached by 2050 and what the economic implications may be. It also assesses the likelihood of such scenarios leading to a long-term warming below 2°C or 1.5°C[4].

[4] Global temperature change values given in this paper relate to the year 2100 unless stated otherwise. There may well be higher warming in-between now and 2100 given that all surveyed scenarios are "overshoot scenarios".

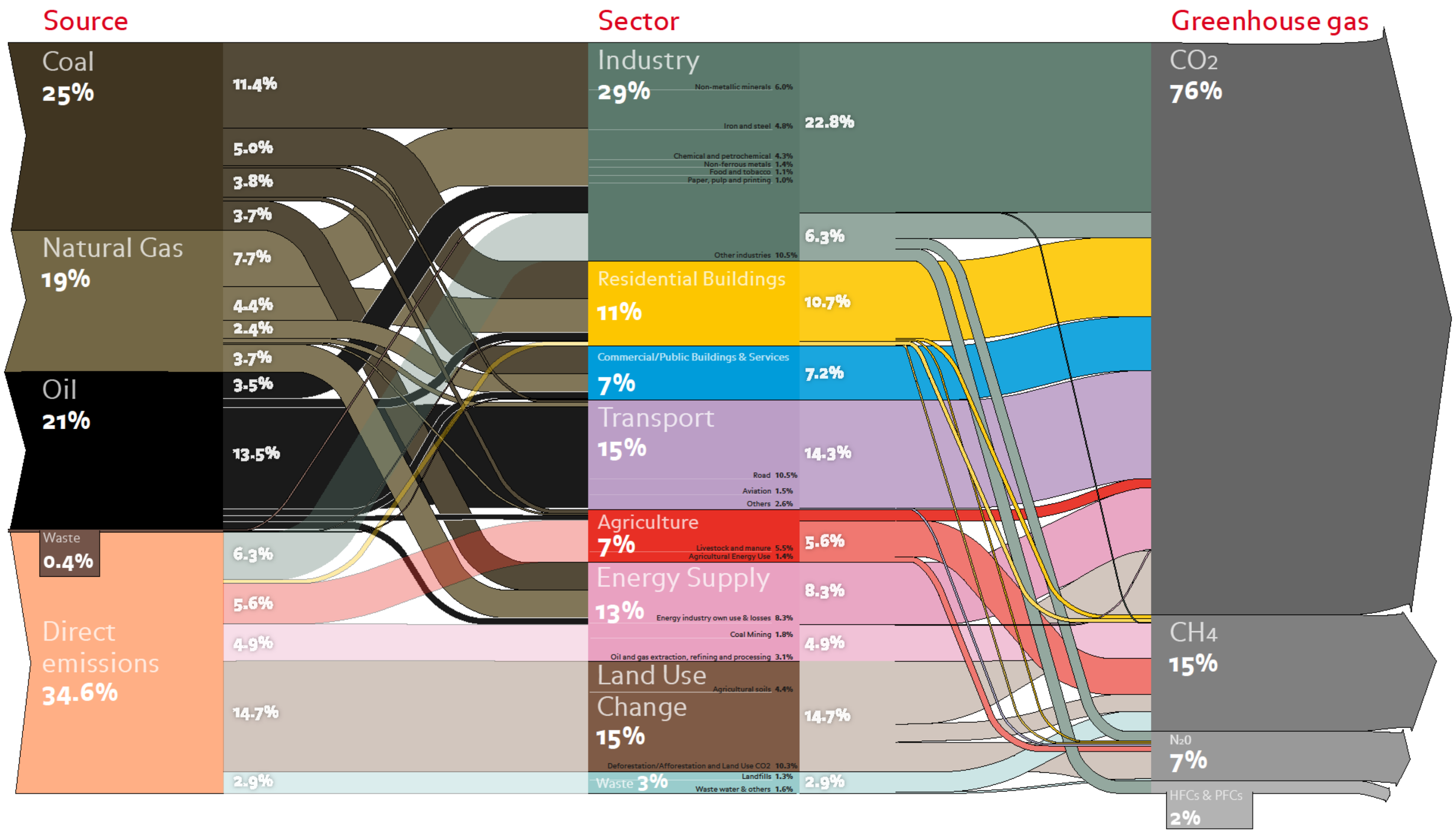

Figure 1 Global GHG emissions in 2010 by source The total emissions are estimated at 48.6 $GtCO_2$. Source: Analysis by Ecofys [ASN, 2013].

The focus of this analysis is primarily on *technical* feasibility, with a brief review of possible economic implications of such a transformation. Whether the surveyed scenarios are *politically* feasible will be seen in the coming years.

2 The way forward: Low emissions pathways

This study surveys existing scenarios which show how a zero or near-zero GHG emissions level can be reached by 2050. Figure 2 shows the results of several existing scenarios originating from different global energy and emissions models that outline a future with very low emissions by the middle of the 21st century [GEA, 2012; Calvin, 2006; UNEP, 2012; Rogelj, 2013; Schaeffer, 2013].[5] We assess the impact on long-term global temperatures for an illustrative pathway informed by these scenarios in Section 5 [Rogelj, 2013].

