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STRATEGY & CHANGE

INNOVATION IN A WARMING WORLD

RESEARCH TACKLING EUROPE'S GRAND CHALLENGE OF CLIMATE CHANGE

THE HAGUE CENTRE FOR STRATEGIC STUDIES AND TNO

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TNO and The Hague Centre for Strategic Studies (HCSS) program Strategy & Change analyzes global trends in a dynamic world affecting the foundations of our security, welfare, and well-being.

The program attempts to answer the critical question: what are the policies and strategies that must be developed to effectively anticipate these emerging challenges?

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THE GRAND CHALLENGES PROJECT

Over the past century, Europe has become more and more prosperous. We are healthier, richer, safer and live longer than ever before. But there is a downside to this success: it poses new challenges that threaten our future wellbeing. Ironically, many of these challenges are the price we pay for progress. Our economic growth comes at the cost of a changing climate and resource scarcity; new technologies breed new types of international organized crime; modern lifestyles lead to new diseases; increasing life expectancy puts pressure on public finances; and new production patterns lead to food safety concerns. Policy makers, researchers, companies and citizens in Europe need to look at ways to deal with these trends. The Grand Challenges project aims to further the debate by looking at how we can use research and development to tackle the most pressing societal challenges to Europe's future. In six separate reports, we highlight Grand Challenges on six key issues. We show how these developments may impact our future and how science can address these challenges and create new opportunities for European societies.

EXECUTIVE SUMMARY

Since the beginning of the industrial revolution, populations have expanded and living standards have risen rapidly in many parts of the world. The correlate of these developments is the ever increasing energy consumption and emissions of greenhouse gases, which lead to the warming of our world, or 'climate change'. Though the impact will be gradual and difficult to predict, we slowly start to understand how this process will affect our planet. This report spells out these negative effects, specifically for Europe. It furthermore looks at ongoing research and development (R&D) efforts and suggests research-based solutions to prevent or mitigate these impacts.

To assess vulnerability to climate change, this report developed a simple country level index based on potential impacts of global warming. The results suggest that poor countries in Africa and Asia are the most vulnerable to the impacts of climate change. Europe in general will likely be less affected than most other regions. At the same time, some countries, like Albania, the Netherlands and Latvia, appear relatively vulnerable. Furthermore, many European countries may face indirect impacts of climate change, such as migration, interruptions of supply chains, and the like.

Europe is one of the largest emitters of greenhouse gas emissions in the world. That, together with the likely direct and indirect future impacts, make climate change a primal concern for European states. To mitigate and adapt to a warming world, innovation has a key role to play. Innovation efforts in the energy sector (both supply and end-use) are especially important, since the sector is responsible for most of anthropogenic greenhouse gas emissions and is expected to account for the lion's share of emissions reduction.

Considering its importance for combatting climate change, this report focuses primarily on energy research. We show that public funding of energy R&D work has increased significantly since the end of 1990s in the EU and the US. Within the Framework Programmes of the EU, climate change research has steadily expanded. This increasing focus on climate change R&D is also reflected in the fact that all OECD countries have research strategies in place. As for the investment priorities, nuclear energy R&D has declined over the last decades, while research in renewables and energy efficiency has gone up. This led to a rise in the number of research articles and patent applications. Some European countries have been quite successful in climate-change mitigation technology innovation. Investments tend to be concentrated in a select group of countries: Germany, Denmark and Spain for wind; France, Italy and Germany for photovoltaic; and Spain, Italy and Germany for concentrated solar power.

Though funding has increased in recent years, current research efforts are widely insufficient to bring down temperature increases to a more sustainable degree. Despite an increase in the last decade, public funding of energy technology R&D is still below the level achieved in early 1980s, especially in Europe. Governments allocate a much smaller proportion of public R&D expenditure to energy technologies than 20 years ago. We suggest some research areas in climate change mitigation, adaptation and geoengineering where additional research funding seems most promising.

- Among ***mitigation*** options, advanced vehicles (hybrid, electric, fuel cell), carbon capture and storage, and energy efficiency have the largest gap between the greenhouse gas emissions reduction potential and research funding.
- ***Adaptation*** approaches are quite diverse and many of them are related to 'soft' issues — better planning and risk communication, improved functioning of institutions (e.g. insurance market), etc. There are large gaps and uncertainties in our understanding of the climate system and impacts of global warming. One important area where substantial progress is needed concerns our knowledge of possible thresholds or tipping points for climate change impacts. This knowledge is essential for better adaptation and for designing more efficient mitigation policies.
- Some ***geoengineering*** approaches such as stratospheric aerosol and cloud brightening promise rapid cooling effects at much smaller costs

than conventional approaches. Potential pay-offs could be very large, but risks remain unclear. Furthemore, geoengineerding could serve as a 'back-up plan' if all else fails. Thus, there is a strong need to undertake serious research on these and other promising geoengineering methods. This research should focus on their feasibility, effectiveness, cost, environmental impacts and potential unintended consequences.

Climate change is a global problem with little regard for country borders. Only a balanced mix of internationally coordinated and intensive R&D efforts that include research on mitigation, adaptation and geoengineering can help abate the challenge of climate change.

INTRODUCTION

Climate change is probably the largest environmental challenge facing humankind. If it continues unabated it might cause tremendous damages, lead to hundreds of thousands of excess deaths from floods, heat waves, malnutrition, vector borne diseases and trigger extinction of many species. Risks of climate change can easily become even more disastrous if some (still uncertain) tipping points in the climate system are crossed. With the rapid rise of new powers like China and India, and continuing high-energy consumption of developed countries, the prospects look bleek indeed. Successfully addressing the climate change challenge requires a new industrial revolution, in particular a comprehensive overhaul of today's energy system. Productive and sustained technological innovation is the key to make this revolution happen and to meet climate change policy targets.

This report first describes the main expected impacts of climate change and presents a country level index of vulnerability to climate change. Then it provides a broad overview of research and development (R&D) efforts related to climate change with the main focus on EU countries. Finally it outlines some gaps in today's climate change research and highlights some research areas where additional investment is needed.

1 THE CHALLENGE OF CLIMATE CHANGE

1.1 CLIMATE CHANGE AS THE DOWNSIDE OF ECONOMIC GROWTH

Modern civilization would be impossible without abundant energy supplies. Energy has been essential for expanding human mobility, making our lives more comfortable, and providing ubiquitous IT services. Driven by rising living standards and population growth, global energy consumption has increased by a factor of 25 in the past 200 years and more than tripled since 1965.[1] Currently, some 85% of global total energy is supplied by fossil fuels.[2]

Extracting, processing, and burning fossil fuels, however, creates numerous by-products, which often have negative effects on people's health and environmental systems. These by-products include greenhouse gases (GHG), such as carbon dioxide (CO_2), methane (CH_4) and other gases that trap the heat that radiates back of the Earth. Greenhouse gases are essential for our survival — without them the average surface temperature of the Earth would drop from 14°C to approximately -19°C.[3] At the same time, rising consumption of fossil fuels has led to steadily increasing emissions of CO_2 which alter our eco-systems and may treaten our very existence in the long run.

1 BP, Statistical Review of World Energy, 2012.

2 Intergovernmental Panel on Climate Change (IPCC), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp., 2012, Figure TS.1.3.

3 Intergovernmental Panel on Climate Change (IPCC), Climate Change 2007: Synthesis Report Core Writing Team, Pachauri, R.K. and Reisinger, A. (Eds.), IPCC, Geneva, Switzerland, 2007.

Since the beginning of the industrial age, temperatures have increased by close to 1°C.[4] This long-term change in the temperature is referred to as 'climate change' (or global warming). On current emission trends, the average global temperature is likely to rise by 2-3°C within the next fifty years or so.[5] Because of large inertia in the Earth's climate system, global temperatures will continue to rise for many years even if anthropogenic GHG emissions suddenly drop to zero tomorrow.

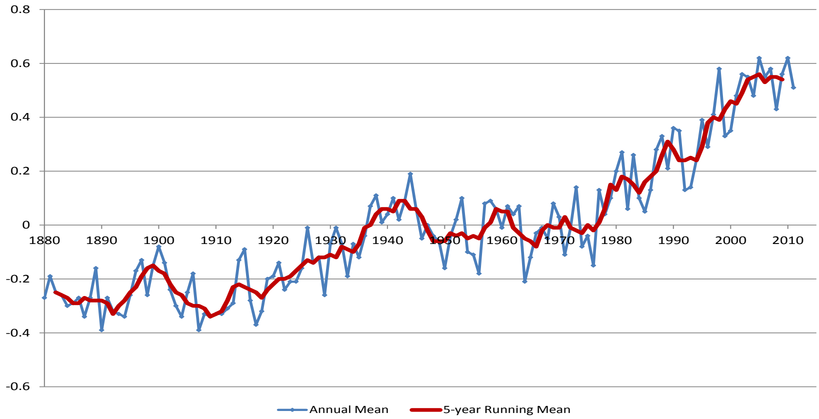


FIGURE 1. GLOBAL MEAN LAND-OCEAN TEMPERATURE INDEX (TEMPERATURE ANOMALY, °C (SOURCE: *NASA*)[6]

Global warming has been especially rapid after 1980 (see Figure 1). That this rise is caused by human activities is more and more established. As the Fourth Assessment Report by the International Panel on Climate Change (IPCC) concludes: that 'Most of the observed increase in global average

4 World Bank, World Development Report 2010: Development and Climate Change, World Bank, Washington DC, 2009.

5 Stern, N., The Economics of Climate Change: The Stern Review, Cambridge, UK: Cambridge University Press, 2007.

6 'GISS Surface Temperature Analysis', National Aeronautics and Space Administration, Goddard Institute for Space Studies, accessed December 3, 2012, *http://data.giss.nasa.gov/gistemp/graphs_v3/.*

temperature since the mid-20th century is very likely due to the observed increase in anthropogenic GHG (greenhouse gas) concentrations.'

High energy consumption is a typical feature of developed societies but it is also associated with high GHG emissions. As Figure 2 illustrates, there is a strong positive correlation between CO_2 emissions and the level of economic development. A higher GDP per capita typically means a higher level of CO_2 emissions per capita, although there is substantial variability in the volume of emissions between countries with roughly the same national income per capita.

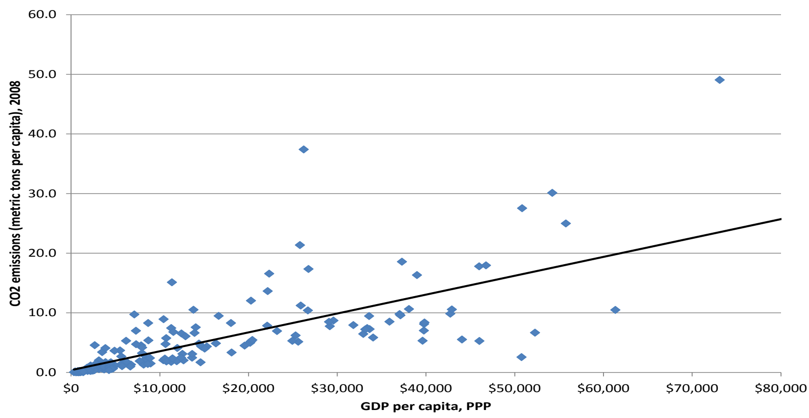


FIGURE 2. GDP PER CAPITA AND CO_2 EMISSIONS FOR COUNTRIES WORLDWIDE (SOURCE: WORLD DEVELOPMENT INDICATORS)

Overall energy supply and use account for approximately two thirds of all anthropogenic GHG emissions (see Figure 3). Other human activities that contribute to GHG emissions include agriculture, forestry and waste management (mainly from land use changes).

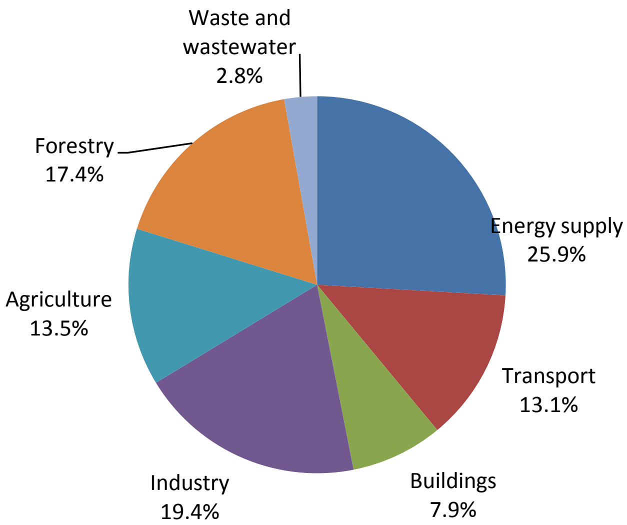


FIGURE 3. SHARE OF DIFFERENT SECTORS IN TOTAL ANTHROPOGENIC GHG EMISSIONS IN 2004 (SOURCE: IPCC AR4)

1.2 MAIN IMPACTS OF CLIMATE CHANGE

Rising temperatures will cause (and are already causing) numerous changes in the climate system. For example, since the water holding capacity of air increases exponentially with temperature, this will intensify the water cycle and will lead to more severe droughts in already dry areas and more intense floods and rains elsewhere.[7] Such changes in the climate system will have multiple and interdependent impacts for societies and ecological systems. Though our understanding of these changes and their impacts is sometimes limited, there is general consensus on some main impacts, which are discussed below.[8]

7 Intergovernmental Panel on Climate Change (IPCC), Climate Change 2007: Synthesis Report Core Writing Team, Pachauri, R.K. and Reisinger, A. (Eds.), IPCC, Geneva, Switzerland, 2007.

8 Stern, N., The Economics of Climate Change: The Stern Review, Cambridge, UK: Cambridge University Press, 2007.

FOOD

In temperate climates (mid to high altitudes), warmer temperatures and the carbon fertilization effect[9] are likely to improve yields of agricultural crops. However, the effect of even small increases in temperature in tropical regions is likely to be negative. If temperatures increase above 2-3°C, global agricultural yields will start to decline because of heat and water stress. This can put millions of people at the risk of hunger, since many tropical countries are quite poor and their population spends a large share of income on food.

HEALTH

Malnutrition will be only one of many effects of climate change on health. Extreme weather events including heat waves, wildfires and floods are expected to become more frequent and are likely to be associated with an increased mortality. For example, the 2003 heat wave in Europe is estimated to have caused more than 70,000 excess deaths.[10] Higher incidence of climate related vector-borne diseases such as diarrhea and malaria might lead to other adverse impacts on population health. The WHO concluded that even the modest warming that has occurred since the 1970s was already causing over 140,000 excess deaths annually by 2004.[11]

INFRASTRUCTURE

Climate change is likely to increase the intensity of storms. This will lead to significantly higher infrastructure damage costs from storms and the resulting floods. The melting of ice sheets due to the rising temperatures will also increase global sea levels. Sea level rise is a vivid example of the inertia in the climate system — it is expected to continue for centuries. It will amplify threats from storms, coastal flooding and erosion in coastal areas. Currently more than 200 million people live in coastal floodplains

9 Higher concentration of carbon dioxide in the atmosphere stimulates photosynthesis.

10 Robine, J-M., S. L. K. Cheung, S. Le Roy, H. Van Oyen, C. Griffiths, J-P. Michel, F. R. Herrmann, 'Death toll exceeded 70,000 in Europe during the summer of 2003'. Comptes Rendus Biologies 331 (2): 171–178., 2008.

11 WHO, Climate Change and Health, Fact sheet N°266, January 2010, http://www.who.int/mediacentre/factsheets/fs266/en/ -accessed September 5, 2012.

and many major cities are vulnerable to coastal flooding. Sea level rise might lead to a large-scale migration from these areas.

Thawing of permafrost in northern latitudes represents another threat. It will cause damages to infrastructure and buildings that were built on it. Canada and Russia are especially vulnerable in this respect.

ENVIRONMENT

Rapid increase in global temperature might exceed the resilience of many ecosystems and lead to loss of biodiversity, i.e. extinction of many plant and animal species (approximately 20-50% of species will face extinction with a 3°C temperature rise). Rising atmospheric CO_2 concentrations makes the ocean more acidic as it absorbs more CO_2. This acidification can, for instance, cause mass destruction of coral reefs.

TIPPING POINTS

There is a risk that at some level rising temperatures might cause abrupt and irreversible impacts. One example of such a 'tipping point' could be the release of vast volumes of methane as a result of the thawing of permafrost. Methane is a strong greenhouse gas and its additional emissions will speed up global warming. Another such risk is the shutdown of the Atlantic thermohaline circulation that brings warm waters to Northern Europe. Temperatures there might drop significantly as a result. Though there is much uncertainty about triggers for such abrupt changes, their potential impacts are significant and will grow with further warming.

1.3 MAPPING CLIMATE CHANGE VULNERABILITY

In order to demonstrate country-level vulnerability to climate change we constructed an aggregate vulnerability index using three indicators.[12] These indicators reflect the main expected impacts of climate change:

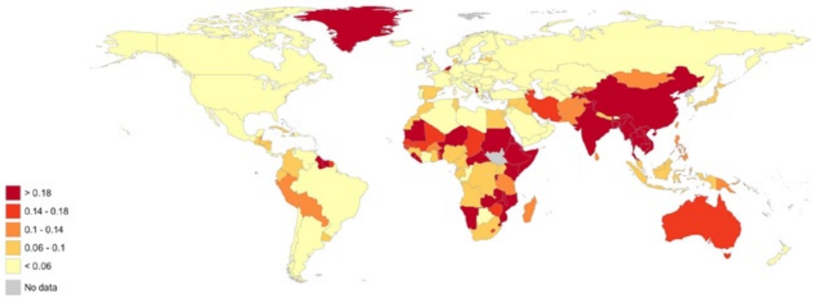
- increase in weather-related disasters,
- sea-level rise, and
- loss of agricultural productivity.

12 D. Wheeler, Quantifying Vulnerability to Climate Change: Implications for Adaptation Assistance, Working paper 240, 2011 http://www.cgdev.org/files/1424759_file_Wheeler_Quantifying_Vulnerability_FINAL.pdf -accessed September 5, 2012.

The aggregate index is calculated as a simple average of three individual indicators normalized at a scale from 0 to 1. The results for individual indicators and the aggregate index are shown using an Internet-based visualization software.[13] A detailed methodology for constructing the index and data sources is described in the Appendix 1.

The index provides information on the relative vulnerability of countries to the major climate change impacts and not on the magnitude of absolute impacts. Obviously it presents only a simplified picture of vulnerability that omits many nuances.[14] Nevertheless, it is a useful tool for a quick assessment and comparison of country vulnerabilities to climate change.

The aggregate index shows that the EU on the whole is not among the most vulnerable regions of the world (see Map 1). The most affected countries are in Africa and Asia (higher index values mean higher vulnerability). Crop yields in many of these countries are expected to decline significantly, and in many cases they are already suffering from weather-related disasters. Some additional risks related to climate change, which are not included in the index, such as spread of infectious diseases, might increase their vulnerability even further.

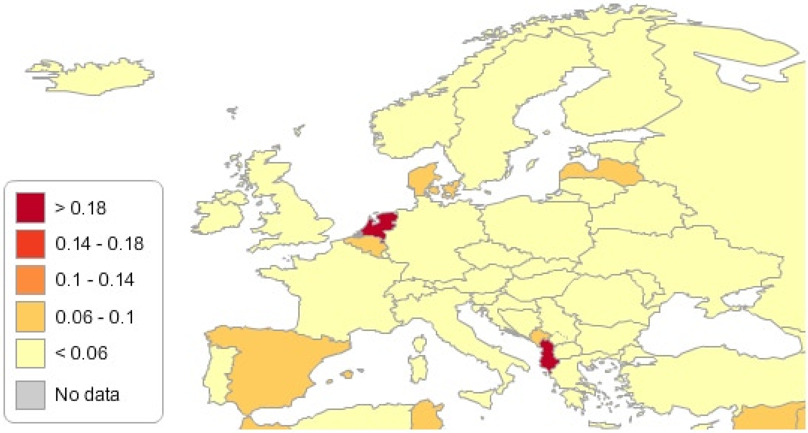


MAP 1. CLIMATE CHANGE VULNERABILITY INDEX, WORLDWIDE *(SOURCE: HCSS)*

13 Available at http://projects.hcss.nl/monitor/.

14 For example, country level aggregation by necessity averages local effects of climate change that might vary significantly in the same country. Since the index includes only three indicators it also omits many other potential impacts of climate change.

In Europe, (see Map 2) the loss in crop productivity is expected to be relatively small and in northern countries climate change might even increase yields. The high level of economic development in Europe helps to mitigate some other risk factors as well. Impact of weather-related disasters is, for instance, constrained by well-developed infrastructure and preparedness measures. Relatively high vulnerability scores in some European countries such as the Netherlands, Latvia, Denmark and Belgium result from the fact that a substantial part of their population lives in areas that are less than 5 meters above sea level. This makes them vulnerable to sea level rise and might require significant investment in related infrastructure. In Albania and in some other middle income countries in the south-eastern part of Europe, the relatively high share of population affected by weather-related disasters also contributed to increased aggregate scores.



MAP 2. CLIMATE CHANGE VULNERABILITY INDEX, EUROPE *(SOURCE: HCSS)*

1.4 CONCLUDING REMARK

This chapter provided a general overview of the likely impacts of climate change. Overall, Europe scores low on vulnerability to global warming. However, some countries such as Albania, the Netherlands, Latvia and few others have elevated vulnerability scores typically because a substantial part of their population lives in low lying areas. Heavy impacts of climate change elsewhere may also indirectly affect Europe through migration, interruption of supply chain, and the like.

Climate change is a global phenomenon, of which all countries in Europe will feel the effects. Furthermore, its energy-intensive economy is at the root of global warming, fuelling high greenhouse gas emissions. In subsequent chapters, we will look at research that can help in mitigating and adapting to the process of climate change.

2 ONGOING RESEARCH

Research and development is essential for tackling challenges of climate change. This chapter provides a broad overview of ongoing research related to climate change. Since production and consumption of energy contribute most to GHG emissions, we will pay special attention to these areas. However, before going into the details of the various research efforts, it is useful to describe generic options for responding to the climate change challenge. These options provide a framework for classifying different research themes related to climate change.

2.1 TECHNOLOGY OPTIONS FOR RESPONDING TO CLIMATE CHANGE

There are several ways in which technologies can address global warming. Responding to climate change has generally led to research in two broad directions:

1) **Mitigation**: actions aimed at limiting the future extent of climate change primarily by reducing GHG emissions.
2) **Adaptation**: actions focused on reducing vulnerability to global warming and its adverse impacts.

Another option is **geoengineering**, which is defined as 'the deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change.'[15] Geoengineering can be logically viewed as a sub-set of mitigation approaches, but given its specific focus on deliberate manipulation of the climate system it is quite controversial and should be considered separately.

15 Royal Society 'Geoengineering the Climate: Science, Governance and Uncertainty,' September, 2009, p.1.

Both adaptation and mitigation are necessary to deal with climate change. Currently, the main thrust in climate change R&D and innovation efforts concerns mitigation options. The main reason is that adaptation, by definition, does not address the root cause of the climate change problem. There are limits to adaption since many impacts of climate change will become stronger and stronger with increasing temperatures. Thus, it is essential to limit the extent of adverse impacts and to make adaptation more affordable.

Another reason is that many adaptation options rely less on government policies and more on decentralised decisions by individuals and firms reacting to a warmer climate. However, adaptation has been gaining more attention recently because of continued rise in GHG emissions[16] and difficulties encountered in international negotiations on replacing the Kyoto protocol with a new legally binding agreement on limiting GHG emissions.[17] In the rest of this paragraph we look at the three technology options in turn.

MITIGATION

Mitigation options aim to decrease emissions of anthropocentric GHG, first of all CO_2, since it accounts for the largest share of emissions and has a long atmospheric lifetime.

To structure thinking about mitigation options it is helpful to use the Kaya identity, which decomposes total emissions of carbon dioxide (or any greenhouse gas) into four factors:[18]

$$CO_2 \text{ emissions} = \text{Population} \times (\text{GDP/population}) \times (\text{TPES/GDP}) \times (CO_2 / \text{TPES})$$

The first two factors in the Kaya identity (population and GDP per capita) are typically outside the realm of climate change policies. It leaves two main avenues to decrease emissions:

16 Global CO_2 emissions increased by 8% between 2009 and 2011 (BP Statistical Review of World Energy 2012).

17 The Economist, 'Adapting to climate change: Facing the consequences,' November 25th, 2010.

18 The Kaya identity was developed by Japanese energy economist Yoichi Kaya, see http://en.wikipedia.org/wiki/Kaya_identity (accessed August 21st, 2012).

- By improving *energy efficiency,* i.e. consuming less primary energy (total primary energy supply –TPES) per unit of economic output (GDP);
- By decreasing *carbon intensity* (decreasing CO_2/TPES), i.e. emitting less CO_2 per unit of energy consumed.

Energy efficiency options can be found in every sector of the economy both on the energy demand and supply sides – from agriculture, to buildings and power generation. Technologies involved are often sector specific but there are many common approaches as well.

Reduction in *carbon intensity* involves the following main options:
- substitution of existing fossil fuels with less carbon intensive ones, for instance, replacing coal or petrol with natural gas;
- use of non-fossil energy sources such as nuclear and renewables including hydro, wind, solar, etc;
- CO_2 capture and storage, i.e. capture of CO_2 from large stationary sources, such as power plants, its transportation and sequestration in geologic formations or in the deep ocean.

The **transportation sector** presents some specific challenges for GHG mitigation. Vehicles' space and weight constraints substantially limit the choice of available technologies for CO_2 emission reduction, in particular they exclude carbon capture and storage as a realistic option. This leaves better energy (or fuel) efficiency and switching to less carbon intensive fuels or to carbon-free energy carriers,[19] such as hydrogen and electricity, as the primary options. However, in the transportation sector it is especially important to consider GHG emissions not just at the point of consumption but also over the whole 'well-to-wheel' cycle. Life cycle analysis or assessment (LCA) helps to assess emissions associated with all the stages of a vehicle and fuel's production, use and disposal. LCA shows, for example, that in some cases total life cycle GHG emissions for biomass fuels are higher than for gasoline.[20]

19 These are energy carriers that do not produce emissions when consumed. However, their production might involve substantial GHG emissions.

20 Knittel, R., 'Reducing Petroleum Consumption from Transportation,' Journal of Economic Perspectives, Vol. 26 (1), Winter 2012, pp. 93–118.

The **power sector** is critical to any GHG mitigation effort. In order to limit the average global temperature rise by 2°C above pre-industrial levels the power sector should be essentially decarbonised by 2050 and therefore is likely to see very substantial changes. In this regard, technologies related to electricity transmission, distribution and storage should play an important role. While these technologies do not always affect GHG emissions directly (although decreasing transmission losses could improve energy efficiency and be a substantial source of energy savings), they might be critical for integration of emission-free but intermittent renewable energy sources. They are also likely to provide additional benefits that are not directly related to climate change mitigation.

The importance of reducing GHG emissions in the power sector is also highlighted in the EU roadmap to a low carbon economy in 2050, which was adopted in 2011.[21] It suggests that the largest reduction in GHG emissions should take place in the power sector and in the residential and commercial sectors (see Table 1). The smallest percentage decrease is expected in agriculture, where emissions in 2050 should decline by 42-49% compared to 1990 or to 27-36% compared to 2005.

GHG REDUCTIONS COMPARED TO 1990	2005	2030	2050
TOTAL	**-7%**	**-40 to -44%**	**-79 to -82%**
SECTORS			
Power (CO_2)	-7%	-54 to 68%	-93 to -99%
Industry (CO_2)	-20%	-34 to -40%	-83 to -87%
Transport (incl. CO_2 aviation, excl. maritime)	+30%	+20 to -9%	-54 to -67%
Residential and services (CO_2)	-12%	-37 to -53%	-88 to -91%
Agriculture (non-CO_2)	-20%	-36 to -37%	-42 to -49%
Other non-CO_2 emissions	-30%	-72 to -73%	-70 to -78%

TABLE 1. SECTORAL GHG EMISSIONS REDUCTION TARGETS IN THE EU *(SOURCE: EUROPEAN COMMISSION[22])*

21 European Commission, A Roadmap for moving to a competitive low carbon economy in 2050, Brussels, 8.3.2011 COM(2011) 112 final.

22 Ibid.

It should be noted that climate change mitigation efforts often bring other environmental benefits as well because burning fossil fuels do not only release CO_2 but also a range of other pollutants such as sulphur dioxide (SO_2), various oxides of nitrogen (NO_x), mercury, volatile organic compounds and others.[23] These pollutants cause severe health problems by affecting the body's respiratory and cardiovascular systems and cause environmental degradation. Unlike for GHG emissions, which have global effects, impacts of these pollutants are either local or regional. This creates more incentives for individual countries to take actions on their own.

ADAPTATION

Adaptation actions focus on anticipating and minimizing potential impacts of climate change. Research aimed at a better understanding of the functioning of the climate system and future impacts of global warming can provide essential information for various aspects of adaptation. This is especially important for planning, in particular for long-term infrastructure planning (e.g. buildings and transport infrastructure). It might be much less costly to design and build infrastructure taking into account the expected future impacts of climate change now rather than to retrofit (or replace) it at some later stage. Therefore, replacement or revitalisation of infrastructure that is approaching the end of its lifetime presents a very important opportunity to prepare for a changing climate.

Adaptation involves a diverse and broad range of technologies that are often quite specific to a particular sector. These technologies can be classified according to the areas of climate change impact.[24] The list below provides examples of specific technologies within each area:

- **Coastal zones:** protection structures (dykes, sea walls, dunes), early warning systems, new building codes and desalination systems.
- **Water resources:** leakage reduction, non-water based sanitation and rainwater storage.

23 'Environmental impacts of coal power: air pollution', Union of Concerned Scientists, accessed December 3, 2012, http://www.ucsusa.org/clean_energy/coalvswind/c02c.html.

24 UNFCC, Technologies for Adaptation to Climate Change, UNFCC, Bonn, Germany, 2006.

- **Agriculture:** improved irrigation techniques, the cultivation of heat and drought-tolerant crops and crops with a shorter growing cycle ('drought-escaping').
- **Public health:** vector control and vaccinations.
- **Infrastructure:** the development of catalytic converters in transport.

GEOENGINEERING

Geoengineering includes several different approaches with varying degrees of feasibility, costs and risks. Broadly, geoengineering methods can be divided into two large categories:

- **Carbon Dioxide Removal (CDR):** methods to remove CO_2 from the atmosphere. They aim to do so either by enhancing uptake and storage by biological systems (terrestrial or oceanic) or by using engineered systems. Approaches under this category include use of biomass with carbon sequestration, enhancement of oceanic uptake of CO_2, direct engineered capture of CO_2 from ambient air and some other techniques.
- **Solar Radiation Management (SRM)**: methods to reduce solar radiation received, by deflecting sunlight, or by increasing the reflectivity (albedo) of the atmosphere, clouds or the Earth's surface. Techniques proposed in this category include such options as human settlement albedo (e.g. painting roofs white), grassland, crop, desert and cloud albedo, space-based reflectors and stratospheric aerosols (i.e. injection of aerosol particles).

Both approaches have advantages and disadvantages. CDR methods address the root cause of climate change but take effect slowly, only over several or many decades. SRM methods can have a quick effect and provide the only option for reducing global temperatures over the short term. However, they do not significantly affect the concentration of GHG in the atmosphere and their effect is temporary. In addition, they only reduce some, but not all, effects of climate change, and might possibly create other problems. This is why CDR methods are typically less controversial and some of them can be considered alongside conventional mitigation approaches. Yet, the main advantage of some SRM methods (more specifically of stratospheric aerosols and cloud brightening) is that their costs are expected to be around a 1000 times less than for conventional mitigation approaches.[25]

The UK Royal Society found in its recent report that 'geoengineering is likely to be technically feasible, and could substantially reduce the cost and risk of climate change.'[26] It can be seen as a complementary measure to emission reductions. SRM methods, in addition, provide a 'back-up option' that can be used in case of a sudden acceleration in global warming. It should be kept in mind though that general statements regarding geoengineering are often quite misleading, given the very wide range of methods that fall under this term.

2.2 R&D EXPENDITURE

In this section, we will provide an overview of current research efforts aimed at mitigating and adapting to the challenge of climate change. As it is the case with other societal challenges, it is not easy to estimate total R&D expenditures related to climate change. Since this challenge is so broad, R&D investments related to climate change can be found in a very broad range of sectors — from energy supply to water management and agriculture. Furthermore, data on private investment R&D is generally hard to come by. All these and some other factors limit our ability to see an overall picture of climate change research landscape.

In this report we focus mainly on energy related R&D activities both in the energy supply sector and end-use sectors. As mentioned previously, energy accounts for about two-thirds of anthropogenic GHG emissions and an even larger share in expected emission cuts. Therefore, innovation in the energy sector is crucial for addressing climate change. Most energy R&D is

25 Royal Society 'Geoengineering the Climate: Science, Governance and Uncertainty,' September, 2009.

26 Ibid, p.57.

now directly related to climate change[27] and expenditure on energy R&D is the largest piece of all climate change related R&D expenditures. Information on these expenditures is also more consistent than for other types of R&D spending, at least for most of OECD countries, and goes back to the 1970s.

WORLDWIDE OVERVIEW

IEA data[28] (see Figure 4) show that after a surge in the second half of the 1970s and early 1980s public investment in energy R&D was steadily declining until early 2000s, with Japan being an exception in this respect.[29] The surge in 1970s followed the 1973 OPEC oil embargo and the associated jump in crude oil prices. Most R&D budgets were directed towards nuclear energy. However, this surge along with other policy measures and high energy prices brought substantial reductions in energy intensity.

27 In some instances, it might be difficult to judge whether a particular area of research is climate change related or not. For example, research that helps to increase production of natural gas or to improve efficiency of coal power plants might not be considered as associated with climate change mitigation. In the end, the answer depends whether these power supply options help to reduce emissions but it is almost impossible to decide without knowledge a specific country context.

28 The IEA has 28 member countries. Only the OECD member states can become members of the IEA. All OECD member states are members of the IEA except Chile, Estonia, Iceland, Israel, Mexico, and Slovenia. IEA Europe data omits data some recent EU member states but nevertheless it accounts for almost 99% of the overall EU-27 energy budget.

29 The large jump in R&D expenditure in the US in 2009 is due to the government stimulus package in that year.

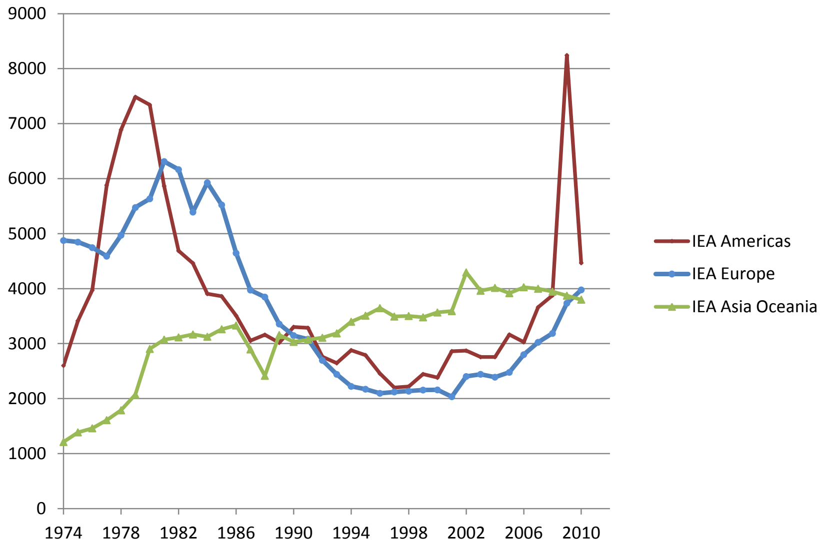


FIGURE 4. TOTAL PUBLIC ENERGY R&D EXPENDITURE, MILLION EURO,2010 PRICES AND EXCHANGE RATES *(SOURCE: IEA DATABASE)*

Public R&D budgets in the energy field started to decline in the early 1980s and fell until around 2000. Diminishing interest in nuclear power was one of the reasons for this downward trend. Although there has been a steady growth since the beginning of the new century, public R&D expenditure in Europe still remains significantly below its level in early 1980s. If one excludes a temporary jump associated with the US government stimulus package in 2009, this is also true for the total expenditure by all the IEA members. The share of energy in total research expenditure declined from 12% in 1981 to about 4% in 2008. It is interesting to note that the general trend in public energy R&D was closely following the trend in crude oil prices (see Figure 5). This should not be totally surprising given the fact that high oil prices provide substantial incentives for the development of alternative sources of energy, including renewable energy, and energy efficiency, as well as increase pressure on politicians to support them (such incentives decline when oil prices are low).

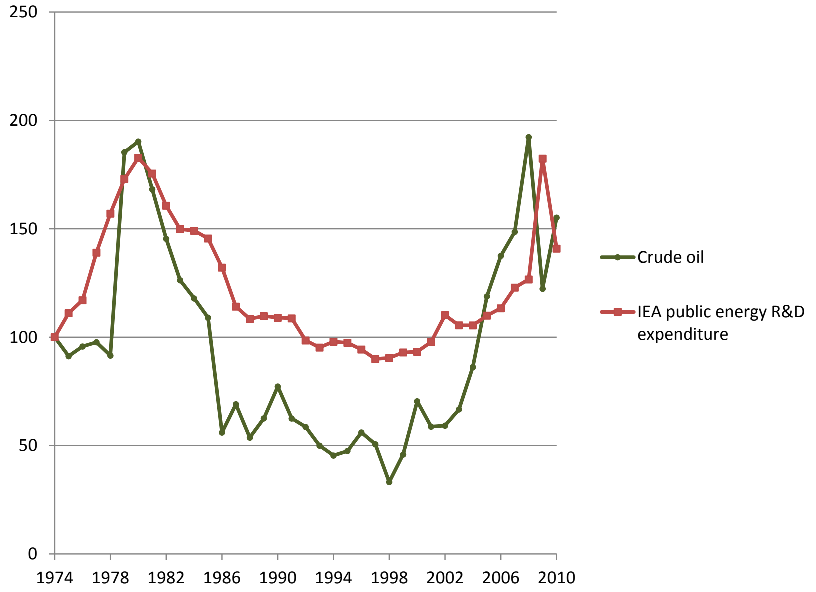


FIGURE 5. TOTAL PUBLIC ENERGY R&D IN IEA COUNTRIES AND CRUDE OIL PRICE, 1974 =100 *(SOURCE: IEA DATABASE AND BP STATISTICAL REVIEW OF WORLD ENERGY)*

Allocation of funding between different areas of energy R&D is also instructive (see Figure 6). Europe and the US closely follow each other not only in total spending on energy research but also in allocation between different areas of R&D. As could have been expected, the US spends proportionally more than Europe on fossil fuel (15.2% for the US compared to 10.5% for Europe) – it is the largest producer of natural gas, second largest of coal and the third largest of crude oil. Perhaps more surprising is that Europe allocates proportionally more resources to nuclear power R&D than the US (24.9% vs. 20.1%). One may have expected a different outcome given the fact that there has recently been more interest in new nuclear power in the US than in the EU.[30] Other than that, the patterns in the

30 Government spending on nuclear fusion in Europe in particular on the international ITER demonstration project in France might explain some of the difference.

allocation of funding in Europe and the US are quite similar. In Asia, nuclear power accounts for a much larger share of all energy R&D expenditure compared to either the US or Europe.

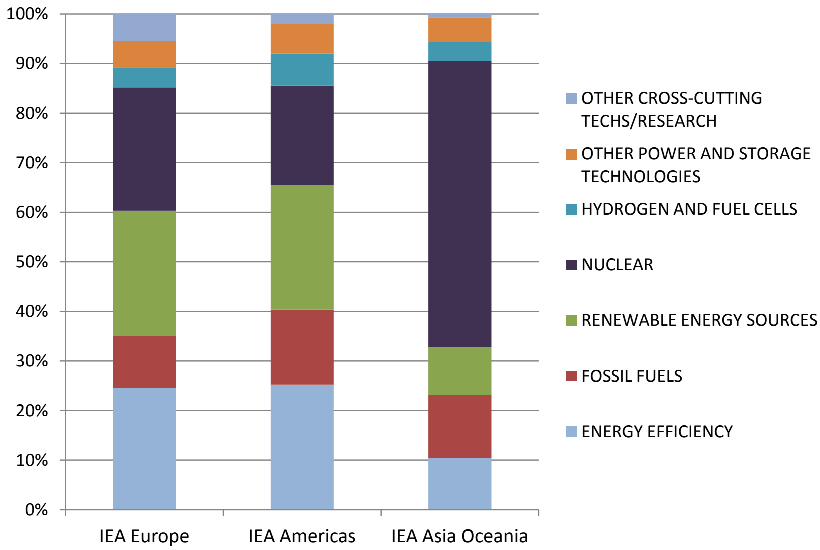


FIGURE 6. TOTAL PUBLIC ENERGY R&D IN 2010 BY THE FIELD *(SOURCE: IEA DATABASE)*

EU RESEARCH

The European Union (EU) has made a strong commitment to climate change mitigation efforts. It adopted a climate and energy policy in 2007, stating as its goals for 2020 the reduction of EU GHG emissions to at least 20% below the level of 1990, the decrease of energy consumption by 20% compared with projected levels by improving energy efficiency, and a minimum share of 20% of renewable energy in the overall energy consumption.[31]

31 European Commission, An Energy Policy for Europe, COM (2007)1 final.

Public funding of energy R&D in the EU in the first decade of 21st century increased significantly, not only in absolute terms but also as a share of total government outlays on R&D (see Figure 7). At the same time, as figure 7 shows, the share of environmental R&D, which also includes climate change related research, remained stable and even declined slightly in 2010 compared to 2000.

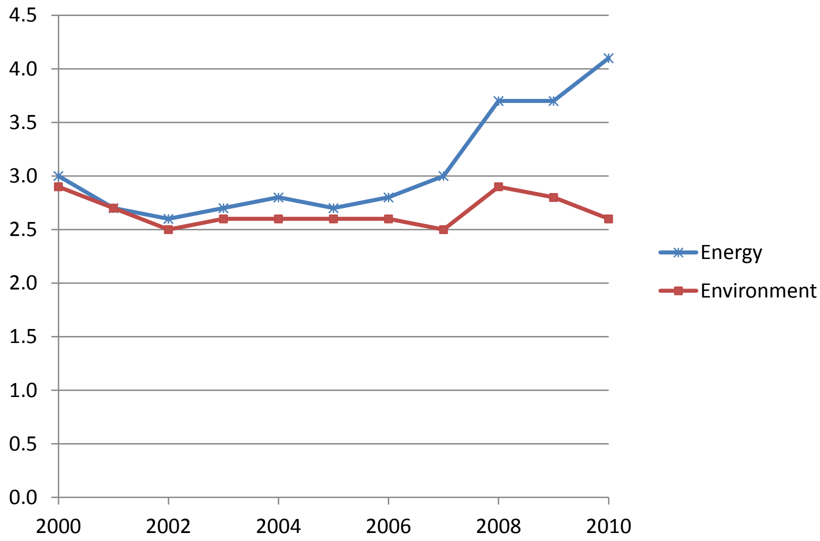


FIGURE 7. EU-27 PUBLIC EXPENDITURE ON ENERGY AND ENVIRONMENT AS % OF TOTAL GBAORD[32] *(SOUCE: EUROSTAT)*

The share of nuclear power has been steadily falling since 1974, when IEA data starts. It accounted for 81% of government energy research expenditure in 1974 and only 25% in 2010 (see Figure 8). The share of energy efficiency started to grow rapidly around 2004 and has more than doubled since then. Expenditure on renewable energy sources has been growing more gradually. By 2010 it accounted for about one quarter of all public energy research expenditure, a proportion similar to nuclear energy and energy efficiency.

32 GBAORD - Government budget appropriations or outlays on R&D.

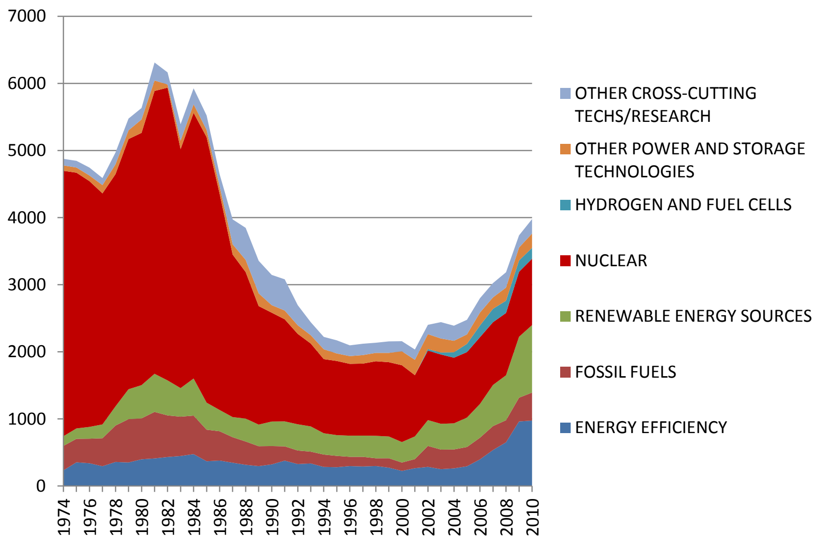


FIGURE 8. TOTAL PUBLIC ENERGY R&D IN IEA EUROPE[33], MILLION EURO (2010 PRICES AND EXCHANGE RATES) *(SOURCE: IEA DATABASE)*

On the EU level the main funding source for climate change related research have been the successive **Framework Programmes** (FP) for research and technological development. Climate change has been one of main topics of research within the latest FPs. The current *FP7* began in 2007 and will continue until 2013, when it will be replaced by the new Horizon 2020 program for 2014-2020. FP7's budget includes two lines in the sub-programme 'Cooperation' that are directly related to the climate change challenge:

- Energy — €2,350 million (or 7% of total for 'Cooperation' sub-programme)
- Environment (including Climate Change) — €1,890 million (or 6% of total)

33 European members of the IEA includes 19 members states of the EU plus Norway, Switzerland and Turkey.

Although the funding for these two themes is significantly less than for some other research areas, it is higher than the share of energy R&D in overall public research expenditure (for IEA countries). It should be noted that, since climate change is a very broad area, many relevant projects can be funded under other themes. For example, nuclear research and training activities by Euratom are funded separately and their budget (€2,751 million) exceeds the budget allocated either to the Energy or the Environment theme under the Cooperation sub-programme. The themes transport and agriculture are also included in quite a few projects directly related to climate change mitigation and adaptation.

The indicative breakdown of the *Horizon 2020* budget allocates €31,748 million to help address major societal challenges facing the EU.[34] Among six challenges listed in the budget three are directly related to climate change:

- Secure, clean and efficient energy €5,782 million (or 18% of funding allocated to societal challenges);
- Smart, green and integrated transport €6,802 million (22%);
- Climate action, resource efficiency and raw materials €3,160 million (10%).

Together these three areas account for almost half of the allocation for societal challenges. In addition, funding for another challenge, Food security and sustainable agriculture, is also going to include some projects related to climate change in particular on adaptation measures in agriculture. Euratom activities are also going to be funded separately although at a smaller scale than in the previous programme (€1,665 million).

34 'Breakdown of the Horizon 2020 Budget', European Commission, accessed December 3, 2012, http://ec.europa.eu/research/horizon2020/pdf/press/horizon_2020_budget_constant_2011.pdf.

A comprehensive overview of climate change related projects funded within the 6th and 7th Framework Programmes is provided in a report prepared by the European Commission in 2009.[35] Most of the projects listed in the report aim at improving our knowledge about various aspects of the climate system, including climate interactions with stratospheric ozone and atmospheric composition, and developing climate monitoring, modeling and prediction tools. Other projects investigate climate change impacts including, natural hazards and extreme events. A final group of projects focuses on climate change adaptation, mitigation and policies.

In most *EU countries* climate change is increasingly recognized as a major societal challenge. A recent OECD report highlights the shift towards environmental sustainability in the strategic priorities for research and innovation across OECD countries.[36] Climate change and environment was the only area that was listed as a science and technology priority theme by every country.[37] Practically all EU member states have published policy documents affirming climate change and resource efficiency as important goals for innovation policy. Compared to other societal challenges, climate change has received more attention in terms of policy declarations and specific policy initiatives.[38] Some national programs supporting R&D and innovation in the areas of climate change, clean energy and energy efficiency are listed in Appendix 2. These programs focus on a broad variety of themes: from fundamental research issues such as risks and impacts of climate change to schemes aimed at commercialization of green technologies or even to large scale technology demonstration projects.

PRIVATE SECTOR RESEARCH

In contrast to the situation with public research expenditure, data for the private sector is either missing or incomplete. There are some estimates for

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35 European Commission, 'European Research Framework Programme Research on Climate Change,' Brussels, 2009, accessed as of August 24, 2012, http://ec.europa.eu/research/environment/pdf/cop-15.pdf ().

36 OECD, OECD Science, Technology and Industry Outlook 2010, OECD, Paris, 2010.

37 Ibid, Table 2.2.

38 Karakasidou, A. and Cunningham, P.N., Innovation, climate change and a more resource efficient economy, Policy Brief No 4 (2010), European Trend Chart on Innovation Policy. Brussels: European Commission.

private research investment in selected sectors. Eurostat provides data on private research expenditure for economic sectors, for example, 'Electricity, gas and water'. However, it does not show a breakdown by technologies, which makes it impossible to separate climate related R&D expenditure from the rest.

To address this problem a study by the Joint Research Centre (JRC) focused on three specific technological areas and collected data from individual companies with additional information from companies' annual reports, EU-financed projects and official databases. It found that public and corporate R&D investment in three selected priority areas – wind, solar photovoltaic (PV) and concentrating solar power (CSP) in Europe totaled €1.23 billion in 2008 and increased by 40% over 2007.[39] Overall, the private sector accounted for 69% of all R&D investment (see Figure 9). In PV and CSP private R&D investment contributed 56% and 55% of the total respectively, while in more technologically mature field — wind energy — it contributed a significantly higher share of 84%.

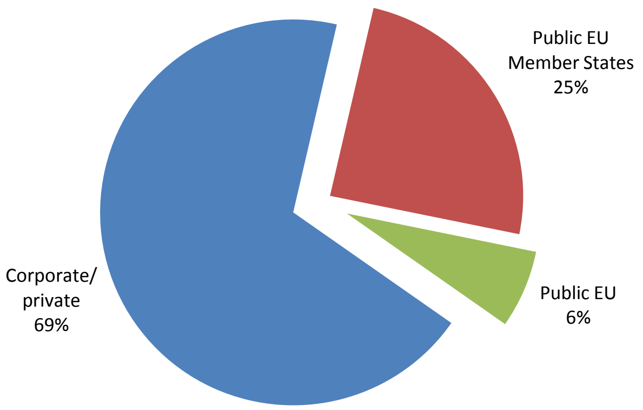

FIGURE 9. R&D INVESTMENT IN WIND, PV AND CSP, 2008 (SOURCE: GNAMUS, 2011)

39 Gnamus A., Capacities Map 2011: Update on the R&D Investment in Three Selected Priority Technologies within the European Strategic Energy Technology Plan: Wind, PV and CSP, European Comission Joint Research Centre, EUR 25024 EN, 2011.

The study also found that both public and private R&D investments were concentrated in a very few EU Member States: wind energy in Germany, Denmark and Spain; PV power in Germany, France and Italy; CSP in Italy, Spain and Germany. The countries with high public R&D investment tend to have the largest private R&D investment in same sectors, which suggests that public and private R&D investments are likely to complement each other. The EU companies had the leading position in the wind energy and CSP sectors where they accounted for 70% or more of global corporate R&D investment, while in the PV sector they contributed only 30%.

2.3 CENTERS OF EXCELLENCE IN THE FIELDS OF CLIMATE CHANGE AND ENERGY

To get an idea of the effectiveness of research investments and identify top-research countries and institutes, we look at two output measures. First, we use bibliometric data to assess what research institutes produce most (impactful) publications. Second, we look at patents filed for climate change mitigation technologies.[40]

BILBIOMETRIC ANALYSIS

A common result from various bibliometric studies is that there has been a rapid increase in the number of scientific publications in the field of climate change since approximately 1990.[41] The main research topics related to climate change include the impact of climate change on natural systems, tropical cyclones, and extinction risks. Word cluster analysis based on titles, keywords and abstracts of research articles also reveals that 'models', 'monitoring', and 'remote sensing' are the leading research methods in this field.[42]

40 The main approach to study research output is bibliometrics. It uses quantitative analysis to measure patterns of research publication and their scientific impact, typically focusing on journal papers. Bibliometrics provides quantitative, less subjective and compared to other methods more robust measures of research output, impact and quality. However, there are important caveats in interpreting results of bibliometric analysis as well. For example, different bibliometric databases have varying coverage of research journals, citation behavior varies between different research fields and attribution of publications to specific funders, authors & institutions is often very difficult.

41 Li,J., M.H. Wang, and Y.S. Ho 'Trends in research on global climate change: A Science Citation Index Expanded-based analysis,' Global and Planetary Change, Vol. 77, 2011, pp.13-20.

42 Ibid, pp.17-19.

To identify leading research organizations in climate change related areas we use results published by ScienceWatch, which relies on citation data from Thomson Scientific. The rankings of research organisations by the number of citations in climate change and energy fields are given in Table 2 and 3 correspondingly. Research in the former area typically focuses on better understanding of the processes in the climate system. The latter area represents the main focus of mitigation research and as such has a more applied character.

RANK	ORGANISATION	CITATIONS	PAPERS	IMPACT
1	National Center for Atmospheric Research, USA	11,341	362	31.33
2	National Aeronautics and Space Administration (NASA), USA	10,731	332	32.32
3	National Oceanic and Atmospheric Administration (NOAA), USA	10,609	420	25.26
4	Columbia University, USA	10,600	412	25.73
5	**Max Planck Society, Germany**	9,925	356	27.88
6	**Met Office, UK**	9,667	313	30.88
7	University of Colorado, US	9,078	414	21.93
8	**Oxford University, UK**	8,622	336	25.66
9	**University East Anglia, UK**	8,386	315	26.62
10	University of Washington, USA	8,153	351	23.23
11	University of Alaska, USA	8,098	347	23.34
12	US Geological Survey, USA	7,976	387	20.61
13	University of California Berkeley, USA	7,811	363	21.52
14	Penn State University, USA	6,981	253	27.59
15	University of California San Diego, USA	6,951	239	29.08
16	Stanford University, USA	6,907	230	30.03
17	Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia	6,665	368	18.11
18	University of California Santa Barbara, USA	6,417	209	30.70
19	University of Wisconsin, USA	6,271	310	20.23
20	Colorado State University, USA	5,946	268	22.19

TABLE 2. TOP RESEARCH ORGANIZATIONS IN CLIMATE CHANGE (RANKED BY THE NUMBER OF CITATIONS OVER 1999-2009, EUROPEAN ORGANIZATIONS IN BOLD, *SOURCE: SCIENCEWATCH*[43])

43 'Climate Change', ScienceWatch, November 2009, accessed October 18, 2012, http://sciencewatch.com/ana/st/climate/institution/.

RANK	ORGANISATION	CITATIONS
1	Sandia National Lab , USA	4,147
2	National Renewable Energy Lab, USA	3,773
3	**CSIC, Spain**	3,678
4	Chinese Academy of Sciences	3,541
5	Indian Institutes of Technology	3,166
6	Pennsylvania State University, USA	2,870
7	**Imperial College London, UK**	2,823
8	Princeton University, USA	2,744
9	University of Illinois, USA	2,647
10	Tohoku University, Japan	2,609
11	**CNRS, France**	2,598
12	AIST, Japan	2,482
13	Argonne National Lab, USA	2,438
14	Lawrence Berkeley National Lab, USA	2,331
15	**Technical University of Denmark**	2,278
16	MIT, USA	2,215
17	Russian Academy of Sciences	2,175
18	**Fraunhofer Institute Solar Energy Systems, Germany**	2,099
19	**University of Leeds, UK**	2,062
20	Stanford University, USA	1,990

TABLE 3. TOP RESEARCH ORGANIZATIONS IN ENERGY AND FUELS (RANKED BY THE NUMBER OF CITATIONS OVER 1998-2008, EUROPEAN ORGANIZATIONS IN BOLD; *SOURCE: SCIENCEWATCH*[44])

American organizations take the lead in both lists. Among top climate change research organizations only two, the Max Planck Society from Germany and CSIRO from Australia, are not from the US or UK. In the energy and fuel field the list has a more international representation and includes organizations not only from OECD countries such as Japan, Germany, Spain and Denmark but also from large emerging economies —

44 King, C., 'Energy Gauge: Who Exactly Is In Power?', ScienceWatch, November/December 2008, accessed October 18, 2012, *http://sciencewatch.com/ana/fea/08novdecFea/*.

China, India and Russia. Using relative research output indicators that can be compared directly for different countries suggests that some EU countries are doing quite well in energy and climate change research. Sweden, the Netherlands and the UK have published more energy research papers per capita than the US (for 1996-2007).[45] Further, a bibliometric study shows that Dutch and Swiss papers are cited more often than papers from the US.[46]

We also used Microsoft Academic Search to identify and verify the lists of the leading research organizations. Interestingly, there were substantial differences between the results compiled from the two sources. For climate change research, the two lists overlap significantly in terms of organizations, but their rankings are quite different. The differences are even more significant in the field of energy research. The ranking from the Microsoft Academic Search shows that Chinese organizations take 7 positions in the top-10,[47] whereas only one Chinese organization made it to the top-20 in the ScienceWatch ranking. One explanation for such divergent results is the differences in coverage of scientific publications between the databases as well as different definitions of the energy research. That said, while one can argue about the specific position of Chinese organizations in various rankings, it is clear that Chinese research output is rapidly increasing.

PATENT OUTCOMES IN GREEN TECHNOLOGIES

Research articles represent only one side of R&D output. Another measure of such an output is the number of patents. A patent provides its owner protection for a specific invention from unauthorized use for a limited period of time. Patent data is often used as a measure of technological innovation since only very few economically significant inventions are not patented.[48]

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45 Archambault, E., and G. Cote, *Bibliometric Analysis of Energy Research at the World Level and Benchmarkeing of CanmetEnergy,* February, 2009.

46 Ibid., p.16.

47 Microsoft Academic Search, accessed December 3, 2012, http://academic.research.microsoft.com/RankList?entitytype=7&topdomainid=8&subdomainid=7&last=10.

48 Hascic, I., N. Johnstone, F. Watsone and C. Kaminker, Climate Policy and Technological Innovation and Transfer: An Overview of Trends and Recent empirical Results, OECD Environment Working Paper No. 30, ENV/WKP(2010)16, 2010.

Several recent publications have looked at patenting activity in various climate change mitigation (or low carbon) technologies.[49] One common theme that emerges from these studies is that there was a significant increase in the patenting activities associated with climate change mitigation technologies (CCMT) since the second half of 1990s. This increase is likely to reflect changing market conditions, which are associated with the introduction of policy incentives for renewable energy in key markets such as feed-in tariffs, renewable energy targets, etc.[50] The increase was especially pronounced for technologies that were closest to being economically competitive — i.e. wind power, some solar power, biofuels, geothermal and hydro energy.[51]

Patent data reveal that the US, Japan and Germany are three leading innovation countries in climate change mitigation technologies. Smaller countries tend to specialize in different areas of CCMT. For instance, South Korea is strong in solar PV technologies, Denmark in wind power technologies, Norway in hydro/marine technologies, and Israel in geothermal technologies. Table 4 presents the top 5 countries in terms of patenting activity for nine CCMTs. The countries are ranked by the number of claimed priorities, i.e. inventions for which an application is filed at an additional office to that of the 'priority office'.

49 For example, Lee, B., I.Iliev and f. Preston, Who Owns Our Low Carbon Future? Intellectual Property and Energy Technologies. Chatham House Report, 2009.

50 Ibid.

51 Hascic, I., N. Johnstone, F. Watsone and C. Kaminker, Climate Policy and Technological Innovation and Transfer: An Overview of Trends and Recent empirical Results, OECD Environment Working Paper No. 30, ENV/WKP(2010)16, 2010.

TECHNOLOGY \ COUNTRY	SOLAR PV	WIND	HYDRO/ MARINE	SOLAR THERMAL	BIOFUELS	CO2 CAPTURE	GEO-THERMAL	IGCC	CO2 STORAGE	TOTAL SELECTED CCMT
Japan	1	3	3	3	3	2	3	2	3	1
USA	2	2	1	2	1	1	1	1	1	2
Germany	3	1	2	1	2	3	2	3	4	3
South Korea	4									4
France	5		5	4	4	4			2	5
UK			4		5	5		4		6
Italy				5						7
Netherlands										8
Canada							5		5	9
Denmark		4								12
Spain		5								13
Finland								5		19
Israel							4			20

TABLE 4. RANK OF TOP INVENTOR COUNTRIES, BY CCMT CLASS, 1988-2007 *(SOURCE: HASCIC ET AL, 2010)*

NOTES: CCMT – CLIMATE CHANGE MITIGATION TECHNOLOGIES; DATA BASED ON CLAIMED PRIORITIES, I.E. PATENTS FOR WHICH AN APPLICATION IS FILED AT AN ADDITIONAL OFFICE TO THAT OF 'PRIORITY OFFICE'

Overall, European organizations and individuals have been quite active inventors in the energy field. Germany was the top country globally by the number of claimed priorities in fossil and nuclear energy over the period 1988-2007. In the area of climate change mitigation technologies Denmark and Germany rank second and third after Japan by the number of claimed priorities per capita.

2.4 CONCLUSION

This chapter provided a general overview of climate change research. Climate change actions, including research and development, can be grouped into two broad categories:

1) Mitigation, i.e. limiting the future extent of climate, and
2) Adaptation, i.e. reducing vulnerability to the impacts of climate change.

Another option is geoengineering, which is aimed at the deliberate manipulation of the climate system.

The main focus of the mitigation efforts is in the area of energy production and consumption, i.e. the energy system in a broad sense. This sector is responsible for most of anthropogenic GHG emissions and likely to account for the largest reductions in emissions. Public expenditure on energy related R&D increased significantly in the last decade, but it is still below the levels achieved in the early 1980s. Both at EU-level and within member states, climate change became a major priority for R&D funding. Within the Framework Programmes, climate change research has been steadily receiving larger shares of funding. Currently all OECD countries have climate change research strategies in place. As for allocation of resources, nuclear energy R&D expenditure has declined over the last decades in absolute and relative terms, while research in renewable and energy efficiency has gone up.

Although the private sector data on R&D expenditure is much more limited than for the public sector, existing information shows that company R&D expenditure related to climate change has also increased substantially in the last decade. The private sector R&D expenditures on CCMT tend to be concentrated in the same countries that have level of public R&D expenditure in the same field. This suggests that public and private R&D investment complement each other. Furthermore, investments are concentrated in a select group of countries: Germany, Denmark and Spain for wind: France, Italy and Germany for Photovoltaic: and Spain, Italy and Germany for concentrated solar power.

These trends have been reflected in output measures of innovation — the number of research articles and patents in the fields related to climate change grew rapidly in the first decade of 21st century. While US institutions top the rankings of research organisations, some European countries produced more articles and patents on per capita basis than the US.

3 FUTURE RESEARCH

Scientific and technological progress is essential for addressing the challenges of climate change. Reducing the cost of cutting GHG emissions and making it easier to adapt to climate change impacts can substantially ease the burden imposed by global warming. This chapter will look at some climate change related research areas that promise substantial benefits and might require additional public R&D investment. Our focus is more on 'hard' technology areas rather than 'soft' behavioural issues, although the latter are also of critical importance. Given the scope of this report we look only at a selected number of priority research areas.[52]

No single breakthrough or small set of technologies can provide 'the solution' for climate change. Given the scale of the problem, its multi-sector character, the ubiquity of its impacts and considerable technological and natural uncertainties, a very broad portfolio of technologies is required. Economic analysis shows that excluding some technologies from consideration increases expected costs of achieving climate change goals. Therefore public technology and innovation policy should use a portfolio approach and support a wide range of technologies, taking into account that failures in R&D are inevitable.[53]

52 A much broader review of R&D needs related to climate change can be found, for example, in the reports prepared by the IPCC or the US National Research Council.

53 Global Energy Assessment: Toward a Sustainable Future. Technical Summary, Cambridge University Press, 2012, http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/GEA-Summary-web.pdf.

3.1 MITIGATION

What are the most important considerations in devising future research agendas aimed at mitigation of climate change? Most studies agree that the current level of spending is not adequate in order to limit global warming by 2°C compared to the preindustrial level.[54] Here we suggest some areas that seem particularly promising from a cost-benefit point of view, based on two authoritative studies and an EU program that aims to stimulate research in low carbon technologies.

One point of departure for answering what mitigation options require further investments, is a recent *IEA report*. It provides an assessment of the gap between the current level and the required expenditure to achieve targets set under its 'BLUE Map scenario', which assumes that global energy-related CO_2 emissions are reduced by 50% in 2050 compared to 2005-2007 levels (see Table 5). It estimates the annual shortfall between the current level of public R&D expenditure and the required investment at USD 40 – 90 billion. Since half of this investment is expected to come from the private sector, the IEA reckons that public investments should increase by a factor of 2 to 5 to achieve climate change targets.

54 Limiting an increase of earth's temperature by 2°C is often assumed as a target for climate change effort.

	ANNUAL INVESTMENT IN RD&D NEEDED TO ACHIEVE THE IEA BLUE MAP SCENARIO OUTCOMES IN 2050	ANNUAL PUBLIC RD&D SPENDING	ESTIMATED ANNUAL RD&D SPENDING GAP
	(USD million)[1]	(USD million)[1]	(USD million)
Advanced vehicles (includes EVs, PHEVs + FCVs; energy efficiency in transport)	22,500 – 45,000	1,860	20,640 – 43,140
Bioenergy (biomass combustion and biofuels)	1,500 – 3,000	740	760 – 2,260
CCS (power generation, industry, fuel transformation)	9,000 – 18,000	540	8 460-17,460
Energy efficiency (industry)	5,000 – 10,000	530	4,470 – 9,470
Higher-efficiency coal (IGCC + USCSC)[2]	1,300 – 2,600	850	450 – 1,750
Nuclear fission	1,500 – 3,000	4,030	0[3]
Smart grids	5,600 - 11,200	530	5,070 – 10,670
Solar energy (PV + CSP + solar heating)	1,800 – 3,600	680	1,120 – 2,920
Wind energy	1,800 – 3,600	240	1,560 – 3,360
Total across technologies	***50,000 – 100,000***	***10,000***	***40,000 – 90,000***

TABLE 5. ESTIMATED GLOBAL GAPS IN PUBLIC LOW-CARBON ENERGY R&D (SOURCE: IEA 2010)

1 R&D investment needs derived using 10% to 20% of average deployment costs for the BLUE Map scenario and adjusted by a factor of 90% to reflect country coverage.

2 Integrated gasification combined cycle and ultra-supercritical steam cycle.

3 The gap for nuclear fission is assumed to be zero excluding any additional R&D for Gen IV technologies. Therefore the sum of the estimates for the gap by technology do not sum to the total.

The IEA found that the largest gap exists in the transport sector, more specifically in the area of advanced vehicles, such as electric vehicles, hydrogen/fuel cell vehicles, and vehicle efficiency measures. It estimates that R&D investment in the sector should increase 10 to 20 times of the current amount to achieve global climate targets. Another large gap — between 9 to 18 billion USD — was found in the area of carbon capture and storage. In part this gap is due to the large size of commercial-scale demonstration projects for carbon capture and storage.

A second study by researchers from the *International Institute of Applied System Analysis*[55] came to similar conclusions. They see energy efficiency as the single most important option for achieving significant reductions in GHG emissions. According to their report, energy efficiency could account for up to 50% of the overall reductions in emissions. However, public research expenditure on energy efficiency has typically been around 10% of overall public sector R&D budget in IEA countries. Conversely, as we already saw in chapter 2, nuclear energy received some 50% of the total public investment in energy technology R&D in the OECD countries over the last 30 years, but it accounts for less than 10% of the GHG emission reduction potential across all scenarios considered by researchers. This imbalance suggests that increasing research investment in energy efficiency might be effective in achieving additional reductions in GHG emissions.

Finally, priority areas for energy R&D have been identified by the EU as well. Its official *Strategic Energy Technology Plan* (SET Plan), which aims to increase, coordinate and focus EU support on key low-carbon energy technologies, selects several priority technologies. For each, the Plan outlines technology roadmaps as a basis for strategic planning and decision-making. These roadmaps provide a master plan of the efforts needed over the next 10 years in the EU based on the best available information.[56] The Plan lists five key technology areas and one initiative:

- electricity grids;
- wind, solar energy (photovoltaic and concentrating solar power);
- bioenergy;
- carbon capture and storage (CCS); and
- nuclear fission;
- a Smart Cities initiative, focused on energy efficiency in cities.

55 Grubler, A., and K. Riahi, 'Do governments have the right mix in their energy R&D portfolio?', *Carbon Management,* Vol. 1(1)pp. 79-87, 2010.

56 Strategic Energy Technologies Information System: Technology Roadmaps, accessed December 3, 2012, http://setis.ec.europa.eu/about-setis/technology-roadmap/technology-roadmaps.

Summing up, **energy efficiency**, **clean transport vehicles**, **CCS** and **renewable energy sources** are widely accepted to be the main areas for energy-related R&D in the next one or two decades. At the same time, the energy system is not the only source of anthropocentric GHG emissions (although it is the largest). The agricultural and fisheries sectors are responsible for a substantial share of emissions as well (see Figure 3). Thus, new technologies and management practices in these sectors are important for developing an effective climate change mitigation strategy. For example, the development of new fertilizers and their application technologies that more closely match crop demand, also called precision or smart farming, can reduce emissions of nitrous oxide, a greenhouse gas.[57] In the same vein, new rice technologies could help to reduce methane emissions. And finally, the opportunities for reducing GHG emissions through the absorption and storage of carbon in soil or plants are as yet under-researched. One proposal in this area involves use of biochar, charcoal from biomass burned in a low-oxygen environment.[58]

3.2 ADAPTATION

Even if drastic measures to reduce GHG emissions are enacted today, the average temperature of the earth's atmosphere would continue to rise for many years. This is due to the earlier noted inertia in the climate system and the fact that the existing energy infrastructure already commits (or locks in) a substantial volume of future GHG emissions. Thus adaptation measures are a necessity rather than a choice. In this section we highlight five important fields that would benefit from further adaptation research.

First, effective adaptation to climate change requires extensive **information about its potential impacts**. Yet there are large gaps and uncertainties in our understanding of the climate system and impacts of global warming.

57 National Research Council, Advancing the Science of Climate Change, National Academies Press, Washington DC, 2010, p.301-302.

58 Ibid., p.302.

For example:[59]

- Some Earth system processes – including the carbon cycle, cloud and aerosol processes and ice sheet dynamics – are not yet fully understood and could have potentially strong influence on future climate changes.
- There is a substantial variation in climate change impacts at the regional level, but climate models typically focus on global or continental-level changes.
- The impacts of climate change depend on the vulnerability and adaptive capacity of human and natural systems, but research on those issues have remained limited.

One important area where substantial research is needed concerns our knowledge of possible *thresholds or tipping points* for climate change impacts. Abrupt changes associated with tipping points are one of the greatest risks of climate change. Research in this area should lead to better understanding of the driving factors, likelihood and consequences of abrupt climate changes. This information is crucial for setting goals for climate change policies, determining their timing and illuminating the limits of adaptation.

Second, climate change is expected to increase the frequency and magnitude of extreme weather events such as hurricanes, droughts, heat waves, floods, etc. Improving our ability to **forecast** such **weather events** and to provide early warning would be important even in the absence of climate change, but it is absolutely crucial for enhancing adaptation and resilience to global warming.[60] The technical side of this effort includes better meteorological models, geographic information systems (GIS), and satellite and aerial monitoring.[61]

59 National Research Council, Adapting to the Impacts of Climate Change, National Academies Press, Washington DC, 2010.

60 OECD, *Economic Aspects of Adaptation to Climate Change. Costs, Benefits and Policy Instruments*, OECD, Paris, 2008.

61 IPCC, Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 2012.

Infrastructure and built environment is a third large area where more research is needed. Infrastructure investments are long-lived and have a substantial influence on the way the economic system is organized, which is especially evident in the areas of urban and transport infrastructure planning.[62] As a result, infrastructure decisions impact not only our capacity for adaptation but also opportunities for mitigation.[63] More than half of the global population is now living in urban areas and the share of urban population will continue to increase. Many cities are located in the coastal areas and might be very vulnerable to sea level rise. Vulnerability of cities to climate change is associated with many issues that are specific to urban areas, such air quality and urban land use. A better understand of some of them will require substantial new research efforts. For example, the physical science of sea level rise remains incomplete, limiting our ability to project its effects.

Adaptation strategies will require not only new approaches to urban infrastructure (e.g. new materials for transportation systems that will be resistant to higher temperatures and water submergence[64]) but also *enhanced decision-support and urban planning tools*. In particular, the identification of vulnerable infrastructure, new methods for adaptive policy making, system-wide asset and risk management are some of the areas that deserve considerable attention.

Fourth, adaptation depends on human actions, but scientific **knowledge of human behaviour** as a factor in climate change adaptation is currently very limited.[65] Behavioural barriers to effective adaptation might be the most serious. Perception of the risk of climate change is often determined by emotional factors, framing biases (i.e. mental filters) and heuristics rather than by expert analysis. Therefore, research on adaptation decision making,

62 World Bank, *Inclusive Green Growth: The Pathway to Sustainable Development*, 2012.

63 For example, more dense cities have lower transportation-related emissions on the per capita basis. But city density is very difficult to change, see Op. cit.

64 National Research Council, *Adapting to the Impacts of Climate Change*, National Academies Press, Washington DC, 2010.

65 Ibid., p.205.

behavioural barriers to adaptation and risk communication should be an important part of adaptation research agenda.

And finally, in agriculture, the **development of heat-, drought- and salt-resistant crops**, which will be better suited to the changing climate, also appears to be a promising area for research. Sometimes mitigation and adaptation are closely related; farming techniques that improve soil moisture retention often help to decrease net GHG emissions as well.[66]

3.3 GEOENGINEERING

Geoengineering methods are not a substitute for climate change mitigation or adaptation. Although general interest in geoengineering methods has increased markedly in recent years, there has been relatively little research in this area. Most of the geoengineering methods have not yet advanced much beyond the outline/concept stage. At the same time, some of them, such as stratospheric aerosol and cloud brightening methods, could theoretically provide rapid cooling effects and might have much smaller costs than conventional approaches.[67] They also might involve substantial **side impacts** such as effects on stratospheric ozone, biological productivity, regional weather patterns, etc. As noted in the previous section on adaptation R&D, existing climate models cannot yet pinpoint these risks.

There is a strong need to undertake serious research on the most promising geoengineering methods. This research should focus on their feasibility, technical aspects, effectiveness, costs, environmental impacts and potential unintended consequences. In the near- and medium-term perspective, this research should focus on better **modelling of geoengineering effectiveness and risks, small scale experiments and field trials** of prototypes.

Industrial **carbon dioxide capture** from ambient air promises some important attractive features. For example, it offers a large potential for mitigation, with minimal side effects (except those for CCS and required energy supply) and the possibility to be located away from population

66 The Economist, 'Facing the Consequences', November 25th, 2010.

67 Royal Society 'Geoengineering the Climate: Science, Governance and Uncertainty,' September, 2009, Table 3.6.

areas.[68] However, the cost of this method is quite high, at least with current technologies.

A final remark concerns issues of **international governance**. This is likely to be one of the main barriers to the implementation of geoengineering methods, especially SRM. Use of some geoengineering options by any single country will often have a global impact (otherwise they will not have any discernible effect on climate). Therefore, research and discussion on appropriate international policies and decision-making frameworks for applying geoengineering techniques should be part of the research agenda. In addition, **public education** and engagement will become very important if geoengineering research moves to the experimental phase.

68 Barrett, S., 'The Coming Global Climate-Technology Revolution', *Journal of Economic Perspectives*, Vol. 23 (2), Spring 2009, pp. 53-75.

4 CONCLUSION

Fossil fuels enabled the industrial revolution and brought a level of prosperity to many parts of the globe that was difficult to imagine a century or two ago. Their widespread use also brought a changing climate. Now is the time to find ways to limit the consequences of this process. In this respect research and development efforts should play a central role. This report provided a short overview of existing efforts in this field and outlined some areas where more efforts are needed.

In the last decade, there was a significant increase in public funding of energy technology research, although spending is still below the level achieved in early 1980s, especially in Europe. Public expenditures on energy research in European members of the IEA have been lagging behind those in America and Asia.[69] Currently governments allocate a much smaller proportion of public R&D expenditure to energy technologies than 20 years ago. Many studies show that public and private R&D investment should increase markedly in order to limit the average temperature increase by 2°C. At the same time, in the next few years, given the fact that the state of public finance in many EU (and more generally OECD) countries remains weak, a further rapid expansion of public research investments into energy technologies could well face stronger headwinds.

Recent increases in R&D funding have led to growth in research and innovation outputs related to the climate change challenge i.e. the number of research articles and patents. Some European countries such as Germany, Denmark, Sweden, Finland and Netherlands perform quite well on these measures. Adoption of national and international policy measures (including

69 Government energy R&D expenditure became slightly higher in IEA Europe than IEA Asia and Oceania in 2010, for the first time since 1990s but it was still much lower if measured as a percentage of GDP.

the Kyoto protocol) aimed at reducing GHG emissions has been a major factor in encouraging innovation in this area as well.

Still, much more R&D effort is required to lower cost and improve performance of mitigation technologies and to find the best ways to adapt to climate change impacts. Dealing with the climate change challenge will require a very broad portfolio of technologies. Public science and technology policies should also aim to support a broad range of research fields.[70]

This report suggests some R&D areas that would merit increased attention. In mitigation energy efficiency, clean transport vehicles, CCS and renewable energy sources are the most compelling areas for additional R&D funding. Important research areas in adaptation include: a better understanding of potential impacts; forecasting of weather events; adapting infrastructure and built environment to a changing climate; understanding the role of human behaviour in adaptation efforts; and development of heat-, drought- and salt-resistant crops. Finally, geoengineering research should focus on better understanding the side effects of various techniques. One important issue will be the governance structures that may help coordinate international geoengineering efforts.

Some European countries already built up expertise in these areas. With regards to mitigation technologies, several EU member states rank high in terms of patents filed: Germany, Denmark and Spain for wind; France, Italy and Germany for photovoltaic; and Spain, Italy and Germany for concentrated solar power. Research efforts should expand on these strengths, with centers (and countries) of excellence in Europe and beyond in a more prominent role.

Climate change is a global problem with little regard for country borders. Only a balanced mix of internationally coordinated and intensive R&D efforts that include research on mitigation, adaptation and geoengineering can help abate the challenge of climate change.

70 No individual country can cover the whole spectrum of R&D required for dealing with climate change. R&D policies in each country should be based on specific circumstance such as expected impacts of climate change, strengths and weaknesses of the science and technology base, extent of international cooperation, etc.

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APPENDIX 1 CLIMATE CHANGE VULNERABILITY INDEX: METHODOLOGY

The Climate Change Vulnerability Index provides an assessment of country-level relative vulnerability to climate change.[71] It uses indicators for three main expected impacts of climate change on social systems suggested by David Wheeler: [72]

1) increase in weather-related disasters;
2) sea-level rise, and;
3) loss of agricultural productivity.

Obviously these are not the only impacts of climate change on the social and ecological systems. However, given our current knowledge they are likely to account for lion's share of economic losses associated with climate change.

There are two basic approaches to measure the future risks of climate change impacts: (i) one relies on the projections for future impacts of climate change; (ii) the other uses historical data reflecting an impact (or vulnerability to an impact) of such events in the past. Each approach has its own benefits and drawbacks. Since we are interested in the future risks the first approach seems natural to use. However, the projections are very uncertain and their quality might be difficult to assess. The second approach assumes that history will repeat itself in the future, which obviously might

71 A similar index was developed by the Global Adaptation Institute (GAIN) – the GAIN Index – that incorporate both country vulnerability to and readiness to increase resilience to climate change (index.gain.org).

72 David Wheeler, Quantifying Vulnerability to Climate Change: Implications for Adaptation Assistance, Working paper 240, http://www.cgdev.org/files/1424759_file_Wheeler_Quantifying_Vulnerability_FINAL.pdf.

not be true. There is no single approach that is right in all circumstances. The choice of one or the other is often subjective and depends on data availability and quality. In the calculation of the Climate Change Vulnerability Index, both approaches were used.

Below we describe risk indicators for the climate change impacts and the construction of the index. Formal definitions and data sources for climate change risk indicators are given in Table 6.

1) WEATHER-RELATED DISASTERS

Global warming is expected to increase the number of weather-related disasters by intensifying the water cycle. We use the historical approach to construct an indicator for their impact mainly because of availability of historical data for extreme weather events — the EM-DAT International Disaster Database maintained by the Belgian university KU Leuven.[73] More specifically, a risk indicator for extreme weather events is the percentage of the population killed, injured, or homeless as a result of weather-related disasters over the 1990-2009 period. Weather-related disasters include droughts, floods, cold waves and heat waves. This indicator focuses not on the frequency or severity of weather-related events per se, but on the impact of such events on the population. As a result, it combines two aspects; a country's exposure to natural catastrophes and its capacity to deal with them.

2) SEA-LEVEL RISE

The risk indicator for sea-level rise uses the percentage of the total population living in areas where the elevation is 5 meters or less.[74] This indicator might not directly translate into the expected risk of sea-level rise since it does not take into account the level of infrastructure development and preparedness, but it reflects long-term vulnerability of any particular country to the impact of sea-level rise (e.g., the Netherlands has a well developed flood control infrastructure, but substantial investments are still needed to address the increasing risks posed by sea level rise).

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73 Disaster Database EM-DAT, http://www.emdat.be/database.

74 Center for International Earth Science Information Network (CIESIN), Place II dataset.

3) AGRICULTURAL PRODUCTIVITY

To measure the impact of climate change on agriculture we use the results of the assessment by William Cline for the expected change in agricultural productivity by 2080s for baseline global warming without carbon fertilisation.[75,76] The estimates combine the results from crop models developed on the basis of agricultural science and the Ricardian models which use statistical regressions across climate regions of large countries.

The importance of agriculture is widely different in various countries. In poor countries agriculture accounts for much higher share of the total economic output than in rich countries. Therefore poor countries' vulnerability to changes agricultural productivity is likely to be higher, all other things being equal. To adjust for the economic importance of agriculture we scale (i.e., multiply) the estimates of changes in agricultural productivity by the agriculture value added as a percentage of GDP (for 2010 or latest available).[77]

75 William R. Cline, Global Warming and Agriculture: Impact Estimates by Country, Ch.5 'Country-Level Agricultural Impact Estimates', Washington, DC: Center for Global Development and Peterson Institute for International Economics, 2007 http://www.cgdev.org/doc/books/Cline%20global%20warming/Chapter%205.pdf.

76 Data on agricultural productivity with and without carbon fertilization are essentially identical when they are normalized. Since index calculations involve normalized data index values are largely not affected by the choice of agricultural data set. In other words, relative standing of countries in terms of climate change impact on crop productivity does not change whether we consider or not the impact of carbon fertilization.

77 We use World Bank's World Development Indicators Database for this variable, http://data.worldbank.org/data-catalog/world-development-indicators.

INDICATOR	DEFINITION	SOURCE	YEAR
Vulnerability to weather-related natural disasters	Annual average percentage of total population affected as a result of either droughts, floods, or extreme temperature events. Population affected is the number of people injured, left homeless or requiring immediate assistance during a period of emergency resulting from a natural disaster; it can also include displaced or evacuated people. Average percentage of population affected is calculated by dividing the sum of total affected for the period 1990-2009 by the sum of the annual population figures for the period stated.	EM-DAT: The OFDA/ CRED International Disaster Database of the Belgian Université Catholique de Louvain. The dataset was last updated in August 2012.	1990-2009
Vulnerability to sea level rise	Population living in areas where elevation is below 5 meters as a percentage of total population	Center for International Earth Science Information Network (CIESIN), Columbia University, PLACE II dataset	2000
Loss of agricultural productivity	Preferred estimates of impact of baseline global warming by the 2080s on world agriculture	Cline, W., Global Warming and Agriculture: Impact Estimates by Country. Washington, DC: Center for Global Development and Peterson Institute for International Economics, 2007	2080

TABLE 6. INDICATORS FOR CLIMATE CHANGE IMPACTS

To construct an overall index of vulnerability we used the following procedure:

1) Individual risk indicators are normalized using the following formula:

$$\hat{x}_i = \frac{x_i - x_{min}}{x_{max} - x_{min}}$$

where: xi – raw value of risk indicator x for country i;
x_{max} – maximum value of risk indicator *x* for all countries;
x_{min} – minimum value of risk indicator *x* for all countries;

In the case of loss agricultural productivity we also subtract the normalized value from one since we want higher normalized values to correspond to higher vulnerability. The normalization step ensures that all indicators are dimensionless and change on the scale from 0 to 1.

2) Three risk indicators described above are aggregated into the Climate Change Vulnerability Index using simple average of their normalized values.

The resulting index shows the relative standing of various countries with respect to three major impacts of climate change. It should be noted that the index does not provide an assessment of an absolute impact of climate change on any country, e.g., the expected economic loss.

Two of the risk indicators — impact of weather related events and impact on agriculture (scaled by the share of agriculture in GDP) — incorporate a country's capacity to deal with climate change impacts (directly or indirectly). Therefore, the vulnerability index also reflects this capacity.

APPENDIX 2 SELECTED CLIMATE CHANGE R&D PROGRAMMES IN THE EU MEMBER STATES

COUNTRY	PROGRAMME	BUDGET	DESCRIPTION
Belgium	Science for a Sustainable Development	€61m for 2006-2012	Multi-annual research programme. Aims to strengthen scientific knowledge and support the federal scientific policy
Denmark	1. Renewal Fund	1. 760m DKK for 2010-2012	1. The purpose of the fund is to promote green conversion and commercial renewal in Danish enterprises, particularly in SMEs
	2. EUDP	2. 400m DKK in 2010-11	2. The EUDP supports the development and demonstration of new, innovative energy technologies
Finland	1. TEKES' Sustainable Community Programme (2007-2012)	1. €100m, 2007-2012	1. Co-investment with companies & organizations in the development of sustainable & energy efficient buildings
	2. Sitra Energy Programme (2008-2012)		2. Focuses on improving energy efficiency of the built environment. Works with the Sustainable Community Technology Programme
France	The Research Demonstrators Fund managed by the French Environment and Energy Management Agency	€400m (2009-2012)	Low emission vehicles, 2nd generation of biofuels, geological capture, transport and storage of CO_2
Germany	Framework programme 'Research for Sustainable Development' (2010)	Over €2b until the year 2015	The Federal Ministry of Education and Research will fund for the development of sustainable technology innovation
Sweden	The Nordic Top-level Research Initiative	€48m over 5 years	A major Nordic initiative for climate, energy and environment. Promotes research and innovation to make a Nordic contribution towards solving the global climate crisis. Consists of 6 sub-programmes
UK	1. UK Research Councils Energy Programme	1. £530m	1. Supports full spectrum of energy research to help the UK meet the objectives and targets set out in the 2007 Energy White Paper
	2. Strategic Investment Fund	2. €1,116m	2. One of the priority areas is investments in low carbon projects (renewable energy and transport)

SOURCE: KARAKASIDOU & CUNNINGHAM, 2010; HCSS

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