Chapter 7

Energy Systems

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Chapter 7: Energy Systems

Contents

Executive Summary

The energy sector, as defined in this report, comprises all energy extraction, conversion, storage, transmission and distribution processes with the exception of those that use final energy in the demand sectors (industry, transport and building). The energy sector is the largest and fastest growing contributor to global greenhouse gas (GHG) emissions. In 2010 it was responsible for 35% of total anthropogenic GHG emissions. [7.3; high agreement, robust evidence]

GHG emissions growth from the global energy supply sector accelerated from 1.7% per year in 1990-2000 to 3.6% in 2001-2010. Rapid economic growth (with the associated higher demand for power, heat, and transport services) and an increase of the share of coal in the global fuel mix were the main contributors to this trend. [7.1, 7.3; high agreement, robust evidence]

From a regional perspective, the acceleration was mostly driven by emissions from non-Annex I countries, which in 2008 surpassed those of the Annex I countries. The Annex I countries as a group have managed to keep emissions below 1990 levels since 2008. [7.3; medium agreement, medium evidence]

Since the industrial revolution, fossil fuel combustion has released almost 400 Gt of carbon into the atmosphere. The remaining hydrocarbon reserves alone contain two to four times that amount of carbon. Therefore, limits to the fossil fuel resource cannot be relied upon to limit global GHG concentrations to levels consistent with the Cancun Agreement. [7.4; high agreement, high evidence]

The primary mitigation options in the energy sector include efficiency improvements and mitigation of fugitive emissions in fuel extraction and conversion, fuel switching, energy efficiency improvements in transmission and distribution systems, carbon dioxide capture and storage (CCS) as well as replacing fossil fuels with renewable energies (RE) and nuclear energy. [7.5; high agreement, robust evidence]

Significant reductions in GHG emissions can be obtained by replacing existing coal fired heat and/or power plants by highly efficient natural gas combined cycle (NGCC) power plants or combined heat and power (CHP) plants. [7.5.1; medium agreement, medium evidence]

Recent life cycle assessments indicate a 50% reduction of specific GHG emissions (per KWh) when shifting from the current world-average coal fired power plant to a modern NGCC power plant when fuelled from a low GHG natural gas source. More modest emissions reductions are achievable by applying best available coal technologies or less advanced gas power plants. [7.5.1; medium agreement, medium evidence]

On one hand, increased focus on shale gas has led to a relaxation of natural gas resource availability concerns compared to the AR4. On the other hand, a better appreciation of the importance of fuel chain issues (especially those related to fugitive methane emissions and their environmental impacts) has resulted in a downward adjustment of the estimated benefit from fuel switching. [7.5.1; medium agreement, medium evidence]

In the long-term, global emissions of NGCCs are too high to meet stringent long-term stabilization targets (e.g. those of the Cancun Agreement) if NGCCs are used for satisfying base-load power demand. Beyond energy efficiency improvements and fuel switching, low carbon energy supply technologies are therefore indispensable if these goals are to be achieved. [7.5.1.] [High agreement, robust evidence]

CCS technologies are capable of significantly reducing the carbon dioxide emissions of fossil-fired power plants, albeit to a lower extent compared to RE and nuclear. Bioenergy CCS (BECCS) might allow negative emissions by effectively taking away CO_2 from the atmosphere. [7.5.5, 7.8.1; medium agreement, medium evidence]

All of the components of integrated CCS systems exist and are in use today in various parts of the fossil energy chain. A variety of recent pilot and demonstration projects have led to critical advances in our knowledge of CCS systems and their engineering, technical, economic and policy aspects. However, as of early 2013, CCS has not yet been applied to a large, commercial fossil-fired generation facility. [7.5.5; medium agreement, medium evidence]

There is a growing body of literature on how to ensure the integrity of CO_2 wells, on associated leakage rates, on the potential consequences of a pressure build up within a formation caused by CO_2 storage (such as induced seismicity and potential human health as well as environmental consequences from CO_2 that migrates out of the primary injection zone), as well as on actively reducing the related risks [7.5.5 medium agreement, medium evidence]

Total practical geologic storage capacity is large and likely sufficient to meet demand for CO_2 storage over the course of this century, but that capacity is geographically unevenly distributed. [7.5.3; medium agreement, limited evidence]

RE technologies have advanced substantially since the AR4. The price of photovoltaic (PV) modules has declined steeply as a result of policy instruments, increased supply competition, improvements in manufacturing processes and photovoltaic (PV) cell efficiencies, and reductions in materials use. Continued increases in the size of wind turbines have helped to reduce the levelised cost of land-based wind energy, and have improved the prospects for offshore wind energy. Concentrated solar thermal power plants (CSP) were built in a couple of countries – often together with heat storages or as gas-CSP hybrid systems. Improvements have also been made in cropping systems, logistics, and multiple conversion technologies for bioenergy. [7.3, 7.5; high agreement, medium evidence]

Although regional potentials of single RE technologies might be limited, taken together, the global technical potential of all available RE does not pose a practical constraint on their contribution to mitigate climate change during this century. [7.4.2; medium agreement, medium evidence]

Nuclear energy is capable of providing carbon free electricity at the plant site and close to that on a life-cycle basis. [7.8.1; High agreement, high evidence]

Although nuclear power has been used for five decades, unresolved issues remain for a future worldwide expansion of nuclear energy. The related barriers include operational safety, proliferation risks, waste management and the economics of power plants. Constraints to resource availability are limited if recycling options (via reprocessing plants) are taken into account, and efforts are underway to develop new fuel cycles and reactor technologies that address the concerns of nuclear energy use. [7.5.4; medium agreement, medium evidence]

The significant release of radioactive materials from the Fukushima accident was rated at Level 7, the maximum level of the International Nuclear and Radiological Event Scale (INES) for nuclear accidents. Albeit the release was lower than that of the 1986 Chernobyl nuclear accident, it is too early to assess the final health, environmental, and economic implications of the Fukushima accident. [7.5.4, 7.9.3; medium agreement, medium evidence]

Infrastructure and integration issues vary by mitigation technology and region. While they are not generally technically insurmountable, such issues must be carefully considered in energy supply planning and operations to ensure reliable and affordable energy supply. In addition, they may require changes in patterns of energy use and consumer expectations, and may result in higher energy costs. [7.6; medium agreement, medium evidence]

Considerable populations do not have access to modern energy services and technologies, especially in Africa and Asia [7.9; high agreement; robust evidence]. Providing universal access to modern energy services will require removing different cultural, institutional and legal barriers; however, this will not necessarily lead to significant changes in GHG emissions – although this obviously depends on the consumption level and the selected supply technologies.

A key challenge therefore will be to deliver modern energy services with limited GHG emissions impacts. [7.9; medium agreement, medium evidence] For least developed countries, the dissemination of low carbon technologies will necessitate a massive technology transfer coupled with financial support. [7.2, high agreement, robust evidence]

There are often co-benefits from the use of mitigation technologies in the energy supply sector, such as reduction of air pollution, local employment opportunities, lower energy production related fatality rates, better energy security, improved energy access and reduced vulnerability to price volatility. [7.9; medium agreement, medium evidence] At the same time, however, some low carbon technologies can have technology and location-specific negative impacts, though those can be mitigated to a degree through the appropriate selection, design, and siting of the technology in order to facilitate a deployment in an environmentally and socially sustainable manner. [7.9; high agreement, robust evidence]

To increase social acceptance of low-carbon technologies, a variety of procedures have been shown to be effective, such as the following: ensuring that accurate and unbiased information about the technology, its impacts and benefits, and its interplay with other technologies is widely distributed; aligning the expectations and interests of different stakeholders; adjusting to the local societal context; adopting benefit sharing mechanisms; obtaining explicit support at the local and national levels prior to development; building collaborative networks, and developing mechanisms for articulating conflict and engaging in negotiation. [7.9; medium agreement, medium evidence]

Integrated analysis tools and modelling frameworks, accounting for the range of possible co-benefits and trade-offs of different policies that tackle access, security and/or environmental concerns, as well as governance, institutional and human capacity for the use of such tools and frameworks, are required to better support integrated decision making. [7.9, 7.10; medium agreement, medium evidence]

Numerous low carbon and GHG mitigating power and heat generation technologies are already available. When taken together, these technologies can facilitate deep reductions in energy-related GHG emissions. However, no single technology or resource alone can transform energy supply and transformation systems to meet long-term low stabilization goals, and while all integrated assessment modelling exercises show transformation pathways that utilize a portfolio of technologies, there are potentially many additional technology combinations that can successfully transform the energy system. [7.11; high agreement, robust evidence]

As many RE technologies are still not competitive with market energy prices, there is a need for direct or indirect financial support in order to further increase their market share. The same is and will be true for CCS plants due to the additional equipment attached to the power plant and the decreased efficiency. The post Fukushima assessment of the economics and future fate of nuclear power is mixed. Additional barriers are seen in the field of technology transfer, capacity building and in some cases public perception. [7.8, 7.9, 7.10; medium agreement, medium evidence]

Although multiple climate and energy policies have already been enacted (e.g., to price GHG emissions externalities, to provide direct technology support and deployment, and to achieve air pollution emission reduction), their current coverage and stringency will not deliver the substantive deviation from current trends by 2020 as required for most 450ppmv CO_{2eq} pathways. Hence, additional mitigation policies must be enacted if the Cancun Agreement is to be fulfilled. [7.12; medium agreement, medium evidence]

7.1 Introduction

The energy sector is the largest and fastest growing contributor to global GHG emissions. In 2010 it was responsible for 35% of total anthropogenic GHG emissions. GHG emissions growth from the global energy supply sector accelerated from 1.7% per year in 1990-2000 to 3.6% in 2001-2010. Rapid economic growth (with the associated higher demand for power, heat, and transport services) and an increase of the share of coal in the global fuel mix were the main contributors to this trend.

The energy sector, as defined in this report (Figure 7.1), comprises all energy extraction, conversion, storage, transmission and distribution processes with the exception of those that use final energy in the downstream consumer sectors (industry, transport and building).

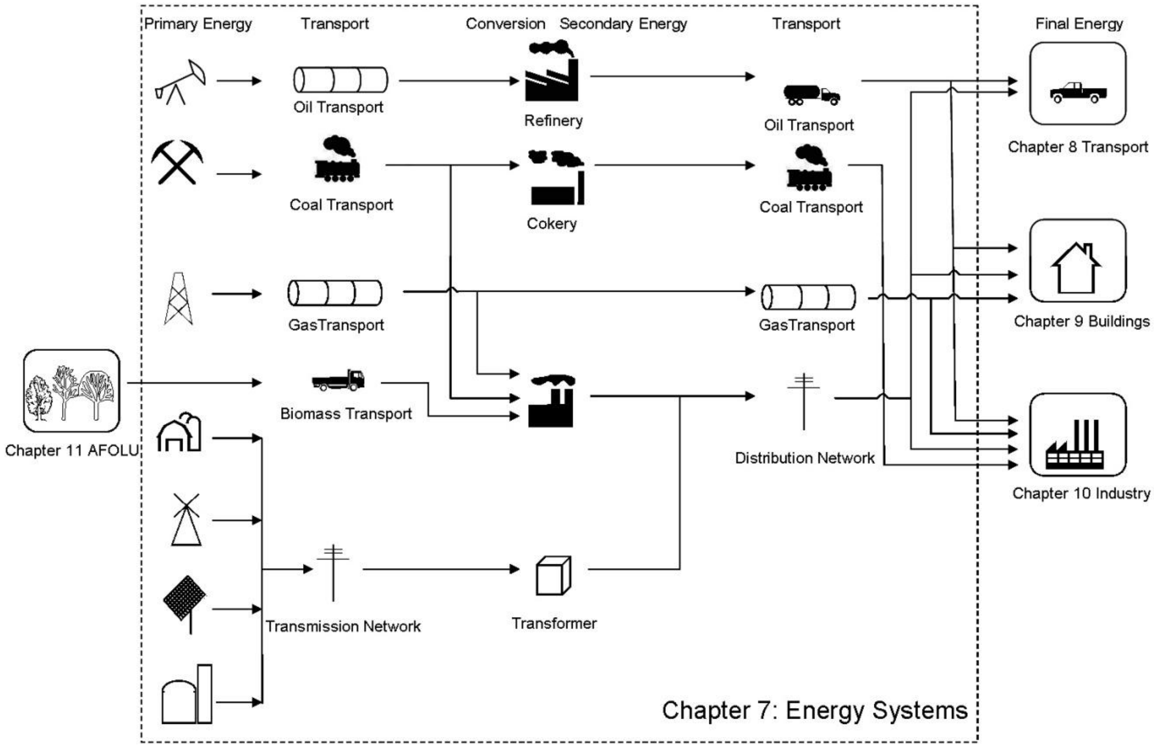


Figure 7.1 Exemplary supply paths shown in order to illustrate the boundaries of the energy sector as defined in this report.

This chapter assesses what is new and different in the literature on energy systems from earlier IPCC reports, comprising the IPCC Special Report on Carbon Dioxide Capture and Storage (2005), the IPCC AR4 (2007), and the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (2011a). Section 7.2 describes the global energy balance together with the status and evolution of global and regional energy markets. Energy sector related GHG emissions together with associated trends and drivers are presented in section 7.3. The following section provides data on energy resources (fossil fuels, renewables and nuclear). Section 7.5 discusses advances in the field of mitigation technologies. Issues related to the integration of low carbon technologies are covered in section 7.6, while section 7.7 describes how climate change may impact energy demand and supply. Section 7.8 discusses technical potentials of mitigation options, their current cost, and their historic evolution. The next section is on issues of co-benefits, technological, environmental and other risks, and spill-over effects, and on public acceptability of energy technologies options. Barriers and opportunities including technological, financial, institutional, cultural, and legal ones, as well as inertia issues are dealt with in section 7.10. Sectoral implication of transformation pathways and sustainable development are covered in section 7.11. This chapter concentrates on medium-term and long-term projections. Section 7.12 presents energy sector specific policies including greenhouse gas pricing and technology specific policies as well as associated enabling conditions. The last section addresses gaps in knowledge and data.

The allocation of cross-cutting issues among other chapters allows understanding better the chapter 7 boundaries (see Figure 7.1). Energy requirements for meeting basic needs, as well as the importance of energy for social and economic development are reviewed in Chapters 4 and 5 and to a lesser degree in section 7.9 of this chapter. Chapter 6 presented long-term transformation pathways and futures for energy systems. Local fuel supply infrastructure for transportation is the subject of Chapter 8. Building integrated power and heat generation as well as biomass use for cooking are addressed in chapter 9. Responsive load issues are dealt with by chapters 8, 9 and 10. Chapter 7 considers mitigation options in energy extraction industries (oil, gas, coal, uranium etc.) while other extractive industries are addressed in Chapter 10. This chapter does not address natural forest management. Together with aspects related to bioenergy usage, this is covered in Chapter 11. Only energy supply sector related policies are covered in this chapter while the broader and more detailed climate policy picture is presented in chapters 13-15.

7.2 Energy production, conversion, transmission and distribution

7.2.1 Global energy balance and energy flows

To enable better energy services to end users, the energy supply sector converts over 75% of primary energy into other forms, namely: electricity, heat, refined oil products, coke, enriched coal, and natural gas. Industry (including non-energy use) consumes 84% of final use of coal and peat, 26% of petroleum products, 47% of natural gas, 40% of electricity, and 43% of heat. Transportation consumes 62% of liquid fuels final use. The building sector is responsible for 46% of final natural gas consumption, 76% of combustible renewables and waste, 52% of electricity use, and 51% of heat (Table 7.1). Forces driving final energy consumption evolution in all these sectors (chapters 8-11) have a significant impact on the evolution of energy supply systems both in scale and structure.

There is a long standing trend of growing contributions from unconventional fuels and renewables to the diversity of primary energy options. Despite this, conventional fossil fuels continue to dominate total primary energy supply (TPES) and this dominance has grown in the last decade driven by increased coal use in the power sector mostly in Asia and specifically in China (Figure 7.2).

The energy supply sector is itself the largest energy user with growth leading to greater diversity in system makeup and supply outcomes. Energy losses assessed as the difference between the energy inputs to (78% of the TPES) and outputs from this sector (48.7% of TPES) account for 29.3% of TPES (Table 7.1).

The energy sector share of the global energy balance is not only a function of end users' demand for higher quality energy carriers, but also the relatively low average global efficiency of energy conversion, transmission and distribution processes (only 37% efficiency for fossil fuel power and just 83% for fossil fuel district heat generation). However, low efficiencies and large own energy use result in high indirect multiplication effects of energy savings from end users.[1]

[1] When indirect energy efficiency effects are estimated, transformation is regularly performed for electricity. It should also be done for district heating, and it can be done for any activity in the energy sector and even for fuels transportation. Bashmakov (2009) argues that global average energy savings multiplication factors are much higher if assessed comprehensively and are equal to 1.07 for coal and petroleum products, 4.7 for electricity and 2.7 for heat.

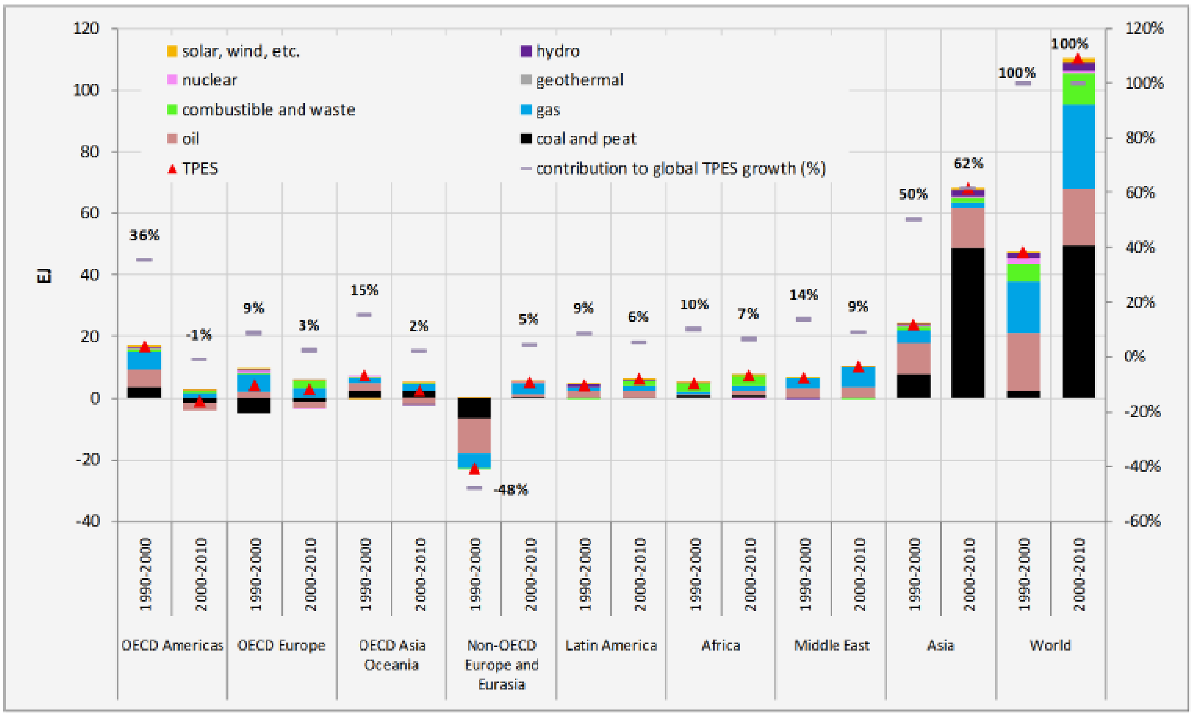


Figure 7.2 Contribution of energy sources to global and regional primary energy use increments. Notes: Modern biomass contributes 40% of the total biomass share. Underlying data from IEA (2012a) for this figure have been converted using the direct equivalent method of accounting for primary energy (see Annex Methodology).

7.2.2 Regional energy systems evolution

In 2000-2010, TPES grew by 27% globally, 119% in China, 66% in the Middle East, 44% in the Non-OECD Asia, 34% in Africa, 35% in Latin America, 13% in Non-OECD Europe and Eurasia, 7% in OECD Asia Oceania, and 4% in OECD Europe, while it was nearly stable for OECD Americas (IEA, 2012a); 88% of additional energy demand was generated outside of the OECD (Figure 7.2).

The evolution of the energy markets in Non-OECD Asia differs considerably from the other markets. This region was responsible for nearly two thirds of the global TPES increment in 2000-2010, for nearly all additional coal demand, 70% of additional oil demand, 72% of additional hydro and 43% of additional nuclear generation (Figure 7.2). In the last decade, China alone was responsible for over half of the TPES increment making it now the leading energy-consuming nation.

Led by Non-OECD Asia, coal consumption grew in 1998-2011 by over 4% per annum. Over the last decade, coal was responsible for 45% of the growth in global energy and this growth alone matched the total increase in global TPES for 1990-2000 (Figure 7.2). China was responsible for 82% of the global coal use increment in 2000-2010, followed by India; coal use in OECD Europe and Americas is declining. Power generation remains the main global coal demand driver (US DOE, 2012). China is the leading coal producer (45% of world 2011 production), followed by the USA, India, Australia and Indonesia. Coal is distributed geographically relatively evenly, which together with high transportation costs limits international trade to about 19% of global coal use which is dominated by two regional markets – the Atlantic market, made up of countries in Western Europe, and the Pacific market. Australia dominates the list of coal exporters. Competitive power markets are creating stronger links between gas and coal markets (IEA, 2012b).