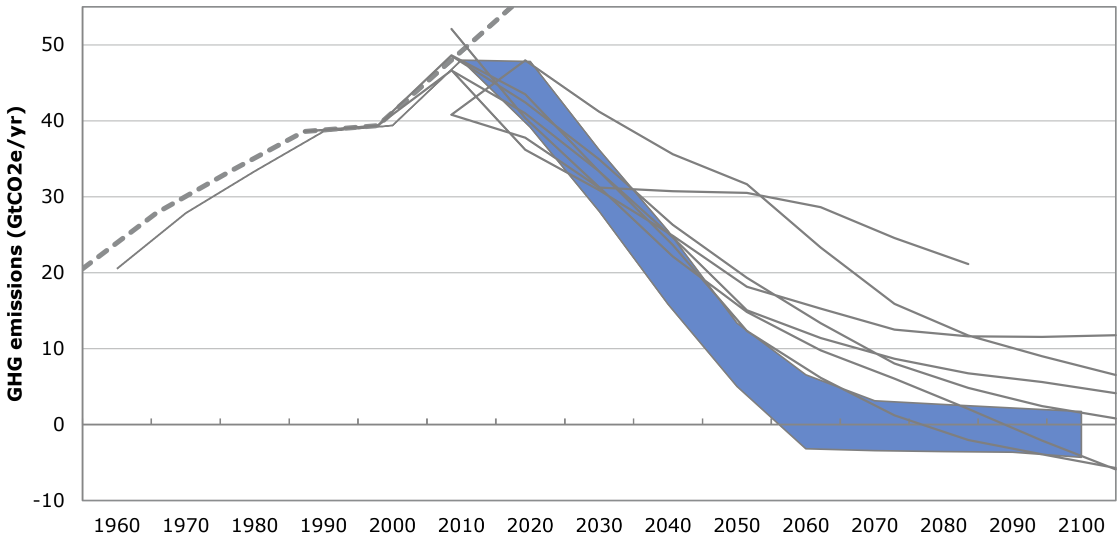

Figure 2 Examples of existing low emissions scenarios showing total global GHG emissions from all sectors. The blue area indicates a collection of stylised pathways that are used to calculate the likelihood of exceeding a 1.5 °C temperature increase by 2100 in Section 5. The dashed line indicates a linearly extrapolated trend over the period 2000-2010. Sources: [Calvin, 2006; Rogelj, 2013; Edenhofer, 2010; Knopf, 2009]

Although efforts at decarbonisation exist on a global and local scale, we are still currently on a pathway which differs substantially from the low emission scenarios depicted here, as

[5] More low emissions scenarios are currently being developed, but are not available yet publicly; for example, modelling comparisons of EMF27, AMPERE, LIMITS are in the pipeline and the IPCC Fifth Assessment Report.

discussed extensively in studies such as the UNEP gap reports [UNEP, 2010; UNEP, 2011a; UNEP, 2012].

There are many scenarios for the *energy system* that reach zero GHG emissions by the *end of the century*, but very few that phase out emissions from energy use by *2050* (Figure 3).

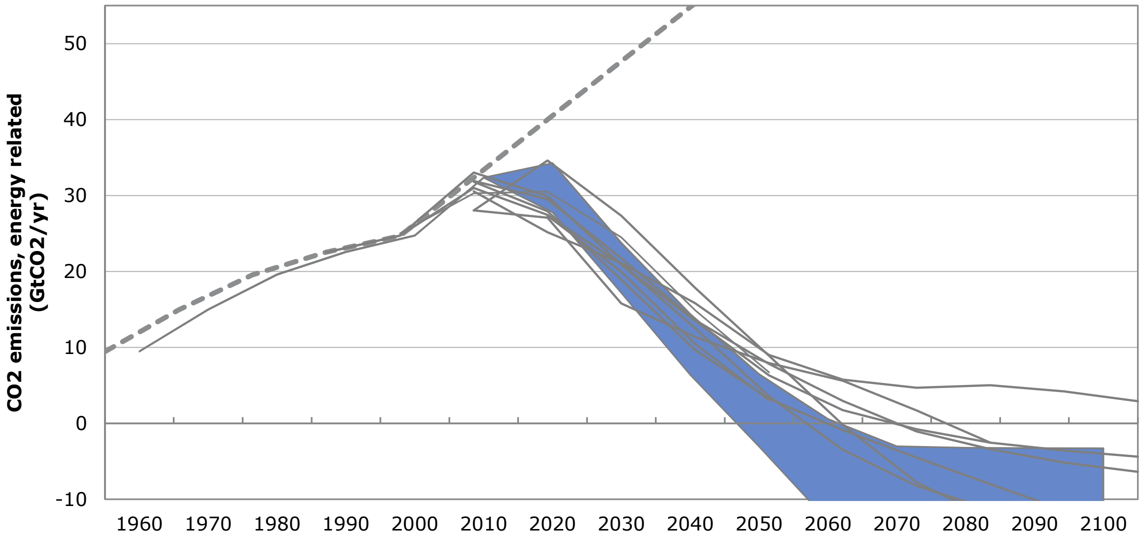

Figure 3 Examples of existing low emissions scenarios showing CO_2 emissions from energy consumption. The blue area indicates a collection of stylised pathways used to calculate warming implications in Section 5. The dashed line indicates a linearly extrapolated trend over the period 2000-2010. Sources: [Calvin, 2012; Deng, 2012; Teske, 2012; Rogelj, 2013; Edenhofer, 2010; Knopf, 2009]

Broadly, these can be categorised as one of two types, reflecting two fundamentally different modelling approaches and resulting strategies:

1. **Scenarios with (near) 100% renewable energy by 2050**: These scenarios aim at a certain emissions target as well as a certain contribution of renewables. Energy efficiency is a key strategy in these scenarios because high efficiency, including electrification, makes it possible to supply almost all energy from renewable sources in the short to medium term. Such scenarios are generally prepared with high sectoral detail, e.g. number of kilometres driven by cars, but do not always consider all interactions between different sectors of the economy.
2. **Scenarios with less than 100% renewable energy but carbon capture and storage (CCS):** Most of the existing scenarios are modelled using so-called integrated assessment models. They aim to achieve cost-optimisation of the global energy system within certain economic and/or emissions boundary conditions. Energy efficiency is modelled on a more generic level, e.g. for the transport sector as a whole, resulting in a lower appreciation of the potential of efficiency. But they are able to model interactions between sectors of the economy. Consequently, these scenarios outline a higher use of energy and a lower share of renewables. To still meet certain emissions targets, the models assume that carbon capture and storage

(CCS) is deployed on a large scale. Due to the use of biomass, these CCS based scenarios can sometimes reach negative emissions in the second half of the century. Some scenarios also include large shares of nuclear energy.

Figure 3 shows an overview of only the energy system related CO_2 emissions for various low emissions scenarios.

The energy system represents the largest source of emissions, but CO_2 emissions can also arise from other sources, primarily from human use of land and land use change. This includes carbon emissions from deforestation and, to a smaller degree, agriculture. Figure 4 shows the evolution of land-based CO_2 in low emissions scenarios. The scenarios span a wide range of values reflecting the uncertainty in the modelling for this sector.

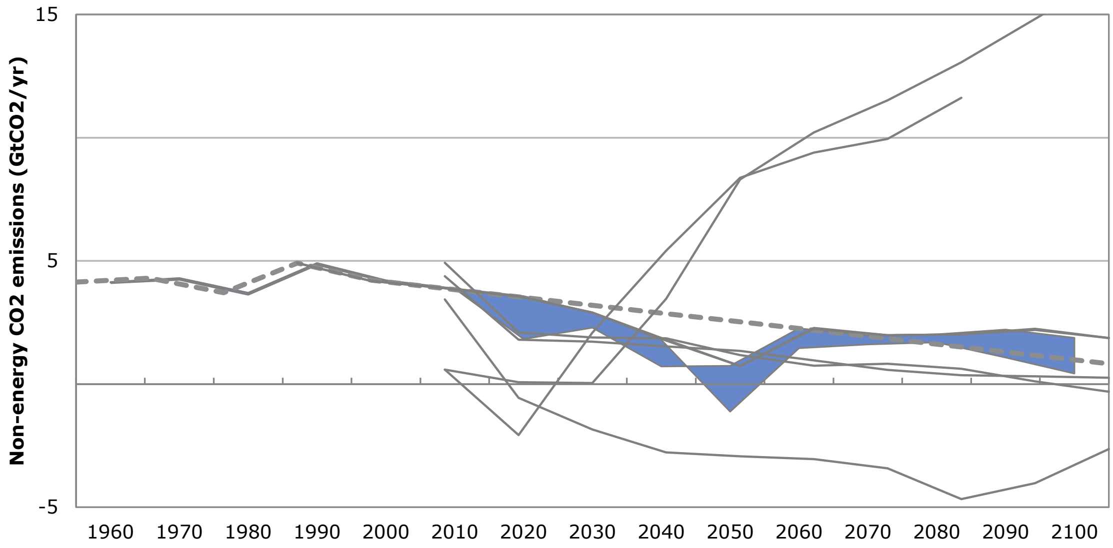

Figure 4 Examples of existing low emissions scenarios showing CO_2 emissions not related to energy consumption, predominantly land use change and process emissions. The blue area indicates a collection of stylised pathways used to calculate warming implications in Section 5. The dashed line indicates a linearly extrapolated trend over the period 2000-2010. Sources: [Calvin, 2012; Rogelj, 2013; Edenhofer, 2010; Knopf, 2009]

Finally, other greenhouse gases aside from CO_2 can contribute to climate change. The most significant contributions come from:

- methane (CH_4), from the agricultural sector or the direct release of natural gas in energy production and industrial processes
- N_2O, which is released during fertilisation of agricultural land, from livestock and, to a smaller extent, from industrial processes
- F-gases from the industrial sector.

Their development in low-emissions scenarios is shown in Figure 5.[6]

In the following sections we give an overview of the actions required to bring global emissions in line with these low-emissions pathways.

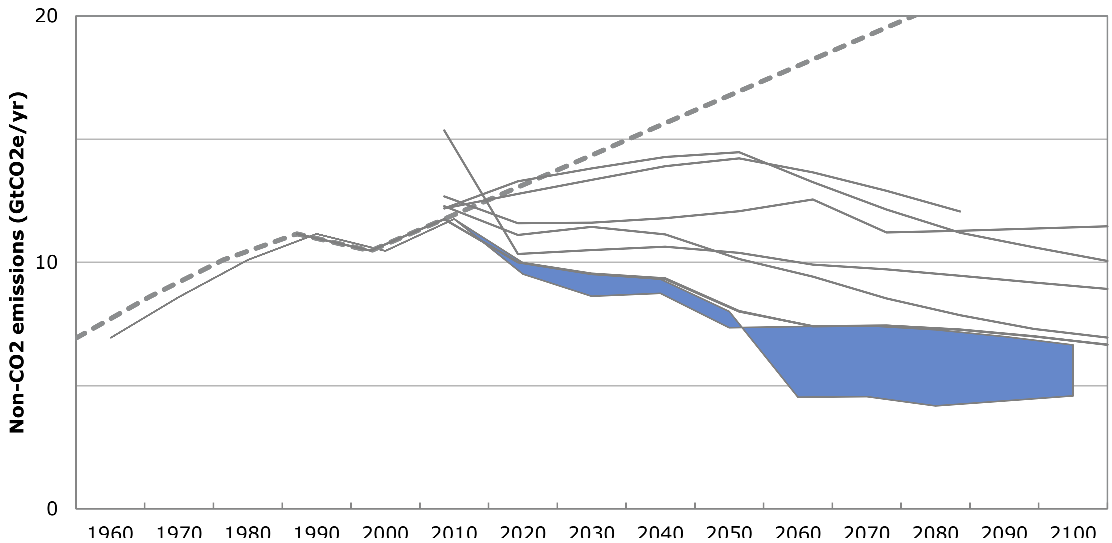

Figure 5 Examples of existing low emissions scenarios showing non-CO_2 emissions (CH_4, N_2O and F-gases). The blue area indicates a collection of stylised pathways used to calculate warming implications in Section 5. The dashed line indicates a linearly extrapolated trend over the period 2000-2010. Sources: [Calvin, 2012; Rogelj, 2013; Edenhofer, 2010; Knopf, 2009]

3 Action focus: Energy system emissions

3.1 Industry

Nearly 30% of global final energy use is consumed in the industry sector, being responsible for 29% of global GHG emissions. Energy-related emissions from industry make up 23% of global GHG emissions. In addition, process emissions result from chemical reactions in the different production processes, e.g. cement or chemical production. These process emissions account for around 6% of global emissions.

[6] The category of 'non-CO_2 emissions' captures many different gases from very different sources and with very different abatement options, which are grouped together here for simplicity. Representation by gas or by sector was unfortunately not possible given the available data resolution.

The following greenhouse gas abatement options are needed for industry to achieve global phase-out of GHG emissions by the middle of the century, especially if aiming for scenarios with high shares of renewables:

- **Boosting material efficiency**. This involves the reduction of materials used in processes by designing long lasting and 100% recyclable products, reducing waste during production, e.g. in the steel, cement and aluminium sectors. This measure will reduce emissions on-site as well as in other parts of the supply chain.
- **More than doubling energy efficiency**. This can be achieved by improving efficiency of electrical equipment such as motors and pumps, but also by improving the efficiency of heat use, for example by optimally designing and integrating different industrial processes. Very ambitious efficiency programmes would be required to bring all industrial plants in line with increasingly efficient benchmarks. All new plants would be required to be built to 'best available technology' standard as of now.
- **Fuel switch from fossil fuels to electricity and biofuels**. Almost all industrial production would need to phase out fossil fuels. Many production processes can be electrified; this electricity can be supplied by low carbon technologies, see Section 3.4. Where electricity cannot be applied, sustainably sourced biofuels with low lifecycle GHG emissions could be employed.
- **Carbon capture and storage where no other options exist**. For some industrial processes, for example in iron and steel production, it is difficult to replace coal and for other processes, for example cement production, CO_2 is an intrinsic result of production. In these cases, CCS can be applied to phase out emissions. In addition, CCS can in principle be used in combination with biomass to achieve negative emissions (see next section).
- **Phase out of HFCs:** HFCs have been identified as an important target for climate change mitigation. Discussions are currently underway to include HFCs in the Montreal Protocol. This protocol was established in 1989 to phase out ozone-depleting substances. These substances were successfully phased out as a result of the Montreal agreement but were replaced with HFCs.

A major challenge in the industry sector remains that for some production processes no technological options are currently and in the near future available to fully replace fossil fuels. This is estimated to be the case for around 15% of industrial energy use or 5% of global energy use. Here, innovation programmes would have to be initiated. As a last resort, limited exemptions for essential uses could be granted. Unavoidable residual emissions in industrial processes may be offset with carbon sequestration either in new sustainably forested lands and/or biomass CCS.

3.2 Buildings

About one third of our final energy use is consumed in buildings making up around 20% of global greenhouse gas emissions. In buildings, energy is used for space heating and cooling, hot water, cooking, appliances and lighting. Heat for cooking is mainly delivered by fuels, in developed regions this is mainly natural gas; in developing regions traditional biomass plays a dominant role. For space and water heating either fuels (mainly natural gas) or electricity is used. The other services are all electricity-based.

The following greenhouse gas abatement options are needed for buildings to achieve global phase-out of GHG emissions by the middle of the century, especially if aiming for scenarios with high shares of renewables:

- **All new buildings have to be net zero or net negative emissions buildings as soon as possible.** On average, 2-3% of existing buildings will have to be renovated every year from now on to the highest possible energy efficiency standard and to be powered by zero emissions energy sources. Improved insulation can drastically reduce the energy needs for heating and cooling and thus reduce the need for electricity and fuels. Remaining heat needs can be sourced from heat pumps, renewable fuels or solar thermal heaters, either on-site or via district heat, and electricity can come progressively from renewable sources, see Section 3.4. These options could become part of the initial building and district design. As renovation is more costly and difficult to implement and buildings have a lifetime of decades, the introduction of zero emissions standards for new buildings is a matter of urgency. Low emissions buildings can already be built at limited additional costs to standard buildings and some regions in the world are introducing legislation to make these mandatory by 2020 [Hermelink, 2013]. Rates of 2–3% per year renovating existing buildings stock have been demonstrated, implying that a country's building stock could be fully renovated in the course of ~40 years.
- **All electric appliances in use (including cooling appliances) and lighting have to be as at least as efficient as the currently most efficient ones.** Increasing efficiency of electric appliances and lighting is still relevant in a world with low carbon electricity production; it will reduce the need for CCS and biomass in the power sector. Furthermore it is, in many cases, cheaper to improve the efficiency of appliances than investing in low-carbon electricity production. Improving energy efficiency in buildings is also very attractive for residents and companies as it reduces the energy bill, which is a significant expense in many countries.
- **Efficient stoves reduce the use of traditional biomass to zero.** In developing countries highly-efficient use of traditional biomass for cooking will substantially reduce emissions of black carbon, a potent short-term contributor to ice melting and global warming. It will further reduce mortality rates from indoor pollution, and reduce local and regional forest degradation. New energy-efficient and non-polluting

wood stoves and biogas digesters using a variety of organic wastes can channel sustainable use of biomass into efficient conversion routes.

A major challenge in the building sector is the energy efficient renovation of existing building stock as this often involves many different individual building owners. New policy instruments to enable outreach and help with the initial investments are currently being tested.

3.3 Transport

About 25% of our total final energy consumption is used for transport of passengers and freight, being responsible for 15% of global greenhouse gas emissions. Emissions originate mainly directly from the fuels used.

The following greenhouse gas abatement options are needed for the transport sector to achieve global phase-out of GHG emissions by the middle of the century, especially if aiming for scenarios with high shares of renewables:

- **Widespread integrated urban planning to reduce demand for transport.** Increasing urbanisation offers an opportunity to start designing 'smart' urban areas, integrating efficient buildings with decentral power generation and efficient transport networks. Early action in this arena promises a benefit for the triple bottom line, i.e. economic, environmental and human health improvements.
- **Increased efficiency of all transport modes and modal shift.** All transport modes (road, rail, aviation, shipping) can increase efficiency by ensuring that new vehicles meet best-in-class efficiency standards. In addition, shifting passenger and freight transport from fuel-inefficient to fuel-efficient or zero-fuel modes can be helpful, where large transport volumes are concerned, e.g. daily passenger commuter transport or road freight. This can also mean shifting transport from modes which cannot be electrified to modes which can be electrified, e.g. from air to rail).
- **100% electrification of individual road transport and rail transport.** Given the large potential for renewable electricity production from a diversity of sources, carbon free energy can be best provided through electricity, not through fuels. Electrification in road transport is already gaining momentum. Electrified road transport will develop around short distance travel, for example, of lightweight vehicles for freight transport in cities and commuting. A beneficial side-effect is an improvement in air quality in urban areas.
- **Biofuels or other alternative low-carbon fuels for aviation and marine transport and other heavy long distance freight.** These modes may be difficult to be electrified with current technologies. While modal shift and efficiency can help reduce fuel needs to a minimum, sustainably produced biofuels are necessary to bridge the remaining gap. The more ambitious and widespread the energy efficiency and modal shifts, the lower the reliance on biofuels.

Major challenges in the transport sector are options for air, water and long distance freight road transport. Currently no alternatives are available other than sustainable biomass, which can have conflicting uses. In order to reduce the need for known liquid biofuels in those sectors, enhanced research is needed to look into new and sustainable bioenergy sources such as algae and other non-bioenergy options for these transport modes. Those include fuel cells based on renewably-produced hydrogen or/and renewably produced methane/methanol.

3.4 Energy supply

Emissions from energy supply include emissions from electricity and heat generation (8% of global emissions are for own use[7] and losses) and methane emissions from fossil fuel extraction (5% of global emissions, see Figure 1).

Currently, electricity constitutes about 18% of global final energy use. In most scenarios demand for electricity is projected to increase because of a global increase in access to electricity and increased electrification, i.e. an increased share of heat production and transport powered by electricity. This trend is amplified if GHG emissions are to be phased out.

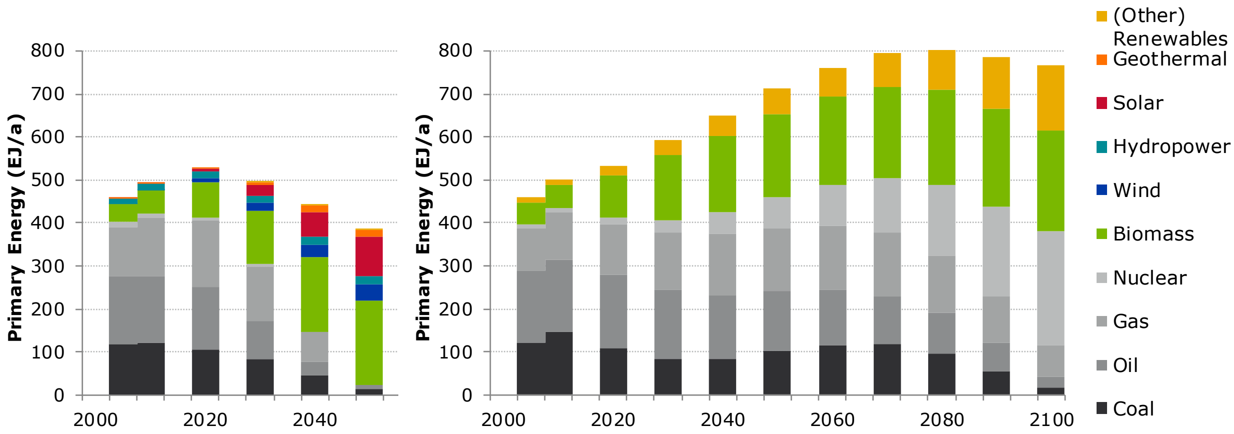

Figure 6 Energy system development in two of the low emissions scenarios: [Deng, 2012] (left) is one example of a high-efficiency and high-renewables scenario; the so-called 'GCAM CO_2 price \$50' scenario (right) from [Calvin, 2012] is a medium-renewables scenario with a significant share of CCS and nuclear power.

The following greenhouse gas abatement options are needed for the energy supply sector to achieve global phase-out of GHG emissions by the middle of the century:

[7] 'Own use' means use of energy inside a power or heat generation plant

- **Very high shares of renewable energy**: Renewable sources such as solar, wind, hydropower, geothermal and biomass replace fossil fuel power plants. The technical potential for renewables does not provide a limiting factor; any constraints on the share of renewables are based on costs, demand for electricity and system integration [IPCC, 2011]. While some scenarios deploy ~95% renewables [Deng, 2012], the scenarios collected in the Asian Modelling Exercise [Calvin, 2012] reach ~40% renewable in primary energy consumption.
- **New fossil power plants only with CCS, if at all:** Replacing fossil fuel power generation with these low-carbon alternatives is a slow process as most power plants have lifetimes upwards of 30 years. From now on almost only carbon free electricity supply would have to be built to avoid costly retrofitting in the future.
- **Fossil fuel carbon capture and storage (CCS):** This technology, which is currently at the pilot stage, can be deployed to industry and power generation plants to reduce or entirely avoid the release of GHG emissions from fuel combustion. Models that allow this technology usually assume a large contribution (up to 24 $GtCO_2$ in 2050 [Calvin, 2012]). Other studies argue that it is a bridge technology at best and therefore investments would be better channelled into long-term solutions [Deng, 2012].
- **Biomass carbon capture and storage:** Biomass driven power plants can also be equipped with CCS systems, which could result in net negative emissions. Plants and trees bind CO_2 during the time they're growing; after combustion, this carbon is captured and stored underground. This results in a shifting of CO_2 from the atmosphere to underground reservoirs. Scenarios rely on this technology to reduce emissions significantly if they have residual GHG emissions in sectors where reduction is costly or not possible by other means.
- **Nuclear power is not essential:** Nuclear power is a controversial energy source, where safety concerns (revived by the Fukushima disaster) have resulted in strong public opposition and a planned phase-out of nuclear power in some countries, while new reactors are being built in others. Its current share in total final energy consumption is around 3%. The low-emission scenarios surveyed in this study differ in the amount of nuclear power they foresee in the long-term; some scenarios include substantial increases of nuclear energy, growing its share by up to a factor of five by 2050 [Calvin, 2012]. Other studies exclude new nuclear power beyond the baseline a priori, or phase it out completely. These scenarios are still able to achieve very low GHG emissions because the electricity can be supplied by other sources (sometimes at slightly elevated costs) [Edenhofer, 2010; Deng, 2012].
- **Almost full capture of methane in fossil fuel production:** If some fossil fuels are still used with CCS, the methane emitted during its production process needs to be captured and reused. Practices exist in most areas.

A major challenge in the energy supply sector is the dependency on **CCS**. While it is generally considered safe by experts, long term safety is still a subject of public debate. Other concerns raised around CCS include:

- Possible competition with renewable energy sources for funds available for R&D and deployment
- Possible competition with renewable energy sources for underground storage space (for heat or compressed air storage)
- Possible (economic) incompatibility of CCS enabled power plants with the highly flexible and responsive grid required for high shares of renewable power sources
- Expected reduction in power production efficiency (the ratio of fuel input and electricity output) from capturing CO_2, as the capture process is energy intensive.

In many scenarios, CCS is a key driver towards a near-zero emissions energy system by 2050. A significant contribution of CCS to a global phase-out of net GHG-emissions would require large scale deployment of this technology to begin between 2020 and 2030.

3.5 Energy system considerations

To ensure a fast phase-out of GHG emissions, global action is needed now. Typical low emissions scenarios show two possible solutions along two broad dimensions:

- We can reduce energy consumption by improving energy efficiency dramatically, which would enable us to (nearly) cover all our energy needs with renewable energy sources or
- we could invest in nuclear power and carbon capture and storage (possibly combined with biomass).

A possible future pathway to significant emission reductions will likely require both of these solution paths and the longer we wait the more likely it is that we need to deploy all possible options at increased costs. It should be noted that energy efficiency measures are typically faster and cheaper and sometimes easier to deploy than fuel shift or supply side measures.

Both types of solutions require large changes to the infrastructure on which our energy systems are based. If we expect a high share of renewables, we need to invest in the design of smart grids and storage to manage the many different supply patterns of a diverse set of renewable energy sources. This would also likely impact the way the electricity infrastructure for electric road transport will be designed.

In the case of a high deployment of CCS, a CO_2 transport and storage infrastructure as well as long term monitoring systems have to be set up.

Safe operation of nuclear power also requires monitoring systems, both during the operation of plants and to safely process and store nuclear waste. Concerns about the safety of nuclear power during operation and waste storage continue in the public debate.

All low emissions scenarios require substantial amounts of biomass for energy consumption. It is therefore important to develop clear and global criteria to manage biomass production and trade to avoid deforestation, impacting food supply or triggering land use change which results in emission increases. The development of biomass energy from algae production might increase the potential of sustainable biomass.

Finally, fossil fuels could become cheaper under a global phase-out of GHG emissions. This could make alternatives economically less attractive. Policy instruments would be required to safeguard the phase-out. These could include pricing the emissions of GHG, carbon efficiency standards or targets for minimum renewable or maximum fossil energy shares.

4 Action focus: Non-energy emissions

4.1 Agriculture, forestry and other land use (AFOLU)

Agriculture, forestry and other land use (AFOLU) are the source for around a quarter of anthropogenic GHG emissions[8]. Around 7% (~3–4 $GtCO_2eq$) of these emissions come from soil and nutrient management and livestock in the agricultural sector [ASN, 2013]. Agriculture is also an important driver of deforestation and land use change which account for up to 15% (~7–8 $GtCO_2eq$) of total anthropogenic GHG emissions.

The following greenhouse gas abatement options are needed for AFOLU to achieve very low emissions levels by the middle of the century (a complete phase-out of gross emissions is not possible in this sector with current technologies):

- **Avoiding deforestation**: Zero deforestation would reduce GHG emissions by 3 $GtCO_2$ annually; avoiding tropical forest land use change and forest degradation could generate up to an additional 2.3 $GtCO_2$ of emissions reduction [Harris, 2012]. Incentives are needed to encourage the conservation and restoration of tropical forests. For incentives to be effective, planning of conservation measures has to go beyond forest borders to address the drivers of deforestation. Agricultural intensification can help to reduce the demand for new agricultural land, and legislation and monitoring are needed to protect forests against agricultural encroachment.[9]
  Several developing countries have set targets to reduce emissions from deforestation. Colombia, for example, pledged to reduce deforestation in the Colombian Amazon to zero by 2020 [UNFCCC, 2011]. Brazil committed to reducing deforestation by 80% of the historical rate (1996–2005) by 2020 [Nepstad, 2009]. Private sector initiatives to reduce deforestation are also underway. The Consumer

[8] Estimates of emissions in the AFOLU sector, especially on land use change, are subject to large uncertainties.

[9] Agricultural intensification has led to additional deforestation in some cases in the past; such unintended consequences need to be carefully managed.

Goods Forum, an organisation of 400 consumer goods manufacturers and retailers, pledged to mobilise resources to help achieve zero net deforestation by 2020.

- **Enhancing carbon sequestration in soils**: Almost 90% of the technical agricultural mitigation potential could be achieved through soil carbon sequestration [Smith, 2008]. Many soil and crop management technologies as well as agroforestry, afforestation and reforestation have the potential to increase carbon stored in soils. To maximise the soil carbon sequestration potential, site-specific technologies and practices have to be identified [Lal, 2009]. Well-selected technologies have other benefits and can, for example, help to restore degraded soils and increase agricultural productivity.
- **Reducing non-CO_2 emissions through improved livestock and agricultural land management:** Measures that reduce CH_4 and N_2O emissions contribute 9% and 2% of the technical agricultural mitigation potential, respectively [Smith, 2008]. Changes in livestock management, especially in feeding, can help to reduce CH_4 emissions. Improved application of organic and inorganic fertiliser is an option to reduce agricultural N_2O emissions.
- **Changes in demand**: An estimated 30–40% of food is lost annually in the global food supply chain. Reducing food loss and waste along the supply chain can contribute to GHG emission reductions. Changes in diets and consumption patterns are measures consumers can adopt to contribute to climate change mitigation. Technical mitigation combined with reduced demand for livestock products, for example, could reduce projected non-CO_2 emissions of 15.3 $GtCO_2eq$ in 2055 down to 2.5 $GtCO_2eq$ [Popp, 2010].

Major challenges still remain in the forestry and agriculture sector for phasing out GHG emissions. For some production systems, it is technically not feasible to reduce emissions to zero, e.g. livestock production. Here innovation or changes in demand could help. In addition, mitigation measures like afforestation and reforestation can contribute to offsetting all GHG emissions, including emissions from agricultural production. This option is ultimately constrained by competition for land. Any implementation of the technical options presented above will need to be sensitive to local circumstances.

4.2 Waste

Methane (CH_4) emissions from solid waste disposal and domestic waste water are responsible for 3% of global GHG emissions.

The following greenhouse gas abatement options are needed for the waste sector to achieve a global phase-out of GHG emissions by the middle of the century:

- **No landfilling of organic waste:** Methane is released from waste landfills. The best option to reduce greenhouse gas emissions from solid waste is to separate the biomass from the solid waste streams and treat the biomass separately, for example by composting or anaerobic digestion (creating methane to combust for heat or electricity) and not in a landfill. Because the source of the carbon (in the methane and produced carbon dioxide) comes from organic material, the resulting heat or electricity is bioenergy. Zero landfilling of organic waste is common practice in many developed countries and could be implemented in all countries by 2050.

- **Treatment of all domestic waste water:** Waste water contains organic content that produces mainly methane and nitrous oxide (N_2O). Waste water can be collected in waste water treatment plants (WWTPs) and subjected to anaerobic digestion. The captured methane can (as with solid waste) be used to fuel heat or electricity production. Currently, the design of WWTP's and their operations are being improved to prevent the release of nitrous oxide. Treatment of 100% of the wastewater is a development objective in many developing countries.

4.3 Short-lived climate forcers: Black carbon

In addition to greenhouse gases, some air pollutants play a significant role in global warming. An important example is soot, or "black carbon", which is thought to contribute to the warming of the planet in two ways:

- by trapping heat in the atmosphere from dispersed particles of black carbon
- by depositing on the world's ice sheets and glaciers.
  This reduces their reflectivity and lessens the so-called 'albedo' effect: the ability of the planet to reflect heat from the sun, leading to exacerbated ice melting in the short-term.

Black carbon is primarily created in diesel cars and trucks, cook stoves, forest fires, and agricultural open burning, during the incomplete combustion of the biomass and fossil fuels used.

While the climate change impact of black carbon is significant, its very short lifetime (of several weeks) makes it a less difficult polluter to address: Technical mitigation options exist to substantially reduce black carbon pollution [UNEP, 2011b]. If deployed widely these would slow the rate of near-term climate change.

The primary benefit of phasing out black carbon, however, lies in improvements in air quality and public health as well as reduced disruption of regional weather patterns.

5 Likelihood of avoiding 2°C or 1.5°C warming

Figure 7 summarises the warming level that would result from the stylised pathways that phase out global net GHG emissions by the middle of the century as shown in Figure 2.[10] As the impact of emissions on temperature increase is uncertain, the percentiles indicate the likelihood below the corresponding temperature line.

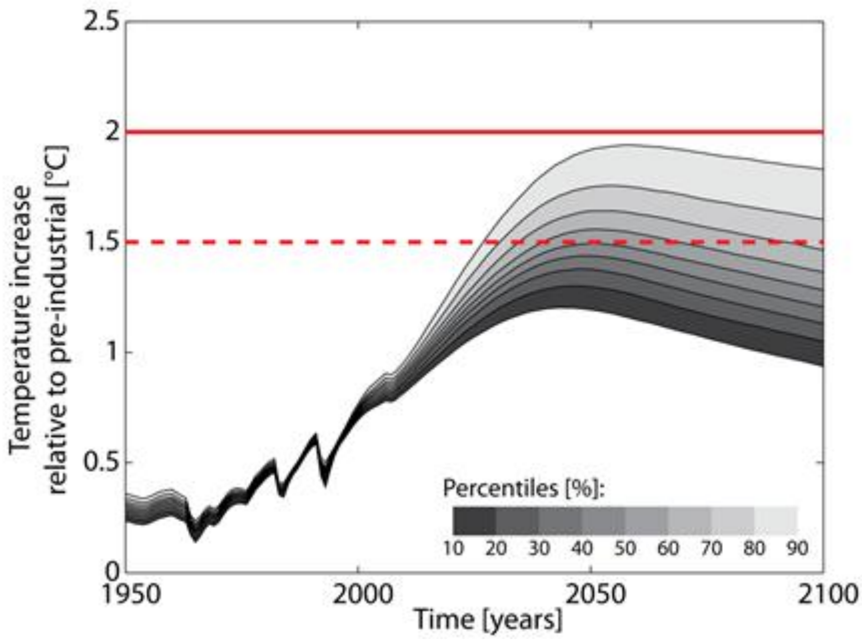

Figure 7 Global mean temperature increase relative to pre-industrial (1850-1875) temperatures, based on the range of stylised emissions scenarios shown in blue in Figure 2. Source: [Rogelj, 2013; Meinshausen, 2011]

Figure 7 demonstrates that a phase-out of net GHG emissions by 2050, as depicted by the stylised pathways in blue in Figure 2, would ensure a very high likelihood of meeting the agreed 2°C goal. There is a more than 90% likelihood that global mean temperatures would not breach this limit for the duration of the 21st century. There is only a 50% chance of staying below 1.5°C over the entire period, a more than 60% chance in 2100.

It must be noted here that the stylised pathways which achieve this temperature stability are slightly more ambitious, i.e. lower in emissions, than the scenarios described in section 0, with regard to their reduction of non-CO_2 emissions (see Figure 5). Those scenarios would still reach a 50% chance global temperature below 1.5°C in 2100. This means

[10] The methodology to calculate the temperatures is the same as used in UNEP [2012].

additional action is required over and beyond that implied by these scenarios to decrease non-CO_2 emissions to the required levels.

6 Economic implications

6.1 Direct costs and investments of reducing GHG emissions

The direct net costs of reducing GHG emissions include investments and costs on the one side minus potential savings on the other side, both in comparison to a business-as-usual (BAU) scenario. For example, the additional cost of building a zero emissions building is calculated on the investments side, and savings on energy costs during the building's operation are counted on the savings side.

Of the most recent low emissions scenarios studied here, two attempt to quantify these total system 'policy costs': the annual share of GDP spent on abatement is estimated at 1-5% until 2050[11]. An alternative approach finds the carbon price required to achieve low emissions: most of the low emissions scenarios included here were based on assumptions of a tonne of carbon dioxide being priced at or above ~50 USD per tonne. It is useful to put these values into perspective: 3% of GDP is comparable to the total subsidies governments around the world currently lavish on fossil fuels [IMF, 2013].

These total system cost estimates necessarily bear very large uncertainties for several reasons: they are compared to a hypothetical BAU scenario, there is uncertainty in the price development of technologies and fuels as well as the underlying economic forecasts and there is a strong influence of existing and potential future policies on costs and benefits.

Examples of historic uncertainties include the volatility of energy prices such as crude oil, even over long timeframes and the speed of cost decrease of new technologies, such as the price of solar photovoltaic technology in recent years, which has been significantly influenced by government policies.

While the global GDP burden of low emissions pathways is projected to be moderate, the ability to invest even a few percent of GDP differs significantly between countries. As action needs to happen in all countries around the world in the very short-term, some countries would need support to undertake the required investment.

[11] Note that in the high renewables scenario, net costs peak around 2040 and then decrease due to cumulative fuel savings and decreasing costs of renewables offsetting investments in infrastructure. The other scenario, which assumes a significant adoption of CCS after 2030, sees increasing costs after 2050

6.2 Social, environmental and other co-benefits

The net direct cost comparisons described above do not show the full picture as indirect costs (for example environmental costs) and social benefits (increased health or well-being) are difficult to quantify and therefore usually excluded from consideration.

In addition to climate change mitigation, low-emissions scenarios often result in additional non-GHG related environmental benefits, primarily from avoided direct environmental water, air and soil pollution associated with traditional energy generation. These in turn have positive impacts on human health and ecosystem preservation.

Social benefits include access to energy, energy security, i.e. reduced reliance on imports for countries poor in fossil resources, and resilience due to the diversification of energy sources and locations.

Studies that have modelled multiple objectives in parallel [GEA, 2012; Bollen, 2010; PBL, 2012] show that pursuing these objectives in parallel and in a coordinated fashion can achieve the policy goal at a lower overall cost than pursuing them in isolation.

An alternative approach is to compare net costs of mitigation to the estimated costs of unabated emissions. Stern et al. suggested that costs of inaction, e.g. from rising sea levels, higher risks of natural disasters, increased health risks, etc., could significantly outweigh emission mitigation costs, estimating them at 5–20% of global GDP annually [Stern, 2006].

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