Table 7.1: 2010 World Energy Balance (EJ on a net calorific value basis applying the *direct equivalent method*)

Supply and consumption	Coal and peat	Crude oil	Oil products	Gas	Nuclear	Hydro	Geothermal . Solar.etc.	Combustible renewables and waste	Electricity	Heat	Total*	*Share in TPES*	*Conversion efficiency* and losses*
Production	**150.56**	**170.38**	**0.00**	**113.84**	**9.95**	**12.38**	**2.91**	**53.47**	**0**	**0.04**	**513.52**	***101.20%***	
Imports	26.83	96.09	44.12	34.21				0.45	2.12	0.00	203.81	*39.92%*	
Exports	-28.52	-92.59	-46.55	-34.60				-0.39	-2.08	0.00	-204.73	*-40.10%*	
Stock Changes	-3.34	0.27	0.26	0.75				-0.02			-2.09	*-0.41%*	
TPES	**145.52**	**174.14**	**-2.17**	**114.20**	**9.95**	**12.38**	**2.91**	**53.51**	**0.04**	**0.04**	**510.52**	***100.00%***	
Share in TPES	*28.51%*	*34.11%*	*-0.43%*	*22.37%*	*1.95%*	*2.42%*	*0.57%*	*10.48%*	*0.01%*		*100.00%*		
Transfers	0.00	-6.56	7.51					0.00			0.95	*0.19%*	
Statistical Differences	-2.07	0.47	-1.13	-0.07			-0.01	-0.02	0.28	0.00	-2.55	*-0.50%*	
Electricity Plants	-82.68	-1.45	-8.44	-29.54	-9.89	-12.38	-1.61	-2.65	65.37	-0.01	-83.28	*-16.31%*	*37.13%*
CHP Plants	-6.75		-0.94	-12.76	-0.06	0	-0.02	-1.47	6.85	5.86	-9.31	*-1.82%*	*57.72%*
Electricity generation (TWh)	*8698*	*28*	*961*	*4768*	*2756*	*3437*	*450*	*332*		*2*	*21431*		
Share in electricity generation	*40.58%*	*0.13%*	*4.49%*	*22.25%*	*12.86%*	*16.04%*	*2.10%*	*1.55%*		*0.01%*	*100.00%*		
Heat Plants	-4.34	-0.03	-0.54	-3.77			-0.34	-0.44	-0.01	7.05	-2.42	*0.47%*	*83.28%*
Gas Works	-0.37		-0.15	0.12							-0.40	*0.08%*	*22.79%*
Oil Refineries		-164.70	162.86	-0.03							-1.87	*0.37%*	*98.86%*
Coal Transformation	-9.19	0.00	-0.13	0.00				0.00			-9.33	*1.83%*	
Liquefaction Plants	-0.68	0.33	0.00	-0.30							-0.65	*0.13%*	*33.69%*
Other Transformation	0.00	0.01	-0.01	-0.09				-2.22		-0.01	-2.33		*0.30%*
Energy Industry Own Use	-3.61	-0.42	-8.81	-11.53			-0.01	-0.56	-6.10	-1.43	-32.46	*6.36%*	*6.36%*
Losses	-0.11	-0.34	-0.02	-1.03			-0.01	-0.01	-6.08	-0.89	-8.49	*1.66%*	*1.66%*
Total energy sector	**-107.73**	**-173.18**	**151.33**	**-58.94**	**-9.95**	**-12.38**	**-1.98**	**-7.35**	**60.02**	**10.56**	**-149.60**	***29.30%***	
Share of energy sector	*74.03%*	*99.45%*	*7.08%*	*51.61%*	*100.00%*	*100.00%*	*68.00%*	*13.74%*	*8.17%*	*18.21%*	*-29.30%*		
Total Final Consumption (TFC)	**35.719**	**1.438**	**148.023**	**55.189**	**0.000**	**0.000**	**0.916**	**46.139**	**60.347**	**10.601**	**358.372**	***70.20%***	*Share in FEC*
Share of energy carriers	*9.97%*	*0.40%*	*41.30%*	*15.40%*	*0.00%*	*0.00%*	*0.26%*	*12.87%*	*16.84%*	*2.96%*	*100.00%*		
Industry	28.38	0.52	12.98	19.42			0.02	8.20	24.26	4.61	98.39	*19.27%*	*27.46%*
Transport	0.14	0.00	91.94	3.73				2.41	0.97	0.00	99.20	*19.43%*	*27.68%*
Buildings	4.25	0.03	13.13	25.15			0.48	35.10	31.46	5.37	114.96	*22.52%*	*32.08%*
Agriculture/forestry/fishing	0.46	0.00	4.51	0.25			0.03	0.31	1.58	0.14	7.29	*1.43%*	*2.03%*
Non-Specified	0.98	0.25	0.60	0.26			0.39	0.11	2.07	0.49	5.15	*1.01%*	*1.44%*
Non-Energy Use	1.51	0.63	24.87	6.38							33.38	*6.54%*	*9.32%*

Source: IEA (2012a) (2011a)data were used due to provision of global split by energy use sectors. IEA data were modified to convert to primary energy by applying the *direct equivalent method* (see Appendix Methodology). Negative numbers in energy sector reflect energy spent or lost, while positive ones – energy generated.*Only for fossil fuel powered generation. Data will be updated upon new statistics are released.

Although use of liquid fuels has grown in non-OECD countries (mostly non-OECD Asia with 71% of the global decadal increment and 19% in the Middle East), falling demand in the OECD has seen oil's share of global energy supply continue to fall in 2000-2010. Meeting demand has required mobilization of both conventional and unconventional liquid supplies. Of 181.3 EJ of global "oil supply" in 2011, natural gas liquids contributed 25 EJ, extra heavy oil and oil sands 4.6 EJ, biofuels 2.7 EJ, and shale and light tight oil 2.5 EJ. Contribution from coal-to-liquids and gas-to-liquids along with others is assessed at 0.2 EJ (IEA, 2012b). Relatively low transportation costs have given rise to a truly global oil market with 55% of crude consumption and 28% of petroleum products being derived from cross-border trade. Most prominent among oil supply security concerns are the more than 3 billion people living in 83 countries (including all of the world's low-income countries) who import more than 75% of the oil and petroleum products they consume (Rogner et al., 2012). OPEC in 2011 provided 42.4% of the world's total oil supply keeping its share above its 1980 level; 33% came from the Middle East alone (BP, 2012). The most significant non-OPEC contributors to production growth since 2000 were Russia, Brazil, Canada, China and Kazakhstan (BP, 2011a; GEA, 2012; IEA, 2012b; US DOE, 2012). Increasing reliance on imports in the importing non-OECD regions, notably Asia, inevitably heighten concerns about the cost of imports and supply security (IEA, 2012b).

Although the 2000-2010 natural gas increments are more widely distributed among the regions than for oil and coal, gas increments in non-OECD Asia and the Middle East dominate. In the global gas balance, the share of non-conventional gas production (shale gas, tight gas, coal-bed methane and biogas) grew to 16% in 2011 (IEA, 2012e). The low energy density of gas means that transmission and storage make up a large fraction of the total supply chain costs thus limiting market development. Escalation of Liquefied Natural Gas (LNG) markets to 32% of international gas trade in 2011 (BP, 2012) has however created greater flexibility and opened the way to global trade in gas (MIT, 2011). International trade in gas continues to grow in scope and scale with its share reaching 30%. Currently, there are almost 650 million people living in 32 Eurasian countries who rely on imports to meet over 75% of their gas needs (Rogner et al., 2012). Increases in U.S. natural gas production (where the share of unconventional gas reached 67% in 2011) and decreasing prices in U.S. markets have resulted in the movement of LNG supplies to higher-priced markets in South America, Europe, and Asia (IEA, 2012b). Natural gas supply by pipelines still delivers the largest gas volumes in North America and in Europe (BP, 2012; US DOE, 2012).

Renewables contributed 13.5% of global TPES in 2010. Global TPES in 2001-2010 increased by 13.3% consisting of 9.1% combustible biomass and waste, 2.7% hydro, 1.5% solar, wind and others, and a small additional geothermal energy use. About one third of the renewable primary energy supply is used in the energy sector to generate electricity and sold heat, while the rest is consumed in the residential, commercial, and public services sectors as a result of widespread traditional biofuels use in developing countries (IEA, 2012c). Solid biofuels and waste grew by 2% per year in 2000-2010 and are by far the largest renewable energy source, representing 10.5% of world TPES (IEA, 2012d). Developing counties account for 78% of its global consumption, led by Non-OECD Asia (27%, mainly South Asia) and Africa (26%, mainly sub-Saharan Africa). At 2.4% of world TPES, the second largest renewable source is hydropower; annual growth over 2000-2010 was 2.8%. Non-OECD Asia was responsible for 72% of additional hydropower generation in the last decade followed by Latin America (17%) and Africa (4%). The share of renewables in global electricity generation exceeded 20% in 2011 (IEA, 2012c) making them the third largest contributor to global electricity production just behind gas, but much ahead of nuclear. Hydroelectricity supplies 16.5% of world electricity, while at 1.4% biofuels and waste play a minor role. Greatest growth during 2005-2011 occurred in wind and solar thermal with generation from these sources increasing more than 4-fold; solar photovoltaic grew 16-fold over the same period. By 2011, wind power accounted for 2% of world electricity production, solar energy and geothermal 0.3% each, and ocean energy 1 TWh. Additional energy use from solar and wind energy was driven mostly by three regions: OECD-Europe 37% of additional global use in 2000-2010, Non-OECD Asia 34%, and OECD Americas 23%, with a small contribution from the rest of the world (IEA, 2012d).

In 2000-2010 nuclear (heavily loaded with public concerns related to safety, radioactive waste disposal, proliferation issues, as well as high capital and maintenance costs) contributed 12.9% in 2010 to world power generation (Table 7.1), but only 0.5% of additional global TPES in contrast to 4.4% in the previous decade (IEA, 2012a). Of that increase, 63% originated from Non-OECD Europe and China. In 2011 power generation at nuclear plants globally was down by 0.5% (by 9.2% in OECD), falling below the 2001 level because of the accident at the Fukushima Daiichi nuclear plant in March 2011 and following revision of policies towards nuclear power by several governments (IEA, 2012e).

7.3 New developments in emission trends and drivers

7.3.1 Global trends

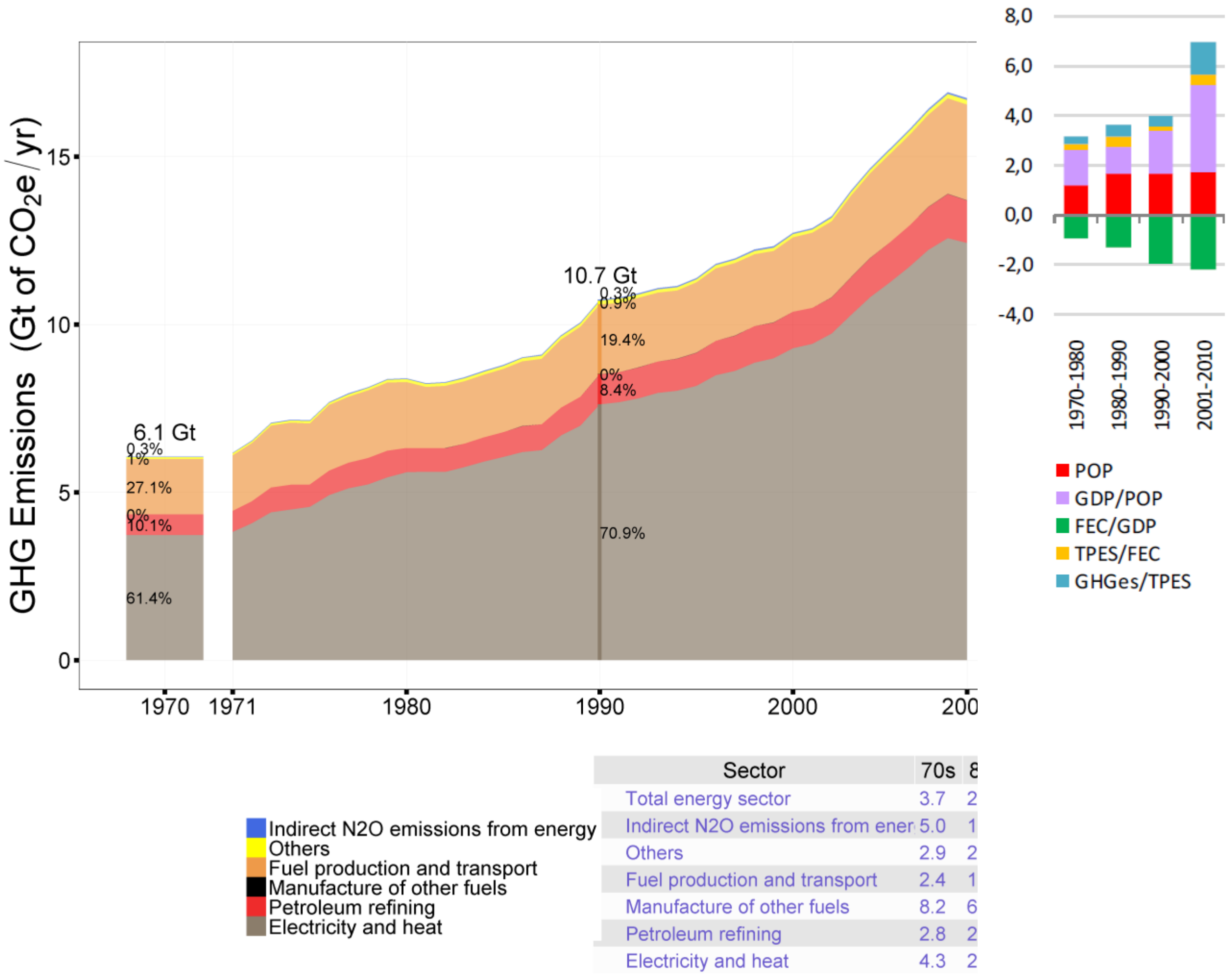
The global energy supply sector GHG emissions growth accelerated from 1.7% per year in 1990-2000 to 3.6% in 2001-2010, and to over 3% in 2011 (IEA, 2012b). This acceleration was mostly driven by emissions from non-Annex I countries, which in 2008 surpassed those of the Annex I countries, who managed to keep emissions since 2008 below 1990 levels (IEA, 2012b). In 2010 the energy sector was responsible for 46% of all energy-related GHG emissions[2] (IEA, 2012f) and 35% of anthropogenic GHG emissions, up 13.2% from 21.8% in 1970 (see Figure 7.3), making it the largest sectoral contributor to global emissions. According to the EDGAR dataset, 2000-2010 global energy sector GHG emissions increased by 37.7% and grew on average 1% per year faster than global anthropogenic GHG emissions. In 2011, the sector emitted 18 Gt CO_2-eq, 3% more than in 2010 (BP, 2012). Emissions from electricity and heat contributed 78% of last decade growth followed by 15% for fuel production and transport and 4.8% for petroleum refining. Although sector emissions were dominantly CO_2, also emitted were methane, of which 31% is attributed to mainly coal and gas production and transmission, and indirect nitrous oxide, of which 9% comes from coal and fuel-wood combustion (IEA, 2012f)[3]. In 2010, 43% of CO_2 emissions from fuel combustion were produced from coal, 36% from oil and 20% from gas (IEA, 2012f).

Decomposition analysis (see Figure 7.3) shows that population growth contributed 36% of additional sector emissions in 2000-2010, with GDP per capita - 72%. Over the same period, energy intensity decline (final energy consumption (FEC) per unit of GDP) compensated 45% of the emissions increment. Since electricity production grew by 1% per year faster than TPES, the ratio of TPES/FEC increased contributing 8% of the additional emissions. Sector carbon intensity relative to TPES was responsible for 28% of additional energy sector GHG emissions.

In addition to the stronger TPES growth, the last decade was marked by the failure to progress decarbonisation of the global fuel mix. With 3.6% annual growth in energy supply sector emissions, the decade with the strongest ever carbon emission mitigation policies will be remembered as the one with the strongest emissions growth in the last 40 years.

[2] The remaining energy-related emissions occur in the consumer sectors (see Figure 7.1)

[3] As in the case with energy, there is some disagreement on the historical level of global energy related GHG emissions (See Andres et al., 2012). Moreover, emission data provided by IEA or EDGAR often do not match data from national communications to UNFCCC. For example, Bashmakov and Myshak (2012) argue that EDGAR does not provide adequate data for Russian GHG emissions: according to national communication, energy-related CO_2 emissions in 1990-2010 are 37% down while EDGAR reports only a 28% decline.

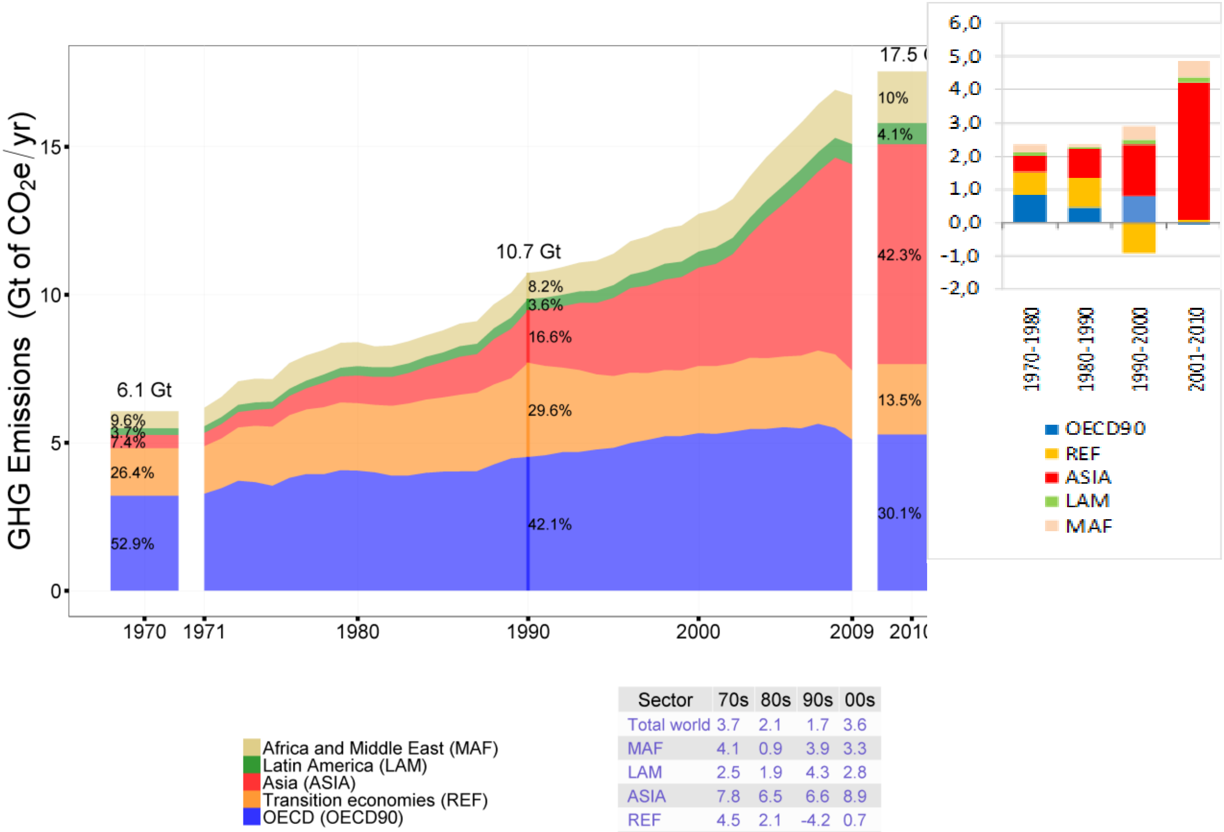


Sector	70s	8
Total energy sector	3.7	2
Indirect N2O emissions from ener	5.0	1
Others	2.9	2
Fuel production and transport	2.4	1
Manufacture of other fuels	8.2	6
Petroleum refining	2.8	2
Electricity and heat	4.3	2

Figure 7.3 Energy supply sector GHG emissions by subsectors. Table shows average annual growth rates of emissions over decades. Right hand graph displays contribution of different drivers (POP – population, FEC- final energy consumption) to energy supply sector GHG (GHGs) decadal emissions increments. The left-hand graph and table is based on the EDGAR dataset (JRC/PBL, 2012). The right-hand graph is based on IEA (2010a).

7.3.2 Regional trends

In 1990, OECD90 was the world's highest emitter of energy supply sector GHGs (42% of global total), followed by the transition economies (REF) region (30%). By 2010, Asia had become the major emitter with 42% share, and China's emissions surpassed those of the US, and India's surpassed Russia's (IEA, 2012f). Asia accounted for 77% of additional energy sector emissions in 1990-2000 and 86% in 2000-2010, followed well behind by Africa, the Middle East and Latin America (Figure 7.4). In 1990-2010, 83% of additional energy sector emissions came from Asia and 69% of the sector's global total originated in the Asian electricity and heat generation sector (Figure 7.4). The rapid increase in energy sector GHG emissions in developing Asia was due to the region's economic growth and increased use of fossil fuels. The per capita energy supply sector CO_2 emissions of Non-OECD Asia (excluding China) in 2010 was, however, only 0.75 tCO_2, against the world average of 2.06. The 2010 Chinese energy sector GHG emissions per capita of 2.86 exceeded the 2.83 of OECD-Europe (IEA, 2012f).



Sector	70s	80s	90s	00s
Total world	3.7	2.1	1.7	3.6
MAF	4.1	0.9	3.9	3.3
LAM	2.5	1.9	4.3	2.8
ASIA	7.8	6.5	6.6	8.9
REF	4.5	2.1	-4.2	0.7
OECD90	2.5	1.0	1.7	0.1

Figure 7.4 Energy supply sector GHG emissions by country groups - OECD90, ASIA countries, transition economies (REF), Africa and the Middle East (MAF), and Latin America (LAM). Table shows average annual growth rates of emissions over decades. Right hand graph shows contribution of different regions to decadal emissions increments. All information based on the EDGAR dataset (JRC/PBL, 2012).

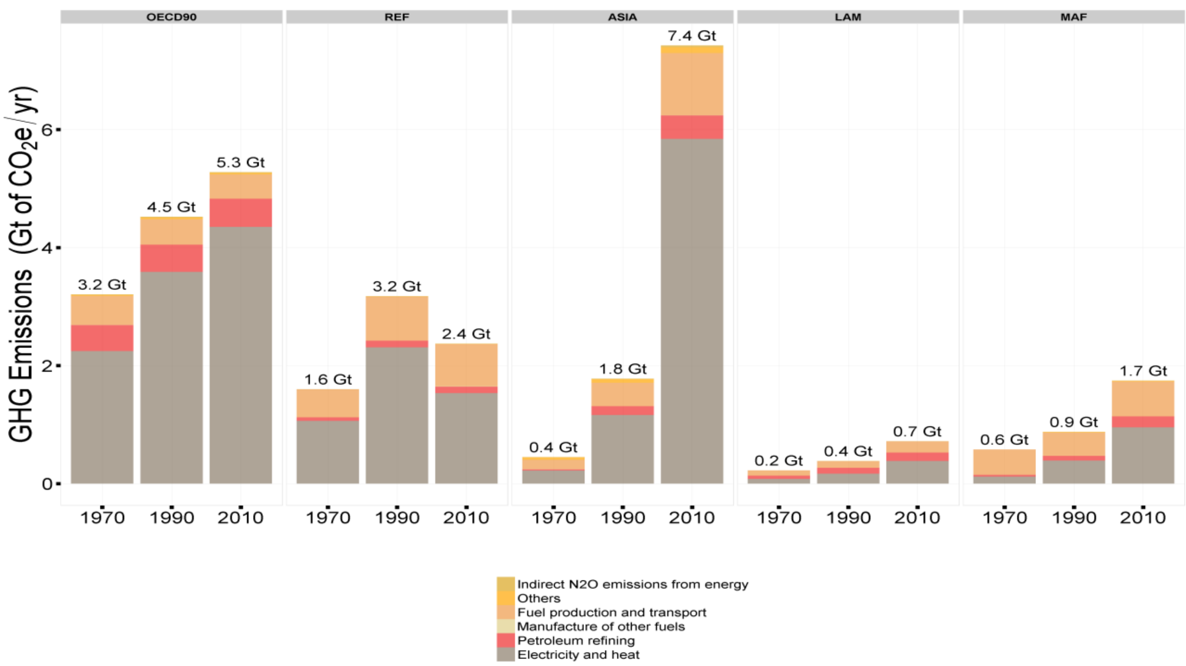


Figure 7.5 Energy sector GHG emissions by subsectors and regions. Based on the EDGAR dataset (JRC/PBL, 2012).

Energy demand driver composition differed in the last decade for Non-OECD and OECD countries. In Non-OECD, which was less affected by the recent economic crisis and whose population and GDP growth accounted for 89% and 78% of global increments respectively, contributed all additional TPES in 2000-2010, while for the OECD, 2010 TPES was slightly below the 2000 level. Two regions - non-OECD Asia (excluding China) and China - led world economic growth, driving their share in global TPES up to 32% in 2010, from 18% in 1990 and 22% in 2000. Another region with large income-driven energy sector GHG emissions in 2000-2010 was Non-OECD Europe and Eurasia, although neutralized by improvements in energy intensity. This region was the only one that managed to decouple economic growth from energy sector emissions; its GDP in 2010 being 10% above the 1990 level while energy sector GHG emissions declined by 25% over the same period (Figure 7.5).

Driven by the use of common technologies, and transition to similar consumption patterns, energy intensity in most regions but the Middle East followed a long-term converging downward trend in 2000-2010 (IEA, 2012a). This was most dominant in OECD Americas, Non-OECD Europe and Eurasia, followed by China and Non-OECD Asia. Carbon intensity decline was fastest in OECD Europe followed closely by Non-OECD Europe and Eurasia in 1990-2000, and by Latin America and OECD Americas in 2000-2010 (IEA, 2012a; US DOE, 2012); most developing countries show little or no decarbonization. Energy decarbonization progress in OECD countries (-0.4% per annum in 2000-2010) was smaller than the three previous decades, but enough to compensate their small TPES increment keeping 2010 emissions below 2000 levels. In non-OECD countries, energy-related emissions increased on average from 1.1% per year in 1990-2000 to 5.2% in 2000-2010 due to TPES growth accompanied by a 0.6% per annum growth in energy carbon intensity, driven largely by coal demand in China and India (IEA, 2012b). As a result, in 2010 non-OECD countries' energy supply sector GHG emissions were 35% over that for OECD countries. Only non-OECD Europe and Eurasia managed to reduce their energy sector GHG emissions in absolute terms during the period 1990 to 2010.

FAQ 7.1 How much does the energy supply sector contribute to the GHG emissions?

The energy sector, as defined in this report, comprises all energy extraction, conversion, storage, transmission and distribution processes with the exception of those that use final energy in the demand sectors (industry, transport and building). In 2010 the energy sector was responsible for 46% of all energy-related GHG emissions (IEA, 2012b) and 35% of anthropogenic GHG emissions, up 13.2% from 21.8% in 1970. Various end-use sectors account for the remaining energy-related emissions.

Not only is the energy sector the largest sectoral contributor to global GHG emissions, the last ten years has seen sector growth outpace that of the combined total of all anthropogenic GHG emissions by 1% per year. Much of the primary energy delivered to the system is transformed into a diverse range of energy outputs provided to end users including electricity, heat, refined oil products, coke, enriched coal, and natural gas.

A significant amount of energy is required to operate the sector making it also the largest consumer of energy. Energy use in the sector is not only a function of end user demand for higher quality energy carriers, but also the relatively low average global efficiency of energy conversion and delivery processes.

Increasing demand for high quality energy carriers by end users in many developing countries has resulted in significant growth in sector GHG emission, particularly as much of this growth was fueled by increased use of coal in Asia, mitigated to some extent by increased use of gas in other regions and continued uptake of low carbon technologies.

While combined output from low carbon technologies, which include but are not limited to hydro, wind, solar, biomass, geothermal and nuclear power, has continued to grow, their share of global primary energy has remained relatively constant; fossil fuels have maintained their dominance and CCS has yet to be applied to electricity production.

Of the RE technologies, biomass and hydro power dominate, particularly in developing countries where biomass remains an importance source of energy for heating and cooking; per capita emissions from many developing countries remain lower than the global average.

If limited to electricity production, RE now makes up around one fifth of global production, with hydroelectricity taking the dominate share. Importantly, the last ten years has seen significant growth in both wind and solar which combine to deliver around one tenth of all RE electricity produced.

Nuclear energy's share of electricity production is around 13%.

7.4 Resources and resource availability

7.4.1 Fossil fuels

The terms reserves, resources and occurrences are routinely used in the resource industry but there is no consensus on their exact meanings. 'Reserves' are generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions (BP, 2011a). 'Resources' are defined as 'concentrations of naturally occurring solid, liquid or gaseous material in or on the Earth's crust in such form that economic extraction is potentially feasible' (UNECE, 2010a). Occurrences then are the remaining materials believed to be present in the Earth's crust based on current geological information. There is also the distinction between 'conventional' and 'unconventional' resources (e.g. extra heavy oils, oil shale, oil or tar sands, coal-bed methane, shale gas, tight gas, hydrates). Unconventional resources require different logistics and production technologies than conventional occurrences and pose different environmental challenges including higher GHG emissions. Their future accessibility is, therefore, a question of technology development and costs relative to prevailing market prices.

Changing economic conditions (demand, costs and prices), technological progress in exploration and production or environmental policy may expand or contract the economically recoverable quantities of a resource. Especially improvements in knowledge which push the frontier of exploitable resources towards deeper, more remote or lower concentration occurrences, making resources a dynamically evolving rather than a 'fixed' quantity (fixed quantities inevitably lead to concepts such as peak oil or gas). Thus, while reserve constraints in cheap conventional oil are expected, other oil sources are available to fill potential gaps. The recent "shale revolution" (unconventional oil and gas) in the USA is one such example. Reserve estimates, therefore, are fraught with uncertainty.

Coal reserve and resource estimates are subject to uncertainty and ambiguity, especially when reported in physical unit (tonnes) and without a clear distinction of their specific energy contents, which can vary between 5 GJ/t and 30 GJ/t. Environmental policy as well as economic, legal, and transportation constraints could limit coal mine capacity expansion. Global coal occurrences are estimated at 17.3 to 21.0 ZJ (reserves) and 291 to 435 ZJ (resources) (see Table 7.2).

Recent global conventional oil reserve estimates range between 4.9 ZJ and 7.6 ZJ. When compared with cumulative past production of 6.8 ZJ, the "peak oil" point is imminent or has already been passed. Including resources extends conventional oil availability considerably - essentially doubling reserves (Figure 7.6). Depending on demand however, even the higher range in reserves and resources will only postpone the peak by about two decades, after which global conventional oil production will begin to decline. Unconventional oil resources are larger than their conventional counterparts. There are about 58 ZJ of shale oil, heavy oil, bitumen, oil (tar) sands and extra-heavy oil trapped in sedimentary rocks in several thousand basins around the world. Oil-shale resources are estimated at about 16 -18.9 ZJ (Dyni, 2006; WEC, 2010). Oil prices in excess of $80 per barrel are probably needed to stimulate investment in unconventional oil development (Engemann and Owyang, 2010; Rogner et al., 2012; Maugeri, 2012).

Figure 7.6 plots a stylised long-term oil supply cost curve for conventional and unconventional oil categories according to their estimated production costs and juxtaposes these quantities with past production. Oil resources (potentially yet to be produced) dwarf past cumulative production.

Conventional natural gas can be found as “associated gas” or non-associated gas. Associated gas occurs jointly with oil in reservoirs and is a by-product of oil production. Non-associated natural gas reservoirs are more abundant than reservoirs with both oil and gas. Unlike oil, natural gas reserve additions have consistently outpaced production volumes and resource estimations have increased steadily since the 1970s (IEA, 2011a). The global natural gas resource base is vast and more widely dispersed geographically than oil. Unconventional natural gas reserves, i.e., coal bed methane (CBM), shale gas, deep formation and tight gas are now estimated to be larger than conventional reserves and resources combined (see Table 7.2). In some parts of the world, supply of unconventional gas already exceeds that of conventional gas; in the US unconventional gas now makes up about 60% of marketed production (IEA, 2011a).

Table 7.2 provides a summary of past production and fossil resource estimates in terms of energy and carbon contents. The estimates span quite a range reflecting the general uncertainty associated with limited knowledge and boundaries.

For climate change, it is the carbon endowment potentially available for combustion that matters. Since the industrial revolution, fossil fuel combustion has released almost 400 Gt C into the atmosphere. As the lower end of fossil fuel reserves alone contain twice this amount of carbon, these reserves present a significant challenge to our ability to meet a 450 ppm CO_2 target and pose a threat to future climate stability.

Table 7.2: Fossil reserves, resources, and occurrences and their carbon content. Sources: (DERA, 2011; BP, 2012; Rogner et al., 2012; Schenk, 2012; Maugeri, 2012).

	Historical production to 2010		Production 2010		Reserves		Resources		Additional occurrences	
	[EJ]	[GT C]	[EJ]	[GT C]	[EJ]	[GT C]	[EJ]	[GT C]	[EJ]	[GT C]
Conventional oil	6 788	135.8	141.2	2.82	4 900 - 7 610	98 -152	4 170 – 6 150	83 - 123		
Unconventional oil	629	12.6	22.7	0.45	3 750 - 5 600	75 - 112	11 280 - 21 000	226 - 420	> 40 000	800
Conventional gas	3 572	54.6	105.5	1.61	5 000 - 7 100	76 - 108	7 200 - 10 650	110 - 136		
Unconventional gas	173	2.6	15.1	0.23	20 100 - 67 100	307 -1 026	40 200 - 121 900	614 - 1 863	> 1 000 000	> 15 200
Coal	7 426	191.7	156.2	4.03	17 300 - 21 000	446 - 542	291 000 - 435 000	7 510 - 11 230		
Total	18 588	397.3	440.7	9.14	51 050 - 108 410	1 002 - 1 940	353 850 – 594 700	8 543 – 13 772	> 1 040 000	> 16 000

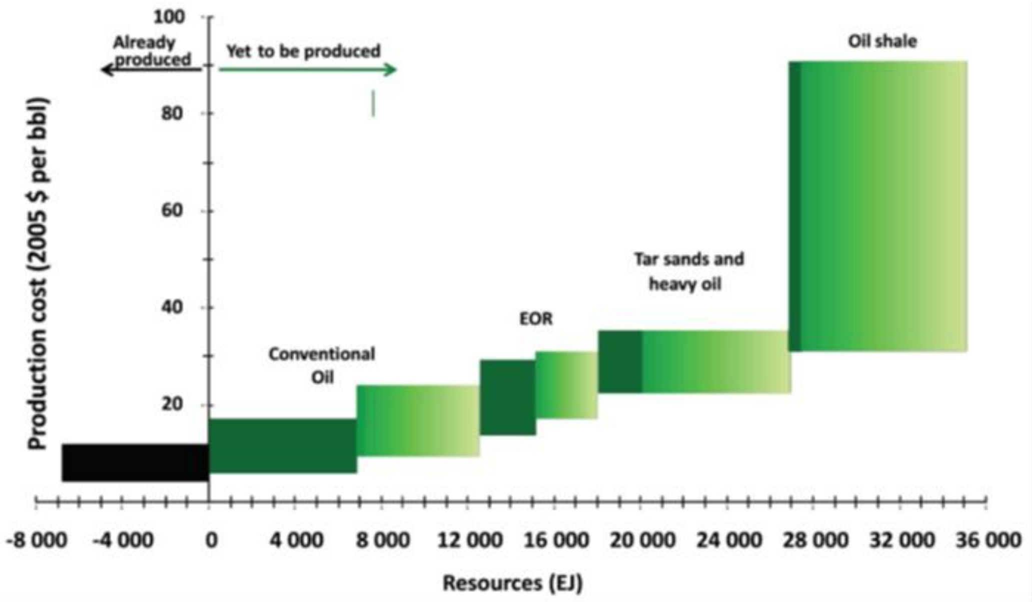


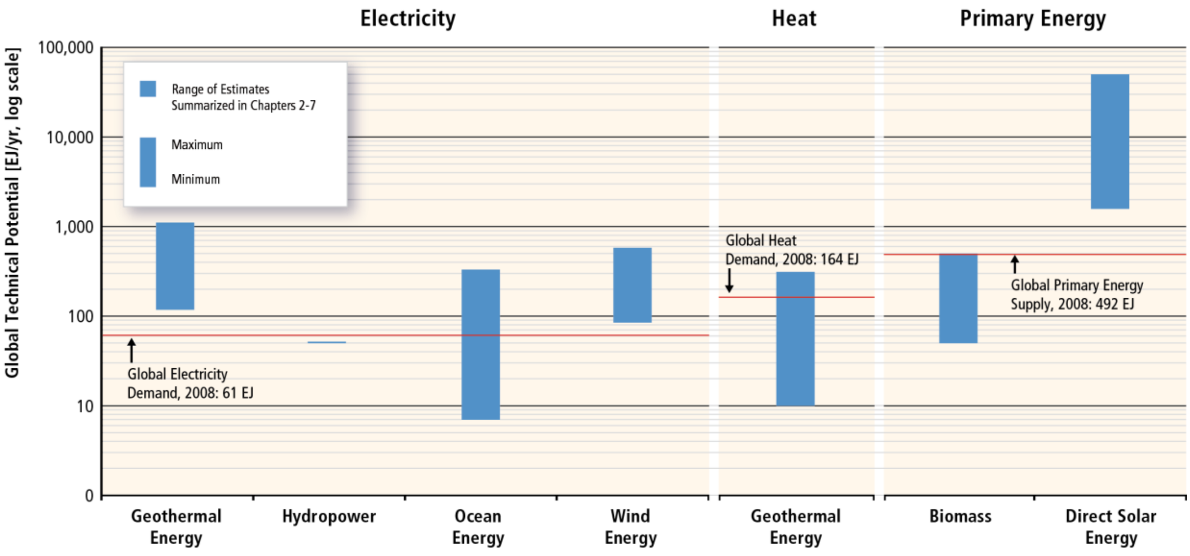
Figure 7.6 Oil based liquid fuel supply potentials and production costs. Production costs are all the costs of getting the material to the surface. The height of each bar indicates the estimated production cost range, and the width indicates the prospective resource availability. The shading reflects the state of current knowledge about the resource – the darker shading points to a higher geological assurance, while the lighter shading indicate the more speculative nature of their existence and producibility. Source: (GEA, 2012)

7.4.2 Renewable energy

Renewable energy (RE) can be defined as energy from solar, geophysical, or biological sources that, in principal, can be replenished by natural processes at a rate that at least equals its rate of use (IPCC, 2011a).[4] For the purpose of AR5, RE is defined to include bioenergy, direct solar energy, geothermal energy, hydropower, various forms of ocean energy, and wind energy. The technical potential for RE is defined in Verbruggen et al. (2011) as: "the amount of renewable energy output obtainable by full implementation of demonstrated technologies or practices." A variety of practical, land use, environmental, and/or economic constraints are sometimes used in estimating the technical potential of RE, with little uniformity across studies in the treatment of these factors, including costs. Definitions of technical potential therefore vary by study (e.g., Verbruggen et al., 2010), as do the data, assumptions, and methods used to estimate it (e.g., Angelis-Dimakis et al., 2011). There have also been questions raised about the validity of some of the "bottom up" estimates of technical potential for RE that are often reported in the literature, and whether those estimates are consistent with real physical limits (e.g., de Castro et al., 2011; M Jacobson and C Archer, 2012).

Though comprehensive and consistent estimates for each individual RE source are not available, and reported RE technical potentials are not always comparable to those for fossil fuels and nuclear energy due to differing study methodologies, the total global technical potential for RE as a whole is substantially higher than current global energy demands. Figure 7.**7** summarizes the ranges of global technical potential as estimated in the literature for the different RE sources. The technical potential for solar is shown to be the largest by a large magnitude, but sizable potential exists for many forms of RE.

[4] In practice, RE sources are sometimes extracted at a rate that exceeds the natural rate of replenishment (e.g., traditional biomass, geothermal energy). Most, but not all, RE sources impose smaller GHG burdens than do fossil fuels.



Range of Estimates of Global Technical Potentials

	Geothermal Energy	Hydropower	Ocean Energy	Wind Energy	Geothermal Energy	Biomass	Direct Solar Energy
Max (in EJ/yr)	1109	52	331	580	312	500	49837
Min (in EJ/yr)	118	50	7	85	10	50	1575

Figure 7.7 Ranges of global technical potentials of RE sources derived from studies presented in (IPCC, 2011a). Notes: Technical potentials represent total worldwide potentials for annual RE supply and do not deduct any of this potential already being utilized. The estimates are based on various different methodologies and apply to different future years; consequently, they are not strictly comparable across technologies. For additional documentation, see (IPCC, 2011a).

Also important is the regional distribution of the technical potential. Though the regional distribution of each source varies (see, e.g., IPCC, 2011a), Fischedick et al. (2011) report that the technical potential of RE as a whole is at least 2.6 times as large as 2007 total primary energy demand in all regions of the world.

Considering all RE sources *together*, the estimates reported by this literature suggest that global and regional technical potentials are unlikely to limit RE deployment even with aggressive GHG reduction goals. Moreover, as noted in IPCC (2011b), “Even in regions with relatively low levels of technical potential for any individual renewable energy source, there are typically significant opportunities for increased deployment compared to current levels.” Moreover, as with other energy sources, all else being equal, continued technological advancements can be expected to increase estimates of the technical potential for RE in the future, as they have in the past (Verbruggen et al. (2011).

Nonetheless, the long-term percentage contribution of several *individual* RE sources to climate change mitigation may be limited by the available technical potential if deep reductions in GHG emissions are sought, e.g., hydropower, bioenergy, and ocean energy, while even RE sources with seemingly higher technical potentials (e.g., solar, wind) will be constrained in certain regions (cf., Fischedick et al., 2011). Additionally, as RE deployment increases, progressively lower-quality resources are likely to remain for incremental use and energy conversion losses may increase, for example, if conversion to alternative carriers is required (Moriarty and Honnery, 2012). Competition for land and other resources among different RE sources may impact aggregate technical potentials, as might concerns about the carbon footprint and sustainability of the resource (e.g., biomass) (cf. Annex Bioenergy in Chapter 11; de Vries et al., 2007). Renewable energy technologies require additional metals, and the future demand for steel, copper and critical materials can be significant compared to current production levels and maybe even geological reserves (Kleijn and E. van der Voet, 2010; Graedel, 2011). In other cases, economic factors, environmental concerns, public acceptance, and/or system integration and infrastructure constraints might limit the deployment of individual RE technologies well before absolute technical limits are reached (e.g., IPCC, 2011b).

7.4.3 Nuclear energy

Uranium is a naturally occurring element that can be found in minute concentrations in all rocks, soils, and waters. The average uranium concentration in the continental Earth's crust is about 2.8 parts per million, while the average concentration in ocean water is 3 to 4 parts per billion (M Bunn et al., 2003). The theoretically available uranium in the Earth's crust has been estimated at 100 teratonnes (Tt) uranium of which 25 Tt occur within 1.6 km of the surface (Lewis, 1972). The amount of uranium dissolved in seawater is estimated at 4.5 Gt. Without substantial R&D efforts, these occurrences do not represent practically extractable uranium. Current market and technology conditions limit uranium extraction to concentrations above 100 ppm U. These quantities are termed conventional uranium resources.

Altogether, there are 3700 EJ (or 6.3 MtU) of conventional uranium reserves available at extraction costs of less than 260 $/kg U (current consumption amounts to about 65 000 t per year). Additional uranium resources estimated at some 12,000 EJ can be mobilized at costs larger than 260 $/kg (NEA and IAEA, 2010).

Present uranium resources are sufficient to fuel existing reactors for more than 90 years, and if all conventional uranium occurrences are considered, for almost 200 years. Reprocessing of spent fuel and recycling of unspent uranium and plutonium doubles the reach of each category (IAEA, 2009). Fast breeder reactor technology can further increase uranium utilisation 50-fold or even more with corresponding reductions in high-level waste (HLW) generation and disposal requirements (IAEA, 2004). However, reprocessing of spent fuel and recycling is not economically viable below uranium prices of 1000 $/kgU (M Bunn et al., 2003).

Further information concerning reactor technologies, costs, risks, co-benefits, deployment barriers and policy aspects can be found in Section 7.5.4, 7.8.2, 7.9, 7.10, and 7.12, respectively.

7.5 Mitigation technology options, practices and behavioural aspects

Following the Kaya identity, options to reduce GHG emissions in the energy supply sector reduce the GHG emissions intensity of a unit of useful energy (electricity, heat, fuels) supplied to end users. Section 7.5 addresses hence options to replace fossil fuels with technologies without direct GHG emissions, such as renewable and nuclear energy sources, and options to mitigate GHG emissions from the production, transport, and conversion of fossil fuels through increased efficiency, fuel switching, and GHG capture. Options to reduce energy demand are addressed in Chapters 8-12. Options mostly addressing technology; behavioural issues concern the selection of and investment in technology; these issues are addressed in sections 7.10 and 7.11. Costs and emission reduction potentials associated with the options are addressed in section 7.8, co-benefits and risks associated with the options are addressed in section 7.9.

FAQ 7.2 What are the main mitigation options in the energy sector and what is their potential for reducing GHG emissions?

The main CO_2 mitigation options in the energy sector are in no particular order (1) energy efficiency improvements (in the field of energy conversion, and – to a lower extent – in fuel extraction as well as energy transmission and energy distribution), (2) fuel switching from coal to oil to gas, (3) usage of renewable energies (RE), (4) nuclear energy and (5) carbon dioxide capture and storage technologies (CCS) which, when combined with bioenergy, can result in negative emissions (BECCS).

There is no silver bullet to the climate mitigation problem. Achieving the limit in global mean temperature change to less than the 2°C established by the Cancun Agreement requires rapid implementation of a combination of some but not necessarily all of these options. Significant emission reductions can be achieved by energy efficiency improvements and fuel switching within the set of fossil fuels, but their combined effect is not sufficient to provide the deep cuts needed to achieve the Cancun target. Achieving these deep cuts will require much more intensive use of low carbon technologies such as RE, nuclear energy, and CCS.

While the combined global technical potential of low carbon technologies is sufficient to enable deep cuts in emissions, constraints at local and regional levels exist for individual technologies. The final contribution of mitigation technologies will therefore depend on site and context specific factors such as resource availability, mitigation and integration costs, potential co-benefits and adverse side effect, as well as public perception.

Additionally, infrastructure and integration issues vary by mitigation technology and region, and while the associated challenges are not generally technically insurmountable, such issues must be carefully considered in energy supply planning and operations to ensure reliable and affordable energy supply.

7.5.1 Fossil fuel extraction, conversion and fuel switching

Given the importance of heat and power production in the energy sector, large reductions in GHG emissions can be obtained by replacing existing coal fired heat and/or power plants by highly efficient natural gas combined cycle (NGCC) power plants or combined heat and power (CHP) plants, including fuel cells . At present, there is a significant concern about fugitive methane emissions both for shale gas (Petron et al., 2012) and for conventional gas, which are both uncertain and probably higher than previously assumed (Wigley, 2011; Alvarez et al., 2012; CL Weber and Clavin, 2012). Taking into account revised estimates for fugitive methane emissions, recent life cycle assessments indicate a 50% reduction of specific greenhouse gas emissions (on a per KWh basis) when shifting from the current world-average coal fired power plant to a modern NGCC power plant, evaluated using the 100-year GWP (Burnham et al., 2012). This reduction is the result of the lower carbon content of natural gas (15.3 gC/MJ compared to 26.2 gC/MJ for sub-bitumenous coal) and the higher efficiency of combined cycle power plants (IEA, 2011a). More modest emissions reductions can be achieved when going to best available coal technology or less advanced gas power plants (Figure 7.8).

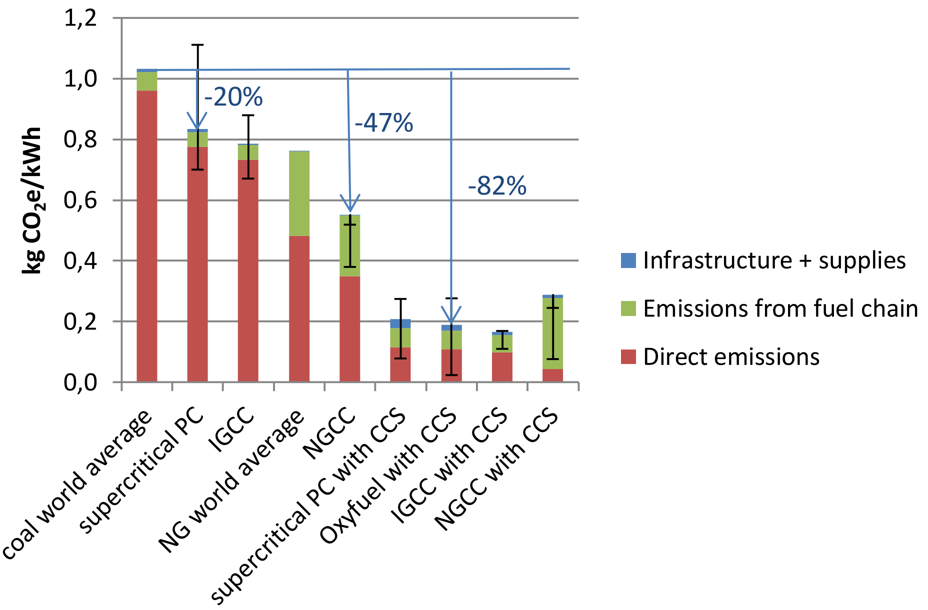


Figure 7.8 Greenhouse gas emissions from current world average coal and gas fired power plants and mitigation opportunities associated with going to best available technology (BAT) conventional plants and plants with CO_2 capture and storage (CCS), taking into account new estimates for fugitive emissions from fossil fuel production. Based on (Bhawna Singh et al., 2011) with updated numbers for fugitive methane emissions (Burnham et al., 2012). The range indicated by the uncertainty bars

represents the ranges of results reported in the peer reviewed literature, based on lower estimates for fugitive emissions from fuel production (Corsten et al., 2013).(Legend: PC: Pulverized black coal, IGCC: Integrated gasification combined cycle of black coal, NGCC: Natural gas combined cycle)

Global NGCCs emissions are too high to meet long-term stabilization targets if NGCCs are used for base-load power production. Further emissions reductions are possible through CO_2 capture and storage (Section 7.5.5). A better appreciation of the importance of fuel chains since AR4 results in a downward adjustment of the estimated benefit from fuels switching. If gas is liquefied using coal power and shipped over long distances, life-cycle GHG emissions of electricity generated with LNG can in the worst case be close to the emissions from current coal technology (Jaramillo et al., 2007).

Fossil fuel extraction and distribution currently contribute 5- 10% of total fossil-fuel related GHG emission, with a large uncertainty associated with fugitive emissions (Alsalam and Ragnauth, 2011; IEA, 2011a; Burnham et al., 2012). Emissions may increase in the future due to the more energy-intensive production of oil and gas from mature fields, because of unconventional sources, and the mining of coal from deeper mines, as well as through longer transportation distances (Gagnon, Luc et al., 2009; Leuchtenböhmer and Dienst, 2010). Emissions associated with fuel production and transport can be reduced through higher energy efficiency and the use of lower-carbon energy sources in mines, fields, and transportation networks (IPIECA and API, 2007; Hasan et al., 2011), the capture and utilization (UNECE, 2010b) or treatment (US EPA, 2006; IEA, 2009a; Karacan et al., 2011; Karakurt et al., 2011; Su et al., 2011) of methane from coal mining, and the reduction of venting and flaring from oil and gas production (IPIECA and API, 2009; MR Johnson and Coderre, 2011).

Fugitive emissions associated with unconventional gas production are controversially discussed (Howarth et al., 2011; Cathles et al., 2012) and both variable and uncertain (Stephenson et al., 2011; O'Sullivan and Paltsev, 2012; CL Weber and Clavin, 2012). These emissions depend to a significant degree on whether practices, such as green completion, are mandated and implemented in the field (Barlas, 2011; J Wang et al., 2011; O'Sullivan and Paltsev, 2012). Emissions associated with synthetic crude production from oil sands are higher than those from most conventional oil resources (Charpentier et al., 2009), and these emissions are related to extra energy requirements, fugitive emissions from venting and flaring (MR Johnson and Coderre, 2011), and land use (Rooney et al., 2012).

7.5.2 Energy efficiency in transmission and distribution

Electrical losses associated with the high voltage transmission system are generally less than losses within the lower voltage distribution system mainly due to the fact that the total length of transmission lines is far less than that for distribution in most power systems. These losses are due to a combination of cable or line losses and transformer losses and of course the patterns of loss do vary with the nature of the power system and in particular its geographical layout. Losses as a fraction of energy generated vary considerably between countries with developed countries tending to have lower losses and a number of developing countries, including India, having losses of over 20% in 2010 according to IEA online data. Combined transmission and distribution losses for the OECD countries taken together were 6.5% of total electricity output in 2000 (IEA, 2003a), which is close to the EU average (European Copper Institute, 1999).

Approximately 25% of all losses in Europe, and 40% of distribution losses, are due to distribution transformers (and this will be similar in OECD countries) so use of improved transformer designs can make a significant impact (see European Copper Institute, 1999 and in particular Appendix A therein), although the investment required to do this should not be underestimated, and the industry would require suitable incentives to move on this. Roughly a further 25% of losses are due to the distribution system conductors and cables. An increase in distributed generation can reduce these losses since generation typically takes place closer to loads than with central generation and thus the electricity does not need to travel so far, although if a large amount of distributed power generation is exported back into the main power system to meet more distant loads then losses can increase again. The use of greater interconnection to ease the integration of time varying renewable into power systems would be expected to increase the bulk transfer of power over considerable distances, maybe up to a thousand kilometers. This has not so far been quantified in any detail but would be expected to increase transmission losses.

A number of other technology developments may also impact on transmission losses. These include new high temperature cable designs, dynamic loading, gas-insulated transmission lines, and high voltage DC transmission (HVDC). High-temperature low-sag (HTLS) conductors incorporate high tensile materials such as carbon or glass fibre alongside the conductors to take the load and limit the thermal expansion that results in sag (Mazón et al., 2004) and thus allows higher load operation. Dynamic loading involves allowing higher loads when natural conductor cooling is high due to low ambient temperature and/or high winds. Both dynamic loading and HTLS allow better use of assets but they both will result in higher losses. The correlation of overhead line cooling with wind power output is also attracting interest in dynamic line rating. On the other hand, gas-insulated transmission lines (GILs) and HVDC have the potential to reduce losses. GILs are much more expensive than conventional lines and are likely to be used only for short buried sections of transmission (Benato et al., 2001). HVDC in contrast becomes cost effective for very long lines (ie over 250 kms, but note that this depends critically on the application) and in such applications will have overall lower losses. HVDC will be used for the connection of large offshore wind farms due to the adverse characteristics of long sub-sea AC transmission cables.

Crude oil transportation from upstream production facilities to refineries and subsequent moving of petroleum products to service stations or end user is an energy extensive process if it is not effectively performed (PetroMin Pipeliner, 2010). Pipelines are the most efficient means to transport fluids. Most crude oil contains wax or asphaltenes or a combination that may cause difficulties in cold weather conditions to pipeline performance. Flow assurance confirm fluid flow in pipelines and keep the pipeline safe by using certain methods, equipment, and additives to ease the flow and to reduce energy requirement (Bratland, 2010). New pumps technology, pipeline pigging facilities, chemicals such as pour point depressants (for waxy crude oil), and drag reducing agents are good examples of these technologies that increase the pipeline throughput and maintain flow in cold weather conditions.

Finally, it is worth noting that the decarbonisation of heat through heat pumps and transport through an increased use of electric vehicles (EVs), will require major additions to generation capacity and aligned with this, a massively improved transmission and distribution infrastructure. Exactly how much will depend very much on whether these new loads are controlled and rescheduled through the day by demand side management. These new investments may allow improvements in efficiency that would not be justified on the basis of reducing emissions in a context of alternative more energy and cost effective alternatives.

7.5.3 Renewable energy technologies

Only a small fraction of the RE technical potential has been tapped so far (see Section 7.4.2, and (IPCC, 2011a)) and, as shown in Section 7.8.1, most, but not all, forms of RE supply have low life-cycle GHG emissions in comparison to fossil fuels. These factors indicate the potential for substantial GHG emissions reduction through many forms of RE deployment.

Though RE sources are often discussed together as a group, the specific conversion technologies used are numerous and diverse. A comprehensive survey of the literature is available in (IPCC, 2011a). RE sources are capable of supplying electricity, but some sources are also able to supply thermal and mechanical energy, as well as produce fuels that can satisfy multiple energy service needs (Moomaw et al., 2011). Many RE sources are primarily deployed within larger, centralized energy networks, but some technologies can be and often are deployed at the point of use in a decentralized fashion (J. Sathaye et al., 2011a; Sims et al., 2011; REN21, 2012). The use of RE in the transport, buildings, and industrial sectors, as well as in agriculture, forestry, and human settlements, is addressed more-fully in Chapters 8-12.

RE technologies have advanced substantially in recent decades, and since the IPCC's AR4 (D. J. Arent, Wise, and Gelman 2011; IPCC 2011a). For example, improvements in manufacturing processes and photovoltaic (PV) cell efficiencies, along with reductions in materials use and changed market conditions (i.e., manufacturing supply exceeding demand), have helped to substantially reduce the price of PV modules. Continued increases in the size and therefore energy capture of individual wind turbines deployed both on land and offshore have reduced the levelised cost of land-based wind energy, and improved the prospects for offshore wind energy. Commercial deployments of various concentrated solar thermal power (CSP) technologies, some of which have been coupled with thermal storage or back-up gas turbines, have occurred in a few countries. Improvements have also been made in cropping systems, logistics, and multiple conversion technologies for bioenergy (see Bioenergy Annex of chapter 11). IPCC (2011a) provides further examples from a broader array of RE technologies.

A growing number of RE technologies have achieved a level of technical and economic maturity to enable deployment at significant scale, while others are less mature and not yet widely deployed (IPCC, 2011a). Large scale hydropower technologies, for example, are technically and economically mature. Bioenergy technologies, meanwhile, are diverse and span a wide range; examples of mature technologies include conventional biomass-fuelled power plants and heating systems, as well as ethanol production from sugar and starch, while lignocellulose-based transport fuels are at a pre-commercial stage (see Bioenergy Annex of chapter 11). The maturity of solar energy ranges from R&D (e.g., fuels produced from solar energy) to relatively more technically mature (e.g., CSP), to technically mature (e.g., solar heating and wafer-based silicon PV), though even the technologies that are relatively technically mature may not have reached a state of economic competitiveness. Geothermal power plants and thermal applications that rely on hydrothermal resources rely on mature technologies, whereas enhanced geothermal systems are in the demonstration phase while also undergoing R&D. With the exception of certain types of tidal barrages, ocean technologies are also at the demonstration phase and require additional R&D. Finally, though traditional land-based wind technologies are already mature, the use of wind energy in offshore locations is increasing but is less technically mature and is almost always more costly than land-based wind.

Because the cost of energy from many (but not all) RE technologies has historically been higher than market energy prices (e.g. Fischedick et al., 2011; Section 7.8), public R&D programs have been important and government policies have played a major role in defining the amount and location of RE deployment (IEA, 2011b; Mitchell et al., 2011; REN21, 2012). Additionally, because RE relies on natural energy flows, some (but not all) RE technologies must be located at or near the energy resource, collect energy from diffuse energy flows, and produce energy output that is variable and, while power output forecasting has improved, to some degree unpredictable (IPCC, 2011b). The implications of these characteristics for infrastructure development and network integration are addressed in Section 7.6.1.

Though modern forms of RE (excluding traditional biomass) remain a relatively small fraction of total global and regional primary energy supply (see Sections 7.2 and 7.3), they contributed 20% of global electricity supply in 2011 (mostly hydropower; see (REN21, 2012)) and deployment has been significant since the IPCC's AR4. In 2011, RE power capacity grew rapidly: REN21 (2012) reports that RE accounted for almost half of the 208 GW of new electricity generating capacity added globally in 2011.[5] As shown in Table 7.3, the fastest growing sources of RE power capacity included wind power

[5] A better metric of the relative contribution of RE would be based on energy supply, not installed capacity, especially because of the relatively low capacity factors of some RE sources. Energy supply statistics for power plants constructed in 2011, however, are not available.

(40 GW added in 2011), solar PV (30 GW), and hydropower (25 GW).[6] In aggregate, the growth in cumulative renewable electricity capacity equalled 8% from 2009 to 2010 and from 2010 to 2011. Biofuels accounted for 3% of global road transport fuel demand in 2011 (REN21, 2012). By the end of 2011, the use of RE in hot water/heating markets included 290 GWth of modern biomass, 232 GWth of solar, and 58 GWth of geothermal heating (REN21, 2012).

Collectively, developing countries host more than half of global RE electricity generation capacity, with China adding more capacity (primarily hydropower and wind power) than any other country in 2011 (REN21, 2012). Cost reductions for solar PV have been particularly sizable in recent years, resulting in and reflecting strong percentage growth rates (albeit from a small base), with the majority of new installations coming from Europe (and to a lesser degree Asia and North America) but with manufacturing shifting to Asia. The USA and Brazil accounted for 63% and 24%, respectively, of global bioethanol production in 2011, while China led in the use of solar hot water (REN21, 2012). Decentralized RE to meet rural energy needs particularly in the less developed countries has also increased, including small hydropower plants, various modern biomass options, PV and wind, thereby expanding and improving energy access (IPCC, 2011b; REN21, 2012).

In a review of the energy scenario literature, Fischedick et al. (2011) find that, while there is no obvious single dominant RE technology that is likely to be deployed at a global level, bioenergy, wind, and solar have been more commonly identified as the largest possible contributors by 2050 (see also other chapters and sections of the AR4).[7] The mix of RE technologies suited to a specific location, however, will depend on local RE resource availability, with hydropower and geothermal playing a significant role in certain countries.

The scenarios literature has often found that, across all energy sectors, RE is likely to penetrate most rapidly in electricity generation, at least in the near to medium term, followed by RE for heating/cooling and transport (e.g., Fischedick et al. (2011)). This is in part due to the fact that some forms of RE are primarily used to produce electricity and only biofuels are used directly on a large scale as a transportation fuel (e.g., Armaroli and Balzani, 2011). As a result, the ultimate contribution of RE to overall energy supply may be dictated in part by the future electrification of transportation and heating/cooling or by using RE to produce other energy carriers, e.g., hydrogen (Sims et al., 2011; Mark Z. Jacobson and MA Delucchi, 2011).

[6] REN21 (2012) estimates that biomass power capacity increased by 5.9 GW in 2011, CSP by 0.5 GW, ocean power by 0.3 GW, and geothermal power by 0.1 GW.

[7] Due to its ability to be coupled with CCS and potentially deliver net-negative GHG emissions, analyses of global carbon mitigation scenarios have sometimes identified a sizable potential role for biomass CCS, especially in cases with particularly low GHG stabilization targets (e.g., see Chapter 6, Section 7.5.5, Section 7.11, and (D. P van Vuuren et al., 2010).

Table 7.3 Selected Indicators of Recent Global Growth in RE Deployment (REN21, 2012)

Selected Indicators	Units	2009	2010	2011	Annual Growth Rate in Total Units	
					2009→ 2010	2010→ 2011
RE electric power capacity	GW, total	1,170	1,260	1,360	8%	8%
Hydropower capacity	GW, total	915	945	970	3%	3%
Wind power capacity	GW, total	159	198	238	25%	20%
Solar PV capacity	GW, total	23	40	70	72%	74%
Solar hot water capacity	GWth, total	153	182	232	19%	27%
Ethanol production	Billion litres/yr	73.1	86.5	86.1	18%	-0.4%
Biodiesel production	Billion litres/yr	17.8	18.5	21.4	4%	16%

Note: A better metric of the relative contribution of RE would be based on energy supply, not installed capacity, especially because of the relatively low capacity factors of some RE sources. Energy supply statistics for power plants constructed in the most recent years, however, are not available.

7.5.4 Nuclear energy

Nuclear energy is utilized for electricity generation in thirty-one regions around the world. There are 437 nuclear reactors in operation with a total installed capacity of 372 GWe as of January 2013 (IAEA, 2013). Nuclear electricity represented 13% of the world's electricity generation in 2010 with a total generation of 2756 TWh (IEA, 2012g). The US, France, Japan, Russia, and Korea (Rep. of) with 101, 63, 44, 24, and 21 GWe of nuclear power, respectively, are the top five countries in installed nuclear capacity and together represent 68% of total global nuclear capacity as of January 2013 (IAEA, 2013). The majority of the world's currently operating reactors are based on light-water technology of similar concept, design and fuel cycle. Of the reactors worldwide, 357 are light-water reactors (LWR), of which 273 are Pressurized Water Reactors (PWR) and 84 are Boiling Water Reactors (BWR) (IAEA, 2013).The remaining reactor types consist of 48 heavy-water reactors (PHWR), 15 gas-cooled reactors (GCR), 15 graphite-moderated reactors (RBMK/LWGR), and 2 fast breeder reactors (FBR) (IAEA, 2013).

New LWRs continue to evolve with designs focused on improved passive and active safety features. For example, new commercial reactors, such as the European Pressurized Reactor (EPR, France), Advanced Passive-1000 (AP-1000, USA-Japan), Water-Water Energetic Reactor-1200 (VVER-1200, Russia), and Advanced Power Reactor-1400 (APR-1400, Rep. of Korea) all have improved safety features over the previous generation of LWRs (Cummins et al., 2003; IAEA, 2006; H-G Kim, 2009; Goldberg and Rosner, 2011). Several of these new generations of reactors are currently under construction and planned for construction (IAEA, 2012).

Other more revolutionary small modular reactors (SMR) with additional passive safety features are under development (IAEA, 2005; Rosner and Goldberg, 2011; Vujic et al., 2012; World Nuclear Association, 2012a). The size of these reactors is typically less than 300 MWe and much smaller than the 1000 MWe size of current LWRs. Their lower power density, large heat capacity, and heat removal through natural means improve their safety designs. Light-water SMRs are intended to rely on the substantial experience with current LWRs and utilize existing fuel cycle infrastructure. Gas-cooled SMRs that operate at higher temperatures have the potential for increased electricity generation efficiencies relative to LWRs and industrial applications as a source of high temperature process heat (EPRI, 2003; Z Zhang et al., 2009). In general, smaller reactors that are constructed in a factory setting with modular construction techniques may benefit from economies of manufacturing and learning by doing. While shorter power plant construction periods, incremental capacity additions to the power grid, and potential for improved financing and economics of nuclear energy use are additional motivating factors, the widespread applicability of SMRs remains yet to be observed.

The current nuclear fuel cycle has a direct impact on uranium resource utilization, nuclear proliferation and waste management. Reliance on U-235, a relatively scarce uranium isotope, as the primary source of nuclear fission with the bulk of fissionable U-238 relegated to the waste stream implies that the current nuclear fuel cycle does not effectively utilize available uranium resources. Red Book estimates of identified conventional uranium resources are sufficient for over 100 years of supply for the global nuclear power fleet at current usage rates, however (NEA and IAEA, 2012). While the ultimate availability of natural uranium resources is uncertain (see 7.4.3), inefficient utilization of existing uranium resources implies quicker transition to ore grades of lower uranium concentration (E Schneider and Sailor, 2008). Uranium ore costs are a small component of nuclear electricity costs (IAEA, 2012), however, and are not likely to have a significant impact on the competitiveness of nuclear power. Additionally, the necessity for uranium enrichment for LWRs and the presence of plutonium in the spent fuel are the primary proliferation concerns. There are differing national policies for the use or storage of fissile plutonium in the spent fuel, however, with some nations electing to recycle plutonium for use in new fuels and others electing to leave it intact within the spent fuel. The presence of plutonium and minor actinides in the spent fuel leads to greater waste disposal challenges as well. Heavy isotopes such as plutonium and minor actinides have very long half-lives, as high as tens to hundreds of thousands of years, which require final waste disposal strategies to address safety of waste disposal on such great timescales. Alternative strategies to isolate and dispose of fission fragments and their components apart from actinides could have significant beneficial impact on waste disposal requirements (Wigland et al., 2006). Others have argued that separation and transmutation of actinides would have little or no practical benefit for waste disposal (NRC, 1996; M Bunn et al., 2003).

Alternative nuclear fuel cycles, beyond the once-through uranium cycle, and related reactor technologies are under investigation. Partial recycling of used fuels, such as the use of mixed oxide (MOX) fuels where U-235 in enriched uranium fuel is replaced with recycled or excess plutonium, is utilized in some nations to improve uranium resource utilization and waste minimization efforts (OECD and NEA, 2007; World Nuclear Association, 2012b). Ultimately, full recycling options based on either uranium or thorium fuel cycles that are combined with advanced reactor designs where only fission fragments are relegated as waste can significantly extend nuclear resources and reduce high-level wastes (GIF, 2002). Higher economic costs increases complexities and associated risks of advanced fuel cycles and reactor technologies are current drawbacks. Potential access to fissile materials from widespread application of reprocessing technologies further raises proliferation concerns. The advantages and disadvantages of alternative reprocessing technologies are under investigation.

There is not a commonly accepted single worldwide approach to dealing with the long-term storage and permanent disposal of high-level waste. Regional differences in the availability of uranium ore and land resources, technical infrastructure and capability, nuclear fuel cost, and societal acceptance of waste disposal have resulted in alternative approaches to waste storage and disposal. Regardless of these differences and the fuel cycle ultimately chosen, some form of long-term storage and permanent disposal, whether surface or geologic (subsurface), is required. Finland and Sweden are the furthest along in their development of geologic disposal facilities for the direct disposal of their high-level waste (Posiva Oy, 2011; SKB, 2011). Other countries, such as France and Japan, have chosen to reprocess spent fuel to use the recovered uranium and plutonium for fresh fuel and to dispose fission products and other actinides in a geologic repository (OECD and NEA, 2007). Yet others, such as Korea (Rep. of), are pursuing a synergistic application of light and heavy water reactors to reduce the total waste by extracting more energy from used fuels (Myung et al., 2006).

In the US, waste disposal options are currently under review with the termination of the Yucca Mountain nuclear waste repository in Nevada. The Yucca Mountain facility, originally approved in 2002 as a geologic repository for spent nuclear fuel and other high-level waste, was cancelled in 2009 (CRS, 2012). Indefinite dry casks storage of high-level waste at reactor sites and interim storage facilities is to be pursued until decisions on waste disposal are resolved.

In March of 2011, an unprecedented earthquake of 9.0 magnitude and ensuing tsunami off the east coast of Japan caused a severe nuclear accident in Fukushima, Japan (Prime Minister of Japan and His Cabinet, 2011). The significant release of radioactive materials from the Fukushima accident rate it a Level 7, the maximum level of the International Nuclear and Radiological Event Scale (INES) for nuclear accidents. The severity of the nuclear accident in Japan has brought about a reinvestigation of nuclear energy policy and deployment activities for several nations around the world, most notably in Japan and Germany. The response to the accident has been otherwise mixed and its full impact may not be realized for many years to come (see 7.9.3). The accident in Japan has not, however, affected the nuclear deployment activities for those nations with rapid growth in the demand for electricity and/or interest in the diversification of power supplies along with motivations for GHG emissions reduction. The significant on going and planned nuclear deployment activities of several countries continue. There are 68 nuclear reactors, representing 65 GWe of capacity, currently under construction in 14 countries (IAEA, 2013).

Fifty-one of the reactors under construction are located in only four countries, China, Russia, India, and Korea (Rep. of). China has the most active nuclear reactor deployment program of any nation with 29 reactors under construction.

Nuclear energy has been around for five decades or more. With low levels of life cycle GHG emissions (see 7.8.1), nuclear power contributes to emissions reduction today and potentially in the future. Continued use and further expansion of nuclear energy worldwide as a response to mitigating climate change require greater efforts to improve the safety, economics, uranium utilization, waste management, and proliferation concerns of nuclear energy use. Research and development of the next generation nuclear energy system, beyond the evolutionary LWRs and SMRs, is being undertaken through national and international efforts (Generation IV International Forum, 2009). New fuel cycles and reactor technologies are under investigation in an effort to address the concerns of nuclear energy use. Further information concerning resources, costs, risks, co-benefits, deployment barriers and policy aspects can be found in Section 7..4.3, 7.8.2, 7.9, 7.10, and 7.12, respectively.

7.5.5 Carbon dioxide capture and storage (CCS)

All of the components of integrated carbon dioxide capture and storage (CCS) systems exists and are in use today by the hydrocarbon exploration, production and transport; petrochemical refining; and power engineering sectors. A complete end-to-end CCS system would mitigate CO_2 emissions by capturing CO_2 from large (e.g., typically larger than 0.1 $MtCO_2$/year) stationary point sources (e.g., fossil-fuelled power plants, petrochemical refineries, cement plants), compressing the captured CO_2, transporting and injecting the compressed CO_2 into a suitable deep (typically more than 800m below the surface) geologic structures, and then applying a suite of measurement, monitoring and verification (MMV) technologies to ensure the safety, efficacy, and permanence of the captured CO_2's isolation from the atmosphere (IPCC, 2005; Howard J. Herzog, 2011). CCS is a technology suite that has the single purpose of capturing and storing CO_2 and therefore is not deployed without either limits on emissions or under very special circumstances in which the CO_2 has special value, such as is the case with tertiary recovery of hydrocarbons (IPCC, 2005). While it is true that all the component technologies that would comprise a complete end-to-end CCS system are in use today as of early 2013, CCS has not been applied to a large, commercial fossil-fired electricity generation facility (Global CCS Institute, 2011) nor has there been commercial deployment of CCS in the many varied industrial (i.e., non-power) sectors where CCS is seen as a key for reducing CO_2 emissions.

As of early 2013, there are five large end-to-end commercial CCS facilities including the requisite MMV programs in operation around the world that collectively store more than 7 $MtCO_2$/year and which have stored more than 30$MtCO_2$ over their lifetimes (Eiken et al., 2011; Whittaker et al., 2011; Global CCS Institute, 2011). There are dozens of other industrial-scale, field demonstration CCS projects across the world that are providing critical advances in our knowledge of CCS systems and their engineering, technical, economic and policy impacts (NETL, 2010; Global CCS Institute, 2011). A considerable body of practical and scientific knowledge has been generated from these first large scales complete CCS deployments. For example, Eiken et al. (2011) and Whittaker et al., (2011), note that advanced drilling technologies (e.g., long horizontal wells with multiple injection intervals) to optimize the placement of the injected CO_2 in the target storage formation have been utilized at these facilities.

In their review of these early CCS deployments Eiken et al. (2011) and Whittaker et al., (2011) also make the case that the acquisition and use of high quality MMV data at each of these sites is integral to the effective management of a CO_2 storage facility in the near, mid and long term. These data for the active management of a storage formation and allow CO_2 storage operators and regulators to have confidence in low leakage detection thresholds; to make informed decisions about the operation of the storage field; and, in turn, can reduce the probability and magnitude of adverse events (Buscheck et al., 2012). A large number of MMV technologies have already been used in the field to monitor injected CO_2 and these MMV deployments have helped to create the beginnings of a still to be fully defined broader portfolio of MMV technologies which can be matched to the site-specific geology and project- and jurisdiction-specific MMV needs (A Mathieson et al., 2010; Vasco et al., 2010; K Sato et al., 2011).

If in the coming decades the commercial deployment of CCS systems is quite significant (e.g., of a magnitude comparable to that described for CCS in Chapter 6 and in Sections 7.11), that would imply that large regional deep geologic basins would have to accommodate multiple large-scale CO_2 injection projects and therefore the literature is reflecting more detailed studies of the impacts of multiple large anthropogenic CO_2 sources storing their CO_2 into a regional deep geologic formation (S. Bachu, 2008; Nicot, 2008; Birkholzer et al., 2009; Oruganti and Bryant, 2009; Ruben Juanes et al., 2010; JP Morris et al., 2011). These papers all stress the need for good CO_2 storage site selection that would explicitly address the cumulative far-field pressure effects from multiple injection projects which should facilitate the responsible management of the basin and avoid most or all of the negative consequences associated with many large CO_2 storage projects within a single regional basin. The technical literature is also quantifying potential consequences of pressure build up within a formation caused by CO_2 storage such as induced seismicity (Mazzoldi et al., 2012; R. Juanes et al., 2012), potential human health consequences from CO_2 that migrates out of the primary injection zone (JJ Roberts et al., 2011; de Lary et al., 2012) as well as mechanisms for actively managing the storage formation and withdrawing formation waters to reduce pressure build up (Esposito and S.M. Benson, 2012; Réveillère et al., 2012; EJ Sullivan et al., 2013).

As noted by Bachu (2008), Krevor et al., (2012) and IPCC (2005) there are a number of key physical and chemical processes that work in concert to help ensure the efficacy of deep geologic CO_2 storage. There is also a growing body of literature that consolidates the significant knowledge base that exists on how to ensure the integrity of CO_2 injector and monitoring wells (J. William Carey et al., 2007; Jordan and Sally Benson, 2009; W. Crow et al., 2010; WJ Carey et al., 2010; M Zhang and Stefan Bachu, 2011; Matteo and Scherer, 2012). Field experience and research from a number of groups around the world confirm this and taken together their work points to a declining long-term risk profile (i.e., a thin tail) for CO_2 stored in deep geologic reservoirs (Hovorka et al., 2006; Gilfillan et al., 2009; Jordan and Sally Benson, 2009) (Hovorka et al., 2006; Gilfillan et al., 2009; Jordan and Sally Benson, 2009).

Research aimed at improving the performance and cost of CO_2 capture systems is significant and broad based across three broad classes of CO_2 capture technologies; pre-combustion (Edward S.

Rubin et al., 2007; Figueroa et al., 2008), post-combustion (Lin and Y-W Chen, 2011; Padurean et al., 2011; Versteeg and E.S. Rubin, 2011) and oxy-based capture (Scheffknecht et al., 2011; Wall et al., 2011).

There is also a broad body of research describing the performance and potential for improvement for CO_2 capture systems that are purpose-built for a number of different classes of industrial facilities (i.e., beyond the electric power sector) such as petroleum refineries (De Mello et al., 2009; van Straelen et al., 2010; Johansson et al., 2012), combined heat and power facilities (T. Kuramochi et al., 2010), cement kilns (Liang and J Li, 2012; Vatopoulos and Tzimas, 2012), and steel mills (HH Cheng et al., 2010; Arasto et al., 2012; Tsupari et al., 2012). Estimates for CO_2 capture costs are summarized in sections 7.8.2.

The high capital costs, low variable cost, and single purpose nature of CO_2 capture equipment when mated to power plants drives these CCS-enabled power plants down the dispatch curve where they serve primarily to produce baseload power (T Johnson and D Keith, 2004; MA Wise and J.J. Dooley, 2005). Jordal et al., (2012), Chalmers and Gibbins (2007), Cohen et al., (2012), and Nord et al., (2009) have examined how natural gas and coal fired baseload CCS-enabled power plants could be modified to also serve peak electricity demand for brief periods. In the long-term the largest market for CCS systems is most likely to be in the electric power sector (IPCC, 2005). However, near-term early deployment of CCS in both developed and developing nations are likely to arise in the aspects of the industrial sector that produce high purity CO_2 waste streams that are typically vented to the atmosphere such as ethanol plants and natural gas processing facilities (IPCC, 2005; Bakker et al., 2010; Vergragt et al., 2011).

Over the past decade a much more robust and standardized CO_2 storage capacity methodology has been developed for different types of deep geologic formations (John Bradshaw et al., 2007; Stefan Bachu et al., 2007; Kopp et al., 2009; Orr, 2009; Goodman et al., 2011; PNK De Silva et al., 2012) and has been applied in many regions of the world. For example since 2009, estimates of geologic CO_2 storage have been published for regions as diverse as: 67 $GtCO_2$ in suitable deep geologic structures in the Norwegian sector of the North Sea (NPD, 2011); 146 $GtCO_2$ in Japan and its nearby territorial waters (Ogawa et al., 2011); 360 $GtCO_2$ in Continental Europe (Vangkilde-Pedersen et al., 2009); 250-560 $GtCO_2$ in depleted natural gas fields around the world (IEAGHG, 2009), 2,300 $GtCO_2$ in China (RT Dahowski et al., 2009, 2011); and 1,300 to 13,600 $GtCO_2$ in the continental USA. Utilizing the "Geologic CO_2 Storage Resource Pyramid" which has been promulgated by a number of key international research consortia (CSLF, 2008; IEAGHG, 2011) as a means of standardizing estimates of geologic CO_2 storage capacity computed with different levels of data and assuming various engineering and economic constraints, Dooley (2012) estimates global theoretical CO_2 storage at 35,000 $GtCO_2$, global effective storage capacity at 13,500 $GtCO_2$, global practical storage capacity at 3,900 $GtCO_2$, matched capacity for those regions of the globe where this has been computed at 300 $GtCO_2$, and lastly approximately 0.03 $GtCO_2$ of global geologic CO2 storage capacity has already been utilized.

For the USA, Szulczewski et al., (2012) show that even when taking into account realistic limits on injection rates the geologic CO_2 storage capacity of the USA should last at least a century. Dooley (2012) extends this analysis to the global level and surveys a broad body of published estimates of the likely demand for CO_2 storage over the course of this century and concludes that the amount of geologic CO_2 storage capacity available is likely sufficient to meet potential demand during this century.

In Dooley's (2012) meta-analysis, the average demand for geologic CO_2 storage across a number of scenarios with end of century CO_2 concentrations of approximately 550 ppmv is on the order of 448 $GtCO_2$, while the average demand for CO_2 storage for scenarios that have end of century CO_2 concentrations of approximately 450 ppmv is approximately 640 $GtCO_2$, and the average demand for scenarios that have end of century CO_2 concentrations between 400-425 ppmv is 1000 $GtCO_2$.

Edmonds, et al., (2007) note that the value of having CCS in society's portfolio of responses to climate change is still in the order of trillions of dollars, "even if the realizable CO_2 storage potentials are an order of magnitude smaller than currently estimated. And even in these highly constrained cases, the relative cost of employing CCS as a means of addressing climate change could still be competitive with other large scale emissions mitigation measures."

Further information concerning costs, risks, deployment barriers and policy aspects can be found in Section 7.8.2, 7.9, 7.10, and 7.12, respectively.

7.6 Infrastructure and systemic perspectives

7.6.1 Electrical power systems

Reducing GHG emissions from the electric power sector will require infrastructure investments and changes in the operations of power systems and these changes will depend on the mitigation technologies employed. The fundamental constraints that underpin this process are the requirements that generation and electricity demand remain in balance at all times (system balancing), that adequate generation capacity is installed to meet demand even at peak time of the residual load (resource adequacy), and that transmission and distribution network infrastructure is sufficient to deliver generation to end-users (transmission and distribution). Studies of high variable RE penetration scenarios (IG Mason et al., 2010; Paul Denholm and Maureen Hand, 2011; M Delucchi and M Jacobson, 2011; Elliston et al., 2012; Haller et al., 2012; Budischak et al., 2013) and the broader literature suggest that integrating significant GHG mitigation technology is technically feasible, though economic and institutional barriers may prevent uptake. Of the GHG mitigation options discussed in this chapter, the challenge of integrating high penetrations of RE resources, particularly those that are intrinsically time variable, or generation technologies that are operationally inflexible in conjunction with high shares of RE, is expected to be the most technically demanding and costly.

System balancing - flexible generation and loads

Nuclear, CCS, and RE technologies like geothermal have relatively high up-front costs and low operating costs, making the technology most suited for base-load operation. Depending on the pattern of electricity demand, a relatively high share of energy can be provided by these technologies operated in a base-load manner. At some point, further increases in their penetration will require part-loaded operation, load following, time shifting of demand (demand side management), and/or deployment of storage where it is cost effective (Knapp, 1969; T Johnson and D Keith, 2004; Chalmers et al., 2009; Pouret et al., 2009). Part-load operation of nuclear plant is routine in France, where the share of nuclear exceeds 80% of the annual demand, though part-load operation in other regions may be restricted by technology or institutional barriers (Perez-Arriaga and Batlle, 2012). Flexible operation of CCS plants is an active area of research (Hannah Chalmers and Jon Gibbins, 2007; Nord et al., 2009; S Cohen et al., 2011).

Operational flexibility of CHP plant may be constrained by the underlying heating needs, though boiler changes, thermal storage, and inclusion of other heat sources such as network heat pumps can mitigate those constraints (e.g., H Lund and Andersen, 2005; Blarke, 2012). Reservoir hydropower can be useful in balancing supply and demand due to the flexibility provided by the storage reservoir; making the hydro capable of pumping (giving so called pumped hydro) as is increasing being done by Norway, makes the storage even more flexible. Environmental constraints and alternative uses for transport or irrigation will constrain operations and/or designs in many locations. Today, (pumped) hydropower storage is the only storage technology deployed at a large scale, but other technologies including compressed air energy storage and batteries may possibly be deployed on a large scale in the future (BP Roberts and Sandberg, 2011). Finally, surplus renewable supply can be curtailed by switching off unwanted plants or through a regulation of the power output. Another option is to translate surplus power to heat and hydrogen or methane ("power to heat" and "power to gas", respectively).

Variable RE resources, on the other hand, especially at high penetration, increase the need for system balancing, beyond what is required to meet variations in demand. Existing generating resources can contribute to this additional flexibility. An IEA assessment, for example, shows the amount of variable RE electricity that can be accommodated using *existing* balancing resources exceeds 20% of total annual electricity supply in 7 regions and is even above 40% in two regions and one country (IEA, 2011c). Care is needed with interpretation since many of the countries are interconnected and power transfers can be important in accomplishing high penetrations of RE; Denmark for example makes extensive use of Norwegian hydro storage to balance its wind power. Obtaining flexibility from fossil generation has a cost (see 7.8.2) and will also, usually only modestly, affect the overall GHG reduction potential of variable RE (Martin Pehnt et al., 2008; Fripp, 2011; Wiser et al., 2011; Perez-Arriaga and Batlle, 2012).

In addition to considerations related to individual technologies, certain combinations of GHG mitigation options may present added challenge: high penetrations of variable RE generation, for example, may not be ideally complemented with high penetrations of nuclear, CCS, and CHP plant (without heat storage) if those plants cannot be operated in a flexible manner. If additional flexibility is required to facilitate higher shares, it can be obtained from a number of sources including investment in new flexible generation, improvements in the flexibility of existing power plants, demand response, and storage as summarised in the SRREN report (Sims et al., 2011).

Resource Adequacy

One measure of reliability in a power system is the probability that demand will exceed available generation. The contribution of different generation technologies to ensuring sufficient generation is available to maintain this probability at a target level is called the capacity credit or capacity value (Keane et al., 2011).

The capacity credit of nuclear, CCS, geothermal, large hydro, and biomass is expected to be near the plant nameplate capacity (e.g., 90% and above) as long as sufficient fuel supply is available and required maintenance is scheduled outside of critical periods. Variable RE will generally have a lower capacity credit that depends on the correlation between of generation availability and periods of high demand. The capacity credit of wind power, for instance, is in the range of 5% to 40% of the nameplate capacity (IG Mason et al., 2010; Holttinen et al., 2011); ranges of capacity credits for RE resources are summarized in Sims et al. (2011). The addition of significant plant with low capacity credit can lead to the need for a higher planning reserve margin (including the contribution of the low capacity credit plants that would lead to higher levels of aggregate nameplate capacity) to ensure the same degree of system reliability.

Energy storage can also be used to contribute to system adequacy, but often at substantial cost. If specifically tied to RE generation it can be seen as increasing the capacity credit of that source so that for example the capacity credit of CSP with thermal storage is greater than without thermal storage (Madaeni et al., 2011), but there are associated additional investment costs that may well not be justified in system terms.

Transmission and Distribution

Due to the location-constrained and often remote nature of RE resources, connecting new RE sources to the existing transmission system will often require the installation of additional transmission capacity and strengthening the existing system if significantly greater power flows are required across the power system. Increased interconnection and strengthened transmission systems, as planned in the EU and Canada for example, provide power system operators the capability to move surplus generation in one region to meet otherwise unmet demand in another, exploiting the geographical diversity of loads and also generation.

Similar considerations may apply to CCS plants depending on the trade-off between the cost of network infrastructure and the cost of pipeline transport of CO_2 to depositories suitable for sequestration (Svensson et al., 2004; H. Herzog et al., 2005; S. Benson et al., 2005; Spiecker et al., 2011), and may also apply to nuclear plant, since these tend to be located at some distance from load centres due to public perceptions of health and safety, access to water for cooling, and other operational factors.

Though there will be a need for additional transmission capacity, the installation of new transmission infrastructure often faces institutional challenges since it is subject to planning consent; it can be visually intrusive and thus unpopular in the affected areas. In addition, where different countries' power systems are concerned there may well be obstacles to bulk power transfer arising due to nationally specific market systems.

Distributed generation (DG), where small generating units are connected directly to the electricity distribution system and near loads, do not have the same need for expansion of the transmission system. The net impact of DG on distribution networks depends on the local penetration level, the location of DG relative to loads, and temporal coincidence of DG generation and loads (Cossent et al., 2011).

As DG grows system operators would like increased visibility and controllability of DG to ensure overall system reliability. This can be achieved by virtual power plants and, in the broadest sense, by smart grids, although the concept of smart grids is not discussed further here due to the fact that the term "smart grid" has not been defined in a non-ambiguous way so far (IPCC, 2011a, p. 658).

7.6.2 Heating and cooling networks

Globally, 15.8 EJ were used in 2010 (2.6% of global TPES) to produce nearly 14.3 EJ[8] of district heat for sale at CHPs (44%) and heat only boilers (56%) (Table 7.1). After a long decline in the 90's district heat returned to the growing trajectory in the last decade escalating by about 21% above the 2000 level (IEA, 2012h). This market is dominated by the Russian Federation with a 42% share in the global heat generation, followed by Ukraine, USA, Germany, Kazakhstan, and Poland. Natural gas dominates in the fuel balance of heat generation (46%), followed by coal (40%), oil (5%), biofuels and waste (5%), geothermal and other renewables (2.4%) and a small contribution from nuclear. Development of smart district heating and cooling networks in combination with (seasonal) heat storage allows for more flexibility and diversity (combination of wind and CHP production in Denmark) and open additional opportunities for low carbon technologies (CHP, waste heat use, heat pumps, solar heating and cooling) (IEA, 2012h). In addition, excess renewable electricity can be converted into heat. Using the related power to heat technologies could allow to replace that what otherwise would have seem produced by fossil fuels.

Statistically reported average global efficiency of heat generation by boilers is only 83%, while it is possible to improve it to 95%. About 6.6% of globally generated for sale heat is lost in heating networks (Table 7.1). In some Russian and Ukrainian municipal heating systems such losses amount to 20-25% as a result of excessive centralization of many district heating systems and of worn and poorly maintained heat supply systems (Igor Bashmakov, 2009). The promotion of district heating and cooling system should also account for future technology development challenging district heating sector (building heat demand reduction, high efficiency single housing boilers, fuel cells with characteristics of CHP, etc.), which may allow switching to more efficient decentralized systems (GEA, 2012). District heating and cooling systems could be physically more energy efficient when heat or coldness load density is high, triple generation is developed, the communities or industrial sites can utilize the waste heat, heat (cooling) and power loads show similar pattern and heat loss control systems are well designed and managed.

[8] UNES reports lower number. For 2008 this sources assess the total production of district heat equal to 10,7 EJ (UNES, 2011).

7.6.3 Fuel supply systems

As noted in 7.5.1, fossil fuel extraction, processing and distribution contributes around 5-10% of total fossil fuel related GHG emissions. It has also been noted that future GHG mitigation from this sector will be limited by the increased energy requirements of extraction and processing of oil and gas from mature fields and unconventional sources, and the mining of coal from deeper mines. The flexibility, long operational life and distributed nature of the supply system infrastructure do however provide opportunities to reduce GHG emissions through the delivery of low carbon fuels. Opportunities for liquid fuels are likely limited to supply of fuels such as biodiesel and ethanol at points in the supply system that enable either storage or blending before transport to distribution nodes, these opportunities are discussed in Section 8.3.3.; for gaseous fuels, supply of low carbon fuels could occur across much of the gas delivery network.

More than 50 countries transport high pressure natural gas through pipe networks greater than 1000km in length (Central Intelligence Agency, 2011). Although individual layout varies, connected to these are the lower pressure networks which distribute gas for power generation, industry and domestic use. Because of their ability to carry natural gas substitutes, these networks provide an opportunity to expand production of these gases; depending on the availability of resources, estimates suggest substitutes could replace 17.4 EJ of natural gas used in Europe by 2020 (IPCC, 2011a). Low CO_2 emitting natural gas substitutes can be produced from surplus fluctuating renewable electricity generation (“power to gas”), other renewable sources such as biomass and waste, or via coal when combined with CCS; CCS can be added to production from renewable sources to further enhance CO_2 mitigation potential (Carbo et al., 2011). Provided the substitute natural gas meets the relevant gas quality standard (IEA Bioenergy, 2006, 2009; IPCC, 2011a), and gas clean up maybe required to achieve this, there are no technical barriers to the injection of gas substitutes into the existing gas networks (European Commission, 2001). Biomethane produced from a variety of sources is already being injected into a number of natural gas networks (IEA Bioenergy, 2011; IPCC, 2011a).

The existing natural gas network also has the potential to transport and distribute hydrogen provided the injected fraction remains below 20% by volume, although estimates vary (European Commission, 2004). Limiting factors are gas quality standard and equipment compliance, pipeline integrity (failure, fire and explosion) and end user safety (European Commission, 2004; Tabkhi et al., 2008). Where the pipelines are suitable and more frequent inspections can be undertaken, a higher fraction of hydrogen can be carried, although the lower volumetric energy density of hydrogen will significantly reduce energy flows unless gas pressure is able to be increased. If required, hydrogen separation is possible via a range of existing technologies. As hydrogen can be produced from renewable sources such as wind and solar (IEA, 2006; Moriarty and Honnery, 2007), as well as biomass, hydrogen potential is greater than that of low CO_2 emitting natural gas substitutes. For dedicated hydrogen delivery, transport distance is an important consideration; pipelines are favoured over shorter delivery distances and at high flow rates, while batch delivery of liquid hydrogen is favoured by long distances (Christopher Yang and Joan Ogden, 2007). Since hydrogen can be stored, a further advantage is the greater flexibility it provides to variable renewable electricity generation through power to gas technologies; drawbacks are the additional cost and reduced overall efficiency in energy delivery (JE Mason and Ken Zweibel, 2007; Honnery and Moriarty, 2009; IPCC, 2011a). An extension of the ideas expressed here is (renewable) “power to methane” which might be injected directly into gas networks (Arvizu et al., 2011).

7.6.4 CO_2 transport

Options for CO_2 capture and geologic storage are presented in 7.5.5, the focus here is the infrastructure required for CO_2 transport between the point of capture and the point where the CO2 will be injected into the deep subsurface. As the literature on CO_2 transport matures, it is becoming increasingly evident that the spatial relationships between where CO_2 might be captured from large point sources and the very heterogeneous (even at the basin scale) nature of candidate geologic storage reservoirs means that a variety of CO_2 transportation systems are likely to be employed in different regions of the world.

For example the work of Dahowski et al., (2005; 2012) suggests that more than 90% of the large stationary CO2 point sources in the US are within 160km of at least one candidate geologic storage reservoir and 80% of China's large stationary point sources are within 80km of at least one candidate storage reservoir. For regions like these, the proximity of most large stationary CO_2 point sources to large and geographically distributed candidate geologic CO_2 storage reservoirs suggests that at least early on in the commercial deployment of CCS technologies facilities might rely on dedicated pipelines linking the CO_2 source to an appropriate sink.

The work of Johnson and Ogden (2011) suggests once there is a critical density of CO_2 capture and storage projects in a region, a more integrated national pipeline network may evolve.For other regions, especially Western/Northern Europe, Japan, and Korea, where onshore storage options are not widely distributed, more care is needed in planning pipeline networks given the geographical (and political) challenges of linking distributed CO_2 sources to the available/usable predominantly offshore geologic storage options. This requires longer-term planning as well as political/legal agreements between countries in those regions as more coordination and cross-boundary transport will be necessary/desired (Huh et al., 2011; Ogawa et al., 2011; N Strachan et al., 2011; ZEP, 2011a). While pipelines are likely to be the transport mode of choice for onshore and most offshore storage projects (IPCC, 2005), in certain circumstances transporting CO_2 by large ocean going vessels could be a technically feasible and cost effective option (Aspelund et al., 2006; Decarre et al., 2010; B-Y Yoo et al., 2011; Ozaki and Ohsumi, 2011).

There are more than 6,300 km of CO_2 pipeline that already exists in the U.S and much has been learnt from the decades of operational experience obtained from these existing CO_2 pipeline systems. However, knowledge gaps exist for systems, which integrate multiple CO_2 source points. Because of their impact on pipeline integrity, gas stream properties and flow management, impurity control is emerging as a major design feature of these systems (Oosterkamp and Ramsen, 2008; IS Cole et al., 2011) with particular importance given to limiting the amount of water in the gas stream in order to avoid corrosion. Estimates for the cost of transporting, injecting into a suitable formation, site closure and long-term post injection monitoring are summarized at the end of in Section 7.8.2.

7.7 Climate change feedback and interaction with adaptation

Climate change will affect heating and cooling energy demands (see also Chapter 9.5; (D Arent et al., Forthcoming)), thereby also influencing energy supply needs. The effect on overall energy demand will vary geographically (Mideksa and Kallbekken, 2010; Pilli-Sihvola et al., 2010; KKW Wan et al., 2011). Many studies indicate that demand for electricity will increase because of greater need for space cooling, while demand for natural gas and oil will decline because of less need for space heating (D Arent et al., Forthcoming; M. Isaac and D. van Vuuren, 2009; Akpinar-Ferrand and A Singh, 2010). Peak electricity demand could also increase because of climate change, especially as a result of extreme events, requiring a disproportionate increase in energy infrastructure investment (Revi et al.; US EPA, 2008). Although impacts on energy demands outside of heating and cooling are less clear, possible effects include increased energy use for climate-sensitive processes, such as pumping water for irrigated agriculture and municipal uses (USEPA, 2008). As another example, reductions or changes to surface water flows could increase energy demand for desalination (Robert Scholes et al., forthcoming; Boyé, 2008).

In addition to impacting energy supply through changes in energy demand, climate change will have various impacts on the potential future role of GHG mitigation technologies in the energy supply sector. Though these impacts are summarized here, further details on potential impacts, as well as a summary of how conventional higher-carbon energy supplies might be affected, are available in the WGII AR5 report, especially but not limited to Chapter 10 (D Arent et al., Forthcoming).

Though the impact of climate change on the primary resource base for fossil fuels is likely to be small (World Bank, 2011a), RE sources can be particularly sensitive to climate change impacts. In general, any impacts are expected to increase with the level of climate change, but the nature and magnitude of these effects are technology dependent and somewhat uncertain, and may vary substantially on regional and local levels (D Arent et al., Forthcoming; IPCC, 2011a; Roberto Schaeffer et al., 2012). IPCC (2011a) summarizes the available literature as follows:

"The future technical potential for bioenergy could be influenced by climate change through impacts on biomass production such as altered soil conditions, precipitation, crop productivity and other factors. The overall impact of a global mean temperature change of less than 2°C on the technical potential of bioenergy is expected to be relatively small on a global basis. However, considerable regional differences could be expected and uncertainties are larger and more difficult to assess compared to other RE options due to the large number of feedback mechanisms involved. For solar energy, though climate change is expected to influence the distribution and variability of cloud cover, the impact of these changes on overall technical potential is expected to be small. For hydropower the overall impacts on the global technical potential is expected to be slightly positive. However, results also indicate the possibility of substantial variations across regions and even within countries. Research to date suggests that climate change is not expected to greatly impact the global technical potential for wind energy development but changes in the regional distribution of the wind energy resource may be expected. Climate change is not anticipated to have significant impacts on the size or geographic distribution of geothermal or ocean energy resources."

The limited lifetime of some RE technologies, such as wind turbines and solar panels, may mean that these technologies are more adaptable to such changes; a decline in resource potential in one area could lead to a shift in the location of projects using these technologies over time to areas where the resource has not degraded. Long-lived transmission infrastructure built to accommodate these technologies, however, may be stranded. The longer lifetimes of hydropower dams may mean that these facilities are also less adaptable to climate changes such as changes in local precipitation; nonetheless, dams also offer the opportunity for energy and water storage that may provide climate adaptation benefits (Roberto Schaeffer et al., 2012).

Climate change may also impact the design and operation of energy production and delivery facilities. Offshore infrastructure, including gas and oil wells but also certain RE facilities such as offshore wind power plants, are vulnerable to extreme weather events (D Arent et al., Forthcoming; Karl et al., 2009; Wiser et al., 2011; World Bank, 2011a; Rose et al., 2012). Production losses from thermal power plants (whether low- or high-carbon facilities) and efficiency losses from energy delivery infrastructures increase when temperatures exceed standard design criteria (Roberto Schaeffer et al., 2012). Power generation facilities and energy delivery infrastructures may also experience performance losses and other impacts due to changes in the access to and temperature of cooling water, as well as sea level rise and extreme weather events (D Arent et al., Forthcoming; Kopytko and Perkins, 2011; Roberto Schaeffer et al., 2012). Adaptation strategies include infrastructure relocation and reinforcement, cooling facility retrofit, and proactive water resource management (D Arent et al., Forthcoming; Rübbelke and Vögele, 2011).

Finally, inter-dependencies between the energy sector and other sectors of the economy are important to consider (De Lucena et al., 2009). For example, if climate change detrimentally impacts crop yields, bioenergy potential may decline and costs may rise because more land is demanded for food crop production (Porter and Xie, Forthcoming); see also Chapter 11). Climate change may also exacerbate water and energy tensions across sectors and regions, potentially impacting hydropower (either positively or negatively, depending on whether the potential climate adaptation benefits of hydropower facilities are realized) and other technologies that require water (Cisneros and Oki, Forthcoming; D Arent et al., Forthcoming; A Kumar et al., 2011).

7.8 Costs and potentials

7.8.1 Potential emission reduction from mitigation measures

Significant opportunities exist to mitigate greenhouse gas emissions and other climate forcing within the energy sector. These opportunities include efficiency gains in the entire supply chain, reduction of methane and black carbon emissions, and albedo and soil carbon management; the most significant opportunity, however, is a shift in energy supply away from unmitigated fossil energy sources, particularly coal. When assessing the contribution of different mitigation options, it is important to evaluate the opportunities from a life-cycle perspective to take into account the emissions in the fuel chain and the manufacturing of the energy conversion technology (Annex II.4.3). This section contains a review of GHG emissions associated with different energy supply technology per unit final energy delivered, with a focus on electricity generation.

The largest GHG emissions are associated with the combustion of coal, with an interquartile range of 880 to 1130 gCO_2e per kWh electricity from coal identified by Sathaye et al. (2011a). Oil fired steam power plants are only slightly better. Modern natural gas combined cycle plants bring significant reductions in CO_2 emissions, but concerns have recently emerged about high emissions of methane from both unconventional and conventional gas production (section 7.5.1). Combined heat, cooling and power can also result in moderate emissions reductions compared to separate, fossil fuel based heat, cooling and power provision (M. Pehnt, 2008). However, average emissions from power generation need to be reduced to below 100 gCO_2e per kWh by 2050 to meet a 2°C mitigation goal (IEA, 2010b) and would eventually need to go to or below zero (chapter 6 and 7.11), so that the employment of technologies with even lower emissions is called for if these goals are to be achieved.

A number of low-GHG electricity supply technologies offer very low life-cycle GHG emissions (Figure 7.**9**). An important source for life-cycle GHG emissions is fossil fuel combustion in the manufacturing of the technologies; these are reduced as energy mixes become cleaner and technologies are improved over time. Figure 7.**9** shows potential reductions in life-cycle emissions due to cleaner manufacturing energy mixes and improved technology performance.

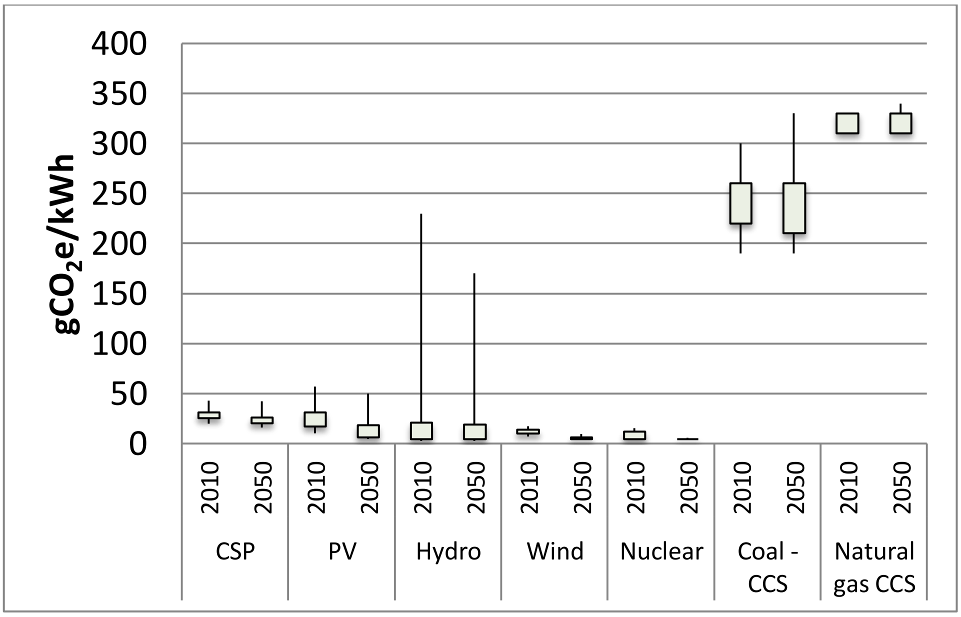


Figure 7.9 Comparative life-cycle greenhouse gas emissions from a range of different technologies for electricity production. The presented range reflects the variation of the regional conditions and

among investigated technologies or cases within a single category, but not the uncertainty in the technology. Biogenic emissions from hydropower are not included.

CO_2 capture plants reduce emission to 180-300 gCO_2e/kWh for coal and 120-170 gCO_2e/kWh for gas power with CCS, assuming a leakage of 1% of natural gas (Koorneef et al., 2008; Bhawna Singh et al., 2011; Andrea Ramírez et al., 2012), but actual leakage rates are now assumed to be higher. Renewable heat and power production and nuclear energy can bring more significant and certain reductions in GHG emissions. The interquartile ranges of life-cycle greenhouse gas emissions reported in the literature are 15-50 gCO_2e/kWh for PV (HC Kim et al., 2012; Hsu et al., 2012), 20-34 for CSP (John J. Burkhardt et al., 2012), and 9-24 for wind power (Arvesen and Edgar G. Hertwich, 2012). The reported interquartile range for nuclear energy is 8-31 gCO_2e/kWh (Warner and Garvin A. Heath, 2012). For all of these technologies, at least 5 studies are reviewed. The empirical basis for estimating the emissions associated with geothermal and ocean energy is much weaker, but ranges of 20-57 gCO_2e/kWh for geothermal power and 6-9 gCO_2e/kWh for ocean energy have been identified (J. Sathaye et al., 2011a). Most of these emissions are associated with the manufacturing and installation of the power plants, but for nuclear power the enrichment can be significant (Warner and Garvin A. Heath, 2012). For all technologies, local resource conditions and other site-specific factors can have a substantial influence on the results, and studies generally assume good conditions. The life cycle climate effects of bioenergy are discussed in a cross-cutting bioenergy annex to chapter 11 and the method of life cycle assessment is discussed in Annex II.4.3.

The climate effect of hydropower is very project specific. An important issue is the emissions of biogenic CO_2 and CH_4, primarily from hydropower reservoirs. Dams change the natural carbon cycle, leading to the accumulation of organic carbon in the reservoirs and the slow aerobic or anaerobic digestion of this biomass. At the same time, power stations also affect the exchange of gases between the water and the atmosphere. A concise presentation of these issues can be found in SRREN (A Kumar et al., 2011). Reservoirs can act both as a sink and a significant source of GHGs (Demarty and Bastien, 2011). Degradation of organic matter from vegetation and soils that are inundated during reservoir formation, added through tributaries, or grow in the reservoir, lead to significant anoxic conditions, where anaerobic digestion produces methane (Tremblay et al., 2005; Barros et al., 2011; Demarty and Bastien, 2011). Methane emissions are usually highest during the first years when initially present labile organic carbon degrades (Abril et al., 2005). CO_2 uptake can happen in older reservoirs (Chanudet et al., 2011). Few studies quantify changes in the net flux[9] of GHG across the affected landscape, including the river after the dam (Teodoru et al., 2012). Measurements are challenging due to spatial and temporal heterogeneity and the release of methane through diffusion and bubbling before and after the dam, as well as degassing (Guérin et al., 2006; A Kumar et al., 2011; Delsontro et al., 2011; Eugster et al., 2011; Kemenes et al., 2011; Fearnside and Pueyo, 2012). Demarty and Bastien (2011) reviewed a large range of measurements and estimates of methane emission from reservoirs in tropical regions, indicating that emissions can have a large range, from only 2 g to 4000 g CO2e/kWh. Ideas for mitigating existing methane emissions have been presented (Ramos et al., 2009). Barros et al. (2011) estimate total gross emissions from hydroelectric dams to be equal to 48 Tg CO_2 and 3 Tg CH_4, which would correspond to a world average 41gCO_2e/kWh, even though these emissions may be underestimated (Fearnside and Pueyo, 2012; S Li and Lu, 2012). Life-cycle emissions of fossil GHGs from producing and operating hydropower stations reported in the literature fall in the range of up to 40 gCO_2e/kWh for the studies reviewed in IPCC SRREN and 3-7 gCO_2e/kWh for studies reviewed in (Dones et al., 2007). The available evidence indicates that there is a high degree of variability and uncertainty associated with the interference of hydropower with the biogenic carbon cycle, and that recent improvements

[9] "Net emissions are defined by the SRREN as Gross emissions minus pre impoundment emissions minus unrelated anthropogenic sources (SRREN ch 5.6.3.2 page 47 first sentence). Gross emissions are the total measured flux. An approach to unrelated anthropogenic sources and to the GHG issue could be found in the IEA Annex XII: managing the carbon balance in reservoirs (Draft), and in the IHA Measurement Field Guide.

in measurement techniques should offer a significant opportunity to improve our understanding and avoid highly emitting projects.

The literature reviewed in this section shows that a range of technologies can provide electricity with less than 5% of the life-cycle GHG emissions of coal power: wind, solar, nuclear and in many cased of hydro power. Further improvements in these technologies will be attained as a feedback to a cleaner energy supply in the production of the technologies and through performance improvements.

7.8.2 Cost assessment of mitigation measures

Though there are limits to its use, in order to compare the competitiveness of energy supply technologies, the concept of "levelised costs of energy" (LCOE, also called levelised unit costs or levelised generation costs)[10] is frequently applied (IEA, 2005, 2010c, 2011a; GEA, 2012). Figure 7.10 shows a current assessment of the cost of various low carbon energy supply technologies and their change compared to those values that were considered in the IPCC SRREN (2011a).[11] A variety of other recent sources also provide a summary of the LCOE of low-carbon supply options (DOE NETL, 2010; IEA, 2010c; Branker et al., 2011; WorleyParsons, 2011; ZEP, 2011a; De Roo and J Parsons, 2011).

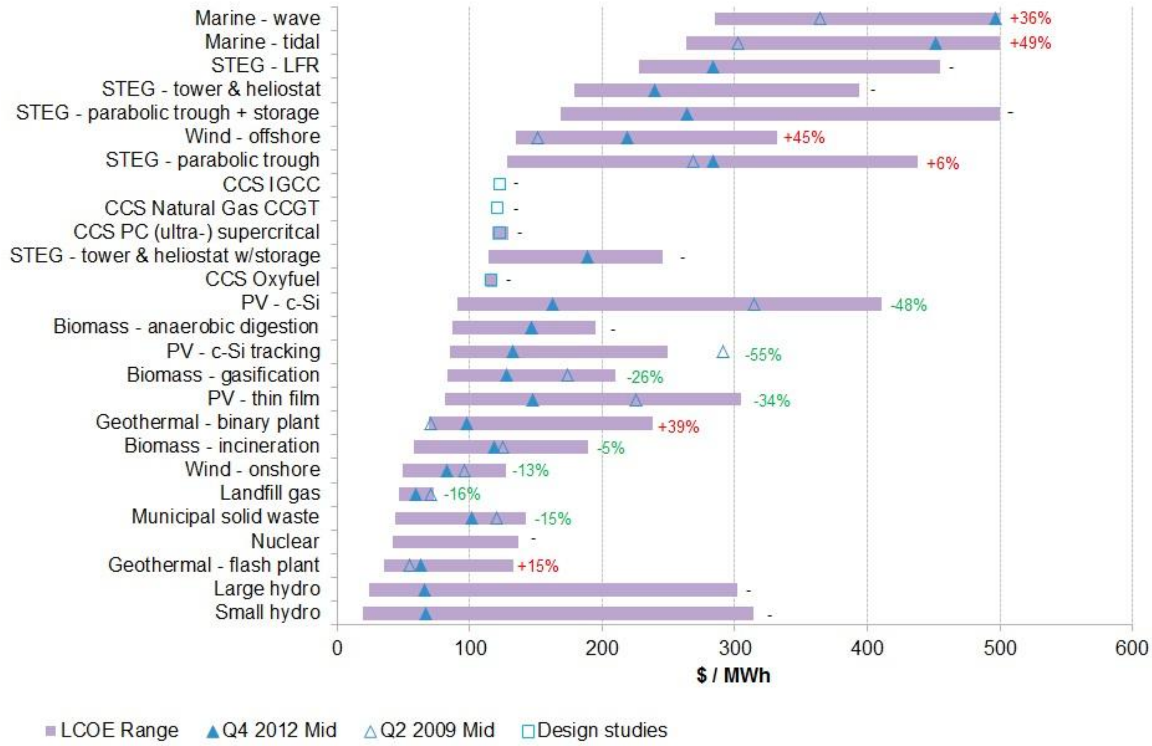


Figure 7.10 Levelised cost of energy as observed for the fourth quarter of 2012 (and for the second quarter of 2009)[12] Source: For renewables and fossil fuels: Bloomberg New Energy Finance (2012); for nuclear: IEA (2010c); for CCS: Global CCS Institute (2011).

[10] A basic description of this concept, including its merits and shortcomings, can be found in the Methodology Annex of this report.

[11] Although the IPCC SRREN was published in 2011, most of the data discussed therein refer to the conditions observed in the year 2009.

[12] For nuclear projected data (for 2015) are shown instead of current ones. For CCS the cost refer to design studies using fuel cost data from 2010. The percentage change is from Q2 2009. A dash denotes no significant change, or insufficient data. The data presented assume an integrated utility requesting a 10% equity internal rate of return. They do not incorporate any policy mechanisms (e.g. feed-in tariffs or subsidies), other than standard taxes faced by the companies. Concerning renewable energies, the diagram is an updated version of

The LCOE ranges are broad as values vary across the globe depending on the site-specific renewable energy resource base, on local fuel and feedstock prices as well as on country specific projected costs of investment, financing, and operation and maintenance. A comparison between different technologies should therefore not be based on LCOE data; instead, site-, project- and investor specific conditions should be considered. Furthermore, in addition to integration and transmission costs, relative environmental impacts (e.g., external costs) as well as the contribution of a technology to meeting specific energy services, for example, peak demands (Heptonstall, 2007; PL Joskow, 2011) play an important role.

The LCOE of many low carbon technologies changed considerably since the release of the IPCC AR4 (see Figure 7.10). Even compared to the SRREN (IPCC, 2011a), the decline of LCOE of some renewable energy (RE) technologies has been significant. PV module prices, for instance, fell by 55 % since 2009. Bazilian et al. (2012) citing articles by (K. Zweibel, 2010; Breyer and Gerlach, 2010), Branker et al. (2011) and Darling et al. (2011) note that "contrary to the view that the arrival of grid parity is still decades away, numerous studies have concluded that solar PV grid parity has already been achieved in a number of countries/regions". Compared to PV a similar, albeit less extreme trend towards lower LCOE (from 2009 to 2012) has been observed for onshore wind (-13%), land fill gas (-16%), municipal solid waste (-15%), and biomass gasification (-26%). Continuous cost reductions are not always a given, as illustrated by the recent developments in costs of offshore wind and other technologies. This however, does not necessarily imply that technological learning has stopped. As observed for PV and wind onshore (see Figure 7.11), phases characterized by an increase of the price might be followed by a subsequent decline, if a shortage of input material is eliminated or a “shake out” due to increasing supplier competition is happening (M. Junginger et al., 2005; Martin Junginger et al., 2010).

a figure published in UNEP and Bloomberg New Energy Finance (2012). A size limit of 10 MW is used to distinguish small hydro power plants from larger ones. Abbreviations: STEG-LFR: Solar Thermal Electricity Generation - Linear Fresnel Reflector; PC: pulverized coal; CCGT: combined cycle gas turbine; IGCC: integrated gasification combined cycle. Nuclear costs take into account both front- and back-end costs. Not included are the costs associated with low probability - high consequence events such as nuclear accidents and limited operator liability. CCS LCOE include transport and storage cost.

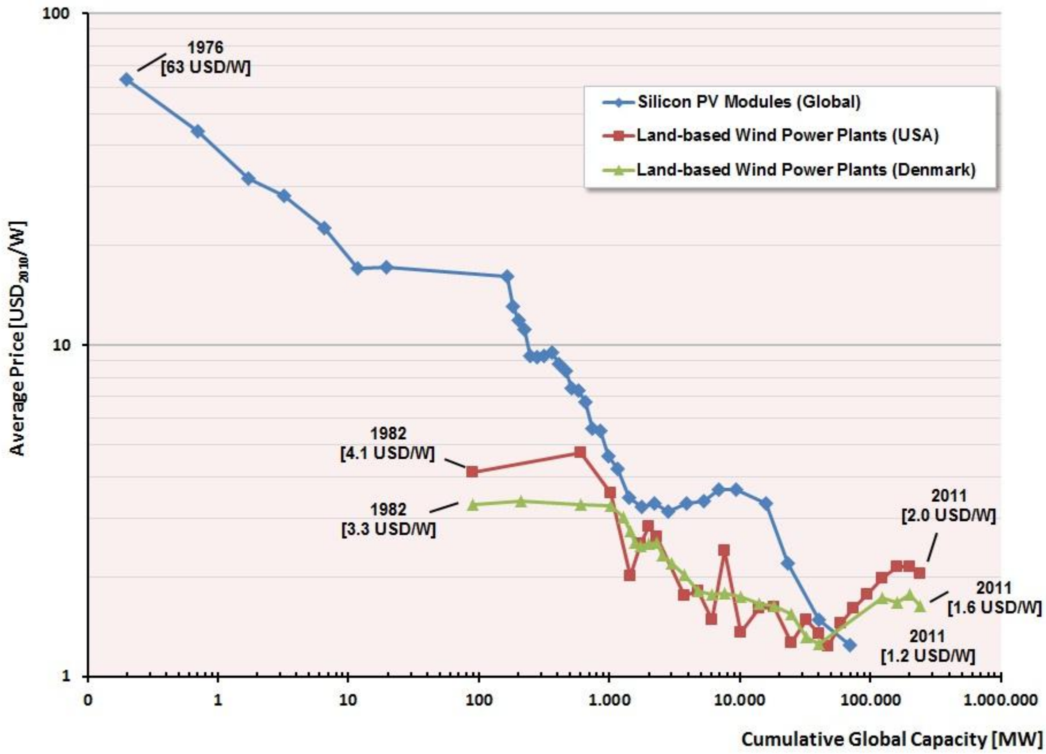


Figure 7.11. Selected experience curves in logarithmic scale for the price of silicon PV modules (Data source: Navigant Consulting) and land-based wind power plants for USA (Date source: LBNL) and for Denmark (Data source: Nielsen et al, (2010); Danish Energy Agency, (2013); both per unit capacity.

Notes: Depending on the location, costs may be different at any given time, depending on transportation costs, local market conditions, and any tariffs applied. Reductions in the cost or price of a technology per unit capacity likely understates reductions in the levelised cost of energy of that technology when technology improvements occur.

The short-run marginal costs of well-run nuclear power plants (i.e., existing plants with sunk capital costs) are generally very low. The economic assessment is different for plants that are yet to be built. In liberalized markets, high upfront capital costs, long construction periods preceded by extended planning, licensing, and public hearing periods expose investors in nuclear power to sizable economic risks (IEA, 2011a). It is too early to assess the impact of the Fukushima accident on the fate of the nuclear industry. According to the IEA, "Post-Fukushima Daiichi, the relative economics of nuclear power compared with other generating technologies may deteriorate (IEA, 2011a, p. 456). In contrast, Joskow (2012, p. 1) assesses that the effect will be quite modest at the global level.

Due to the cost for the additional equipment needed to capture the CO_2, the specific investment costs of CCS plants are significantly higher compared to conventional ones (see Figure 7.10). In addition, due to the efficiency loss,[13] additional fuel costs must be incurred (IEA, 2010c). As there is still no commercial large-scale coal-fired CCS power plant in operation today, the estimation of their projected costs has to be carried on the basis of design studies and few existing pilot projects. The associated problems are described in (S. Yeh and E.S. Rubin, 2010; Global CCS Institute, 2011; E.S. Rubin, 2012).

System integration costs (cf. 7.6.1), which typically increase with the level of deployment, are dependent on the mitigation technology and the state of the background energy system. They comprise (1) balancing costs (originating from the required flexibility to maintain a balance between

[13] Typical efficiency penalties projected for 2015 are on the order of 8 - 11 % points.

supply and demand), (2) adequacy costs (due to the need to ensure operation even at peak times of the residual load), and (3) grid integration costs. (1) Based on assessments carried out for OECD countries, the provision of additional balancing reserves increases system costs by approximately $1 to $7 USD/MWh for wind energy market shares of up to approximately 30% (IEA, 2010c, 2011c; Wiser et al., 2011; Holttinen et al., 2011). Balancing costs for PV have been reported to be in a similar range (Hoke and Komor, 2012). Balancing costs can be higher in some regions particularly due to institutional constraints. (2) While determining the cost of additional conventional capacity needed to ensure that peak demands are met is contentious (Sims et al., 2011), estimates of this cost for wind power range from $0 to $10 USD/MWh (IEA, 2010c, 2011c; Wiser et al., 2011). Because of the coincidence of solar generation with air conditioning loads, solar at low penetration levels can in some cases displace a larger amount of capacity, per unit of energy generated, than other supply options, yielding estimates of infrastructure savings as high as $23 USD/MWh greater than the savings from base load supply options (Mills et al., 2011). (3) Estimates of the additional cost of transmission infrastructure for wind energy in OECD countries are often in the range of $0 to $15 USD/MWh depending on the amount of wind energy supply, region, and study assumptions (IEA, 2010c, 2011c; Wiser et al., 2011; Holttinen et al., 2011). Infrastructure costs are generally higher for time-variable and location dependent RE, at least when developed as large centralized plants, than for other sources of energy supply (e.g., Sims et al., 2007; Hoogwijk et al., 2007; Delucchi and Jacobson, 2011). If mitigation technologies can be deployed near demand centres within the distribution network, or used to serve isolated autonomous systems (e.g., in less developed countries), such deployments may defer or avoid the need for additional transmission and distribution, potentially reducing infrastructure costs relative to a BAU scenario.[14]

CCS requires infrastructure for long-term storage of waste products, which includes direct CO_2 transport and storage costs, along with costs associated with long-term measurement, monitoring and verification. The related cost are unlikely to exceed $15/ton-$CO_2$ for the majority of CCS deployment scenarios (H. Herzog et al., 2005; Howard J. Herzog, 2011; ZEP, 2011b) and some estimates are below $5/ton-$CO_2$ (McCoy and Edward S. Rubin, 2008; RT Dahowski et al., 2011).

7.8.3 Economic potentials of mitigation measures

Quantifying the economic potential of major energy supply mitigation options – fuel switching, energy efficiency, renewables, nuclear, CCS – is problematic due to the definition of welfare metrics, broader impacts throughout the energy-economic system, and the background energy system carbon intensity and energy prices (see Chapter 3.10.2 for a general discussion).

One approach is to use energy supply cost curves, which summarize energy resource estimates (section 7.4) into a production cost curve on an annual or cumulative basis. Uncertainties associated with energy cost curves include the relationship between confirmed reserves and speculative resources, the impact of unconventional sources of fuels, future technological change and energy market structures, discounting, physical conditions (e.g. wind speeds), scenarios (e.g. land-use trade-offs in energy vs. food production) and the uneven data availability on global energy resources. Illustrative renewable resource cost curves are discussed in section 10.4 and Figure 10.29 of Fischedick et al. (2011).

A broader approach to energy supply cost curves are marginal abatement cost (MAC) curves. MAC curves (discussed in chapter 3.10.2) discretely rank mitigation measures according to their (GHG) emission abatement cost (in US$/t$CO_2$) for a given amounts of emission reduction (in million tCO_2).

[14] The ability for distributed resources to defer distribution investments depends on the correlation of the generation profile and load, as well as on location specific factors (Mendez et al., 2006; M Thomson and DG Infield, 2007; Hernández et al., 2008; DT-C Wang et al., 2010; Agah and Abyaneh, 2011). At higher penetrations of distributed generation, additional distribution infrastructure may be required (e.g., Cossent et al., 2011).

MAC curves have become a standard policy communication tool in assessing cost-effective emissions reductions (Kesicki and Ekins, 2011). There is wide heterogeneity (Chapter 3.10.2) in the method of construction, the use of experts vs. models, and the year/region the MAC is applied to. Recent global MAC curve studies [Nauclér and Enkvist (2009), van Vuuren et al. (2004), IEA (2008), Clapp et al. (2009)] give overall mitigation potentials ranging from 20% - 100% of the baseline for costs up to \$100/tCO_2. MACs are a useful summary mechanism but sophisticated modeling of interactions between mitigation measures and with the wider economy are required. Chapter 6.3.4 presents such cost ranges from a set of IAM models under consistent scenarios.

7.9 Co-benefits, risks and spillovers

Besides economic cost aspects, several other aspects have implications on the final deployment of mitigation technologies. Co-benefits, co-costs, risks and uncertainties associated with alternative mitigation technologies as well as public perception thereof can affect investment decisions of companies and priority setting of governments. Table 7.4 summarises important attributes of greenhouse gas emissions mitigation options discussed in this chapter. The extend of the co-benefits and risks will differ greatly across regions, and depend on local circumstances, implementation practices as well as the scale and pace of the deployment of the different options.

Table 7.4 Overview of main GHG emissions mitigation measures in the energy supply sector and possible co-benefits and risks for other sustainability objectives

Energy Supply	**Economic**	**Social (incl equity)**	**Environmental**	**Other**
Nuclear replacing coal power	Affordability (increases the cost of electricity generation) (1) Energy security (import dependency) (2)	Risk due to (unresolved) long-term waste disposal requirement (7) Risk of large-scale accidents (8)	Health and ecosystem benefits due to reduction of air pollution and mining accidents (19)	Proliferation risk (1)
RES (Wind, PV, CSP, hydro, geothermal, biomass) replacing fossil fuels	Affordability (increases in many cases the cost of electricity generation) (3) Energy security (import dependency) (2,4)	Local employment and value added at the place of deployment (4,9) Contribution to (off-grid) energy access and technology transfer to rural areas (4,10) Risk of conflicts about the siting of plants (mainly wind and hydro) (4) Noise (mainly wind) (4,11) Displacement (hydro) (4,12,13) Risk of food security and interference with subsistence farming (biomass) (14,15)	Health and ecosystem benefits due to reduction of most forms of air pollution (excluding biomass) and mining accidents (4) Biomass: water security risk and other ecological impacts, e.g., biodiversity, soil quality etc. (14,20) Wind: impact on wildlife (21), low water requirements (4) PV: low water requirement (4) Hydro: Risk of loss of habitat and other ecological impacts (22,23) CSP & hydro: high water consumption (4,24) Geothermal: water use and pollution (25,26)	Supply from variable RES requires extra measures to match demand (30) Higher material requirements (e.g., supply of rare earths) (32,33)
Fossil CCS replacing coal	Affordability (increases the cost of electricity generation) (5) Energy security (import dependency, resource efficiency) (5) Possibly less controllable power output (but possibly better compared to variable and unpredictable RES) (5)	Preserves fossil industry jobs, infrastructure and investments (5) Risk of conflicts about the siting of storage facilities and transport pipelines (16) Concern about risk of CO_2 leakage (5) Lock-in effect (5,17)	Environmental risk of CO2 leakage (27) Increase of upstream environmental risks due to higher fuel use (28)	
BECCS instead of coal power	*See fossil CCS*	*See fossil CCS. For possible upstream effect of biomass supply, see biomass co-benefits/risks*	*See fossil CCS. For possible upstream effect of biomass supply, see biomass co-benefits/risks*	Innovation risk because feasibility not yet established (34)
Fugitive methane capture and use or treatment	Energy security (potential to use gas in some cases) (6)	Improved occupational safety at coal mines (18)	Health benefits due to reduction of hydrocarbon emissions and hence summer smog (29)	

References: (1) von Hippel et al., 2012; (2) Cherp et al., 2012; (3) Bruckner et al., 2011; (4) (J. Sathaye et al., 2011b); (5) SRCCS; (6) Wilkinson, 2011, Song and Liu, 2012; (7) see Section 7.5.X; (8) see Section 7.9.3; (9) Turkenburg et al., 2012; (10) (Pachauri et al., 2012); (11) (Lovich and Ennen, 2013); (12) Bao (2010); (13) (Scudder, 2005); (14) see Bioenergy Annex to Chapter 11; (15) (Tilman et al., 2009; M Harvey and Pilgrim, 2011); (16) (P. Ashworth et al., 2012; Einsiedel et al., 2013) ; (17) (Vergragt et al., 2011); (18) (Karacan et al., 2011); (19) (KR Smith and Haigler, 2008; KA Smith et al., 2012); (20) (D. van Vuuren et al., 2009); (21) (Lovich and Ennen, 2013); (22) (Alho, 2011a); (23) (Dudgeon et al., 2006); (24) (Kerstin Damerau et al., 2011); (25) (Aksoy et al., 2009); (26) (Vasilis Fthenakis and HC Kim, 2010); (27) (OR Harvey et al., 2012); (28) (J. Koornneef et al.; Bhawna Singh et al., 2011); (29) (IEA, 2009b); (30) (Sims et al., 2011; Holttinen et al., 2011); (31) ; (32) (Kleijn and E. van der Voet, 2010); (33) (Graedel, 2011); (34) Rhodes and Keith, 2008; Gough and Upham, 2010.

7.9.1 Socio-economic effects

Policies for improving energy security tend to focus on the interconnected factors of availability of resources, affordability of energy services, efficiency of energy use, and minimizing energy-related environmental degradation (Kruyt et al., 2009; JC Jansen and Seebregts, 2010; Vivoda, 2010; BK Sovacool and Mukherjee, 2011; J. Sathaye et al., 2011a). In meeting these criteria of energy security, there will be trade-offs between technology options that are effective along one dimension, which may have implications for other aspects of security. Such trade-offs include shifting from coal to natural gas in the power sector intended to reduce greenhouse gas emissions but having the effect of increasing dependence on imported liquefied natural gas (BK Sovacool, 2008).

The challenges to achieve energy security differ for developed and developing countries (Cherp et al., forthcoming). The drive for improved energy services by increasing the supply growth for increasing food security, and improving health, education, and living conditions is an important dimension of energy security in developing countries (Kuik et al., 2011). As a consequence, the degree to which low carbon options may or may not contribute to energy security is dependent on the local resource situation and specific national economic circumstances and social priorities. Whilst renewable energy resources can contribute to diversify the portfolio of supply options (WEC, 2010) and create local employment and value added (Table 7.4), the integration of higher shares of variable renewable energy resources into existing electricity networks places higher demands on system stability (Sims et al., 2011).

There is a correlation between modern energy consumption and economic and social development, both within and across countries. As shown in Figure 7.12, countries with higher Human Development Index (HDI) are generally the largest energy consumers with higher per capita carbon emissions. It is important to note that a higher HDI correlates well with a higher energy use up to 100 GJ per capita, but tends to flatten beyond this point (Steinberger and JT Roberts, 2010). Energy access and affordability are hence important concerns up to that point.

Providing clean, affordable and reliable modern energy services is an important means for decoupling development from carbon emissions, and has entered the policy domain of many developing countries (Brew-Hammond, 2010; Mulugetta and Urban, 2010; Sokona et al., 2012). More than 1.3 billion people worldwide, especially the rural poor in Sub-Saharan Africa and developing Asia, are estimated to lack access to electricity and between 2.7 to over 3 billion people are estimated to lack access to modern fuels for heating and cooking (IEA, 2010a, 2011a) (Figure 7.13). The target of increasing access to modern affordable energy services as part of low carbon strategies has triggered a number of major national programmes (IEA, 2011d; Winkler et al., 2011). With renewables already playing an important role in some of these programmes as well as in smaller local initiatives (ARE, 2011; Gurung et al., 2011; REN21, 2011; Behrens et al., 2012), improvements in energy access do not need to entail significant changes in GHG emissions and cost (IEA, 2011d). Indeed, in many remote and rural areas, small-scale hydro, wind or solar photovoltaic installations are cost-competitive options to increase energy access (Bhuiyan et al., 2000; M Kolhe et al., 2002; Nguyen, 2007; Casillas and D.M. Kammen, 2010; Thiam, 2010).

Box 7.1 Energy systems of LDCs: Opportunities & challenges for low carbon development

[COMMENTS ON TEXT BY TSU TO REVIEWER: Boxes highlighting further LDC-specific issues are included in other chapters of the report (see chapter sections 1.3.1, 2.1, 6.3.6.6, 8.9.3, 9.3.2, 10.3.2, 11.7, 12.6.4, 16.8) and a similar box may be added to the Final Draft of chapters where there is none in the current Second Order Draft. In addition to general comments regarding quality, reviewers are encouraged to comment on the complementarity of individual boxes on LDC issues as well as on their comprehensiveness if considered as a whole.]

One of the critical indicators of progress towards achieving development goals in the Least Developed Countries (LDCs) is the level of access to modern energy services. It is estimated that 79%

of the LDC population lack access to electricity, compared to 28% average for in the developing countries (WHO and UNDP, 2009), and only about 71% of people in LDCs rely exclusively on biomass burning for cooking and (Guruswamy, 2011). The dominance of subsistence agriculture in LDCs as the mainstay of livelihoods, combined with high degree of population dispersal, and widespread income poverty have shaped the nature of energy systems in this category of countries (Banuri, 2009; Sokona, Y. et al., 2012). To this end, the energy system in the (LDCs) is characterized by a number of distinct features: i) an energy model of production, transformation and consumption in which biomass energy (firewood and charcoal) has an important share in national energy balances; ii) low per capita demand profile; iii) significant proportion of final energy consumption by the household sector for cooking; vi) low level of energy use in the productive sector (Bazilian et al., 2010). Although a number of these features are also shared by energy systems in non-LDC developing countries, the presence of a growing modern sector creates a more fluid energy environment in these countries.

The GHG emissions from bioenergy in LDCs, particularly from charcoal sourced from open forests or woody areas are, significant – accounting for over 30% of combusted woodfuel in most LDCs (FAO, 2011). This trend is likely to continue in view of the fact that biomass will remain an important source of energy before a significant switch to non-biomass energy is achieved. Moreover, the low energy efficiency of transformation processes and the urbanization trends, often accompanied by a transition from firewood to charcoal with increased energy inefficiency is likely to intensify harvesting for wood, contributing further to rises in GHG emissions, along with other localized environmental impacts. Despite its environmental, economic and social importance, biomass energy has received little attention from governments and the international community. According to UNDP, 25 governments in LDCs have set targets to increase access to electricity, but only 8 for modern fuels and just seven for improved stoves (WHO and UNDP, 2009). Therefore, promoting holistic biomass programmes that address the full value chain, from sustainable production of wood-based fuels to their processing, conversion, distribution and marketing and use could help reduce future GHG emissions. There may also be other co-benefits such reduced burden of fuel collection, employment, and improved health conditions of the end-users (Owen et al., 2013).

The LDC contribution to climate stabilization requires avoidance of future GHG emissions while meeting unmet (or suppressed) energy demand, which is likely to rise. For example, the rate of growth in emissions in Africa is currently above the world average, and the continent's share of global emissions is likely to increase in the coming decades (Canadell et al., 2009). Opportunities exist for LDCs to scale up modern energy access by embracing cleaner and more efficient energy options, and reducing deforestation as a pathway towards low emissions development, consistent with regional and global sustainability goals.

In pursuing low carbon development pathway, LDCs will face challenges. Collier and Venables (2012) argue that while abundant natural endowments in renewable resources in Africa and other LDCs should create opportunities for green energy development, energy generation and usage are economic activities that require the fulfilment of factors such as capital, governance capacity and skills. Taking the example of Africa, Collier and Venables (2012, p. S83) stress that these 'intensity-derived factor scarcities offset the advantages conferred by natural endowments and are often decisive', and so 'will require international action that brings global factor endowments to bear on Africa's natural opportunities' (Collier and AJ Venables, 2012, p. S83)

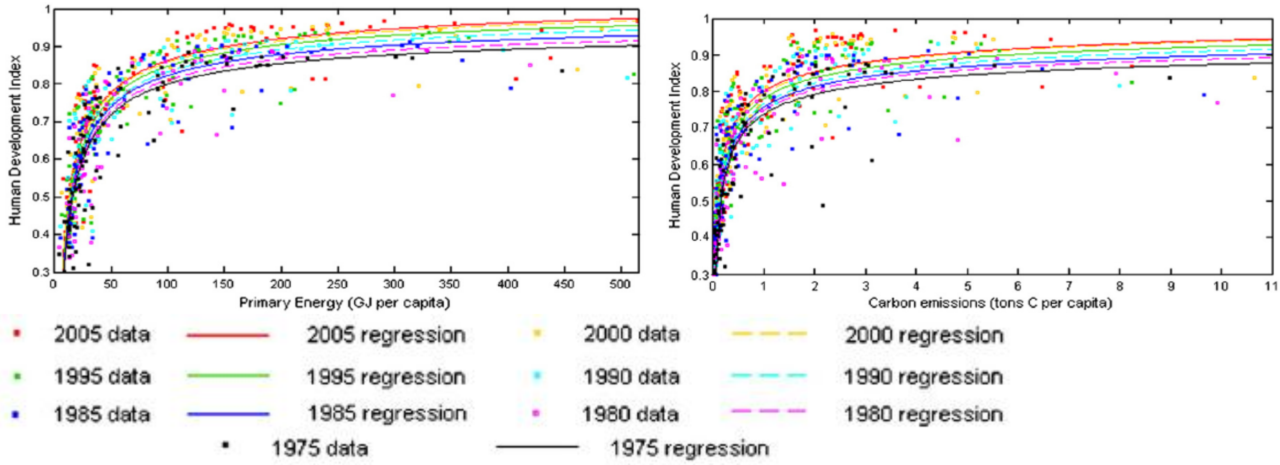
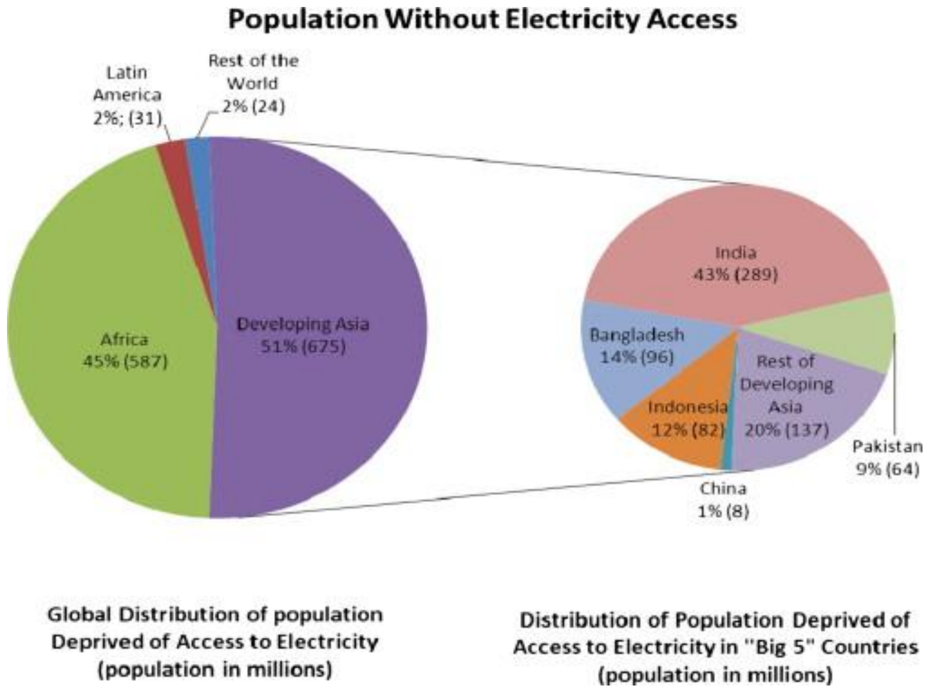
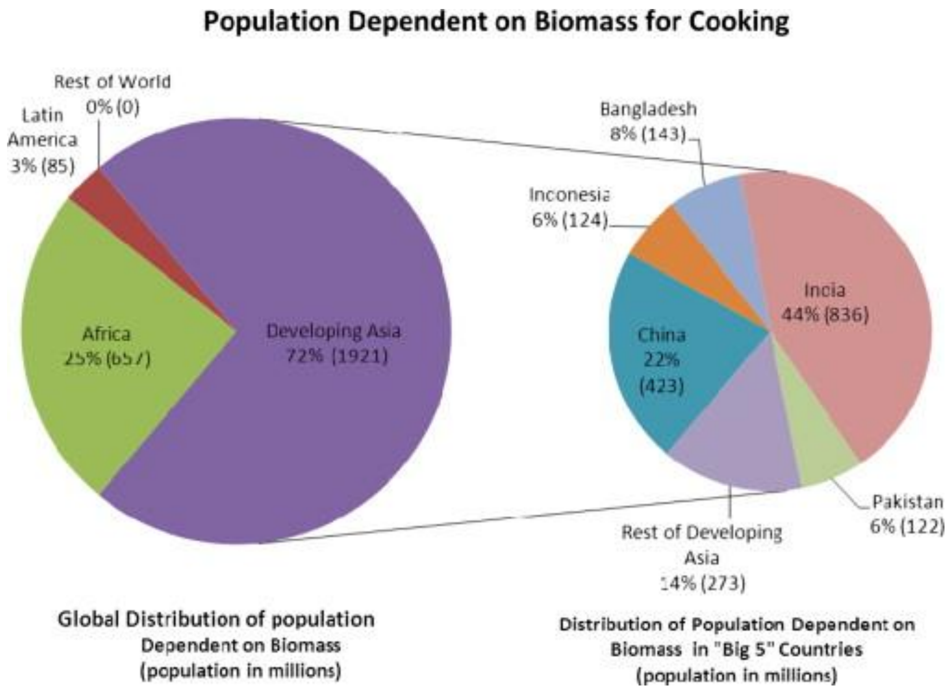


Figure 7.12 Correlation between a) primary energy use per capita and b) carbon emissions per capita and the Human Development Index (Steinberger and JT Roberts, 2010).

The provision of access to clean, efficient, affordable and reliable energy services entails multiple co-benefits (Shrestha and Pradhan, 2010). The creation of employment opportunities can be seen as a co-benefit in the promotion of renewable energy for GHG mitigation (IPCC, 2011a; UNEP, 2011). In many developing countries, such as India, Nepal, Brazil and parts of Africa, renewables have already been shown to stimulate local and economic development (Goldemberg et al. 2008; Cherian 2009; Walter et al. 2011). Positive spill-over effects from technological innovation relate to technology trade and knowledge transfer (see Chapter 13). Health benefits from improved household cooking conditions (Hutton et al., 2007; Wilkinson et al., 2009; A Riahi et al., 2012); reduced hardship associated with fuelwood collection on women and children (Cooke et al., 2008; Oparoacha and Dutta, 2011), educational benefits as a function of rural electrification (Kanagawa and Nakata, 2008), and enhanced support for the productive sector and income generation opportunities (Bazilian et al., 2012) are some of the important co-benefits of some mitigation options that would enhance the HDI and support economic development.



a)



b)

Figure 7.13 Population distribution a) without electricity and b) dependent on biomass for cooking (global and "Big 5" countries) (IEA, 2011a).

7.9.2 Environmental and health effects

Energy supply options differ with regard to their overall environmental and health impacts, not only their GHG emissions (Table 7.4). Renewable energies are often seen as environmentally benign by nature: while the use of fossil and nuclear technologies depletes natural capital stocks, renewable energies are 'sustainable' as long as their rate of use does not exceed their regeneration rate. However, no technology – particularly in large scale application - comes without environmental impacts. To evaluate the relative burden of energy systems within the environment, full energy supply chains have to be considered on a life-cycle basis, including all system components, and across all impact categories.

To avoid creating new problems, assessments of mitigation technologies need to address a wide range of issues, for example, land and water use, as well as air, water and soil pollution. Some of these impacts tend to be site specific, information is scarce and often difficult to generalise. The attribution of actual impacts to specific causes results in methodological challenges. Trade-offs among different types of impacts, affecting different species and at different times, become apparent in assessments (J. Sathaye et al., 2011a). Also, the analysis has to go beyond marginal changes in the existing system to address alternative futures. In the following paragraphs we will briefly discuss environmental implications of different low carbon technologies.

Combustion-related emissions cause substantial human and ecological impacts: particulate matter formed from products of incomplete combustion, sulphur and nitrogen oxides are an important cause of respiratory damages, causing on the order of 2.5 million premature deaths for outdoor air pollution (Pope et al., 2009; GEA Chapter 4). Sulphur and nitrogen oxides are involved in the acidification of fresh water and soils; Nitrogen oxides in the eutrophication of water bodies, both threatening biodiversity, and the formation of photochemical oxidants (summer smog, ozone) (Edgar G. Hertwich et al., 2010). Coal is an important source of mercury (IEA, 2011a) and other toxic metals (EG Pacyna et al., 2007). About half of the impact categories commonly traced in life cycle assessment are well correlated with fossil fuel use (MAJ Huijbregts et al., 2010). Reducing fossil fuel combustion, especially coal combustion, can reduce many forms of pollution and may thus yield co-benefits for health and ecosystems (Aunan et al., 2004; KR Smith and Haigler, 2008; Creuzig and He, 2009; Shrestha and Pradhan, 2010; Markandya et al., 2012).

Ecological and health impacts of renewable energy have been comprehensively assessed in SRREN, which also provides a review of life cycle assessments of nuclear and fossil-based power generation (J. Sathaye et al., 2011a). Renewable energy sources depend on large areas to harvest energy, so these technologies have a range of ecological impacts related to habitat change which - depending on site characteristics and the implementation of the technology – is often higher than those of fossil fuel based systems (J. Sathaye et al., 2011a). For wind power plants, collisions with raptors and wake-induced damage to bats, as well as site-disturbance during construction, cause ecological concerns (Garvin et al., 2011; Grodsky et al., 2011; Dahl et al., 2012). Adjustments in the location, design and operation of facilities can mitigate some of these damages (Arnett et al., 2011; M de Lucas et al., 2012). For hydropower plants, the large-scale modification of river flow regimes affects especially migratory species (Alho, 2011b; Ziv et al., 2012). Geothermal energy (Bayer et al., 2013) and concentrating solar power (K. Damerau et al., 2011) have high water requirements and cause potential concerns about water pollution, depending on design and technological choices.

Hydropower, wind power, solar power, and nuclear power, in particular, perform favourable compared to fossil fuels on pollution-related indicators. These systems have higher material requirements per unit electricity produced than fossil based system; metals and cement production cause various air pollutants. On a life cycle basis, however, modern renewable energy technologies generally cause less pollution-related impacts than fossil-based systems.

While reducing atmospheric emissions from energy generation, CCS will increase environmental burdens associated with the fuel supply chains due to the energy, water, chemicals, and additional equipment required to capture and store CO_2 , thereby increasing the pressures on human health and ecosystems through chemical mechanisms by 0- 60% compared to the best available fossil fuel power plants (Singh, et al., 2011). However, these impacts are evaluated to be smaller than the ecological and human health impacts avoided through reduced climate change (B. Singh et al., 2012). Uncertainties and risks associated with long-term storage also have to be considered (Chapter 7.9.3; Ketzer et al., 2011; Koorneef et al., 2011). For an overview of mitigation options and their unresolved challenges, see section 7.5.

An issue is the vulnerability of thermal generation to cooling water availability and temperature, in particular for large centralised structures with high cooling loads (Bates et al., 2008; Dai, 2011). Reduced water availability or substantial temperature increases of water bodies will lower cooling system efficiency, and may ultimately result in thermal power plants running at lower capacities or shutting down completely, as experienced during the 2003 heat wave in France (Poumadére et al., 2005). Water availability is also an issue for solar-thermal electricity generation, which is often located in hot, dry climates (J.J. Burkhardt et al., 2011; K. Damerau et al., 2011). Air cooling systems reduce water use substantially but decrease efficiency and increase costs.

While any low carbon energy system should be subject to scrutiny to assure environmental integrity, the outcome must be compared against the performance of the current energy system as a baseline. In this context it should be noted that the environmental performance of fossil technologies is expected to decline with the increasing use of unconventional resources with their associated adverse environmental impacts of extraction (Jordaan et al., 2009; S. Yeh et al., 2010).

7.9.3 Technical risks

This section updates the risk assessment presented in chapter 9 of the IPCC SRREN report (IPCC, 2011a). Each technology carries specific operational risks including accidents. The comparative assessment of accident risks associated with current and future energy systems is thus a pivotal aspect in a comprehensive evaluation of energy and sustainability. Accidental events can be triggered by natural hazards (e.g., Steinberg et al., 2008; Kaiser et al., 2009; Cozzani et al., 2010), technological failures (e.g., Hirschberg et al., 2004; Burgherr et al., 2008), purposefully malicious action (e.g., Giroux, 2008), and human errors (e.g., Meshakti, 2007; Ale et al., 2008). In the event of accidents, fatality and injury may occur among workers and residents. Evacuation and resettlements of residents also may take place. With a coal chain, mining accidents are the major component of the accident related external costs. The numbers presented here address only severe accidents with more than 5 fatalities as recorded in the Energy-Related Severe Accident Database (ENSAD) database (Burgherr et al., 2011). Over 33,000 fatalities with severe coal-related accidents have been reported until 2008, 25000 in China.

With the oil and natural gas chains, fatalities related to severe accidents at the transport and distribution stage are the major component of the accident related external costs. Over 22,000 fatalities in the severe accidents for the oil chain, 4000 for LPG and 2,800 for the natural gas chain are reported (Burgherr et al., 2011).

For hydropower, a single event, the 1975 Banqiao/Shimantan dam failure in China, accounted for 26,000 fatalities. Total fatalities from hydro chain amount to nearly 30,000, but only 14 were recorded in OECD countries.

Severe nuclear accidents have occurred at Three Mile Island (1979), Chernobyl (1986), and Fukushima-Daiichi (2011). For Three Mile Island no fatality or injuries are reported. For Chernobyl, 31 immediate fatalities and injury of 370 persons occurred. Chernobyl resulted in high emissions of I131 which has caused measureable increases of thyroid cancer in the surrounding areas, with the total incidence estimated to 1000 cases so far and another 15000 cases until 2065, mostly non-fatal. Epidemiological evidence for other cancer effects does not exist, and risk estimates depend on the assumption of a linear no-threshold dose-response relationship, which is controversial (Tubiana et al., 2009). 14,000 to 130,000 cancer cases may potentially result (Cardis et al., 2006), and potential fatalities have been estimated 9,000 to 33,000 (Hirschberg et al., 1998).

The Fukushima-Daiichi accident resulted in much lower radiation exposure. 30 workers received radiation exposure above 100 mSv, and population exposure has been low (Boice, 2012). Following the linear, no-threshold assumption, 130 (15-1100) cancer-related mortalities and 180 (24-1800) cancer-related morbidities have been estimated (Ten Hoeve and M. Z. Jacobson, 2012).

Figure 7.14 shows risk assessment results for a broad range of currently operating technologies. For fossil energy chains and hydropower, OECD and EU 27 countries generally show lower fatality rates and maximum consequences than non-OECD countries. Among fossil chains, natural gas performs best with respect to both indicators. The fatality rate for coal in China (1994 to 1999) is distinctly higher than for the other non-OECD countries (Hirschberg et al., 2003; Burgherr and Hirschberg, 2007), however, data for 2000 to 2009 suggest that China is slowly approaching the level of other non-OECD countries (see Annex II of IPCC SRREN (2011a)). Among large centralized technologies, modern nuclear and OECD hydropower plants show the lowest fatality rates, but at the same time the consequences of extreme accidents can be very large.

Design improvements for nuclear power since Chernobyl resulted in so-called Generation III+ designs with simplified and standardized instrumentation, strengthened containments and some contain “passive” safety systems based on laws of nature that operate automatically even if electrical power to the control system and pumps is lost and make emergency cooling independent of the availability of power for days. Nuclear power plants designs incorporate a 'defence-in-depth' approach, with multiple safety systems both physical barriers with various layers and institutional controls, redundancy and diversification - all targeted at minimizing the probability of accidents, and avoiding major human consequences from radiation when they occur (NEA, 2008).

Non hydro renewable energy technologies exhibit distinctly lower fatality rates than fossil chains, and are fully comparable to hydro and nuclear power in highly developed countries. Concerning maximum consequences, those renewable sources clearly outperform all other technologies because their decentralized nature strongly limits their catastrophic impacts.

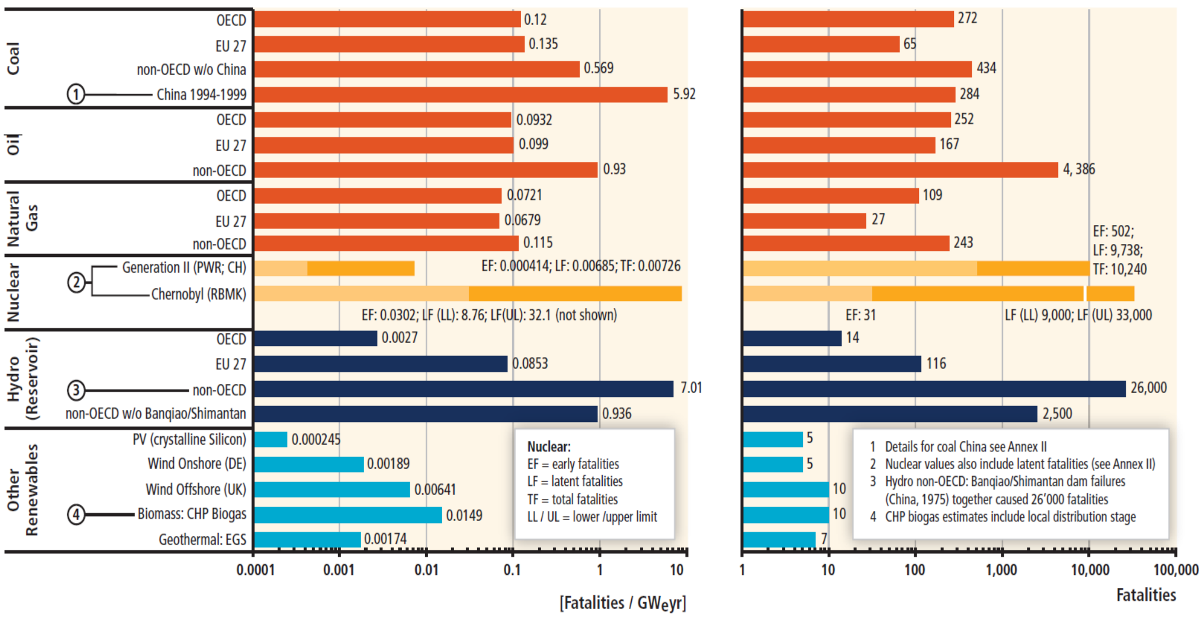


Figure 7.14 Comparison of fatality rates and maximum consequences of severe accidents of currently operating large centralized and decentralized energy technologies. Fossil and hydropower is based on the ENSAD database (period 1970 to 2008); for nuclear PSA is applied; and for other renewable sources a combination of available data, literature survey and expert judgment is used. See Annex **II** for methodological details. Note: RBMK = reaktor bolshoy moshchnosty kanalny, a boiling water-cooled graphite moderated pressure tube type reactor; PWR = pressurized-water reactor; CHP = combined heat and power; EGS = Enhanced Geothermal Systems. Source: IPCC SRREN (2011a)

As indicated by the IPCC SRREN report, accidents can also result in the contamination of large land and water areas. Accidental land contamination due to the release of radioactive isotopes however, is only relevant for nuclear technologies. Regarding accidental releases of crude oil and its refined products into the maritime environment, substantial improvements have been achieved since the 1970s due to technical measures, but also to international conventions, national legislations and increased financial liabilities (see eg IPCC SRREN, (2011a) or Kontovas et al., (2010)).

Still, accidental spills from the extraction and production of petroleum fuel are common and can affect both saline and freshwater resources (Jernelöv, 2010; Rogowska and Namiesnik, 2010). Furthermore, increased extraction of deep offshore resources (e.g., Gulf of Mexico, Brazil) as well as in extreme environments (e.g., the Arctic) provides an additional threat of accidents with potentially high environmental and economic impacts.

Spills of chemicals can also occur via hydraulic fracturing during shale natural gas and geothermal operations, which can potentially result in local water contamination (Aksoy et al., 2009; Kargbo et al., 2010). Additional research is needed in this area to better account for a variety of risk aspects that are currently not amenable to full quantification due to limited data and experience or since they cannot be fully covered by traditional risk indicators focusing mainly on immediate consequences. This is specially the case for CCS storage issues (cf. section 7.5.5)

7.9.4 Public perception[15]

Although public concerns are often directed at higher-GHG-emitting energy sources, concerns also exist for lower-emitting sources, and opposition can impede their deployment. Although RE sources often receive relatively wide public support, public concerns do exist, which, because of the diversity of RE sources and applications, vary by technology (J. Sathaye et al., 2011a). For bioenergy, for example, concerns focus on direct and indirect land use and related GHG emissions, deforestation, and possible competition with food supplies (e.g., Chum et al., 2011; and Bioenergy Annex of chapter 11). For hydropower, concerns include the possibility of the displacement of human populations, negative environmental impacts, and altered recreational opportunities (e.g., A Kumar et al., 2011). For wind energy, concerns primarily relate to visibility and landscape implications as well as potential nuisance effects, such as noise (e.g., Wiser et al., 2011). For solar energy, land area requirements can be a concern for large, utility-scale plants (e.g., Arvizu et al., 2011). For ocean energy, sea area requirements are a concern (e.g., Lewis et al., 2011). Concerns for geothermal energy include the possibility of induced local seismicity and impacts on natural - especially recreational - areas (e.g., Goldstein et al., 2011).

For nuclear energy, concerns often focus on health and safety (e.g., accidents, disposal of wastes, decommisioning) and proliferation (e.g., terrorism, civil unrest); further, perceptions are dependent on how nuclear is framed relative to other sources of energy supply (e.g., Bickerstaff et al., 2008; Sjoberg and Drottz-Sjoberg, 2009; Corner et al., 2011; Ahearne, 2011). Among CCS technologies, early[16] concerns include the ecological impacts associated with different storage media, the potential for accidental release, and related storage effectiveness of stored CO_2, and that CCS technologies do not avoid the non-GHG social and environmental impacts of fossil energy sources (IPCC, 2005; e.g., E Miller et al., 2007; de Best-Waldhober et al., 2009; Shackley et al., 2009; Wong-Parodi and Ray, 2009; Wallquist et al., 2009, 2010; DM Reiner and WJ Nuttall, 2011). For natural gas, the recent increase in the use of unconventional extraction methods, such as hydrological fracturing, has created concerns about potential risks to local water quality and public health (e.g., US EPA, 2011; IEA, 2012i).

Though impacts, and related public concerns, cannot be entirely eliminated, assessing, minimizing and mitigating impacts and concerns are elements of many jurisdictions' planning, siting, and permitting processes. Technical mitigation options show promise, as do procedural techniques, such as: ensuring the availability of accurate and unbiased information about the technology, its impacts and benefits; aligning the expectations and interests of different stakeholders; adjusting to the local societal context; adopting benefit sharing mechanisms; obtaining explicit support at local and national levels prior to development; building collaborative networks; and developing mechanisms for articulating conflict and engaging in negotiation (e.g., Peta Ashworth et al., 2010; Fleishman et al., 2010; Mitchell et al., 2011; Terwel et al., 2011).

FAQ 7.3 Are there any additional benefits and/or adverse side effects associated with mitigation in the energy supply sector?

Co-benefits can often be found from the use of mitigation technologies in the energy supply sector and although they are not unique to these technologies, examples include: reduced air pollution, lower energy production related fatality rates, local employment opportunities, better energy security, improved energy access and reduced vulnerability to price volatility. At the same time

[15] Other portions of this chapter and AR5 contain discussions of actual ecological and environmental impacts of various energy sources. Although not addressed here, energy transmission infrastructure can also be the focus of public concern. See also Chapters 2, 6, and 10, which cover issues of public acceptance through complementary lenses.

[16] Knowledge about the social acceptability of CCS is limited due to the early state of the technologies' deployment (De Best-Waldhober et al., 2009; Malone et al., 2010; Ter Mors et al., 2010; Corry and D Reiner, 2011).

however, some low carbon technologies can have substantial negative impacts; such as those related to health and ecological aspects as well as operational and proliferation risks. Examples include habitat change and effects on wildlife in the case of some large scale renewable energy projects and proliferation risk through poor handling and storage of nuclear materials. Many of these impacts can be mitigated to some extent through the appropriate selection, design, siting and operation of the respective technology.

7.10 Barriers and opportunities (technological, physical, financial, institutional, cultural, legal)

7.10.1 Technical aspects

A number of bottom-up and top-down studies have investigated the principal feasibility and mitigation costs that are associated with ambitious climate protections strategies, e.g., those that are consistent with a stabilization of global mean temperature change at a level below 2°C compared to the pre-industrial state (IEA, 2010b; c; Chapter 6; IPCC, 2011a; Chapter 10 and references therein; Rogner et al., 2012). From a global perspective, the large number of different technologies that are available to mitigate climate change facilitates the achievement of the aforementioned climate protection goals (see section 7.5). As many different combinations of the mitigation technologies are feasible, least cost portfolios can be determined that select those options which interact in the best possible way (see section 7.11). On a local scale and/or concerning specific technologies, however, various physical and technological barriers might constrain their mitigation potential. These limits are discussed in Section 7.5., 7.6 and 7.9.

7.10.2 Financial and investment barriers and opportunities

In the New Policies Scenario of IEA (2012b) (correspond to a long-term average global temperature increase of 3.6 °C), a cumulative investment of \$(2011) 37 trillion is needed in the world's energy supply system over 2012-2035 which is 1.5% of world GDP. This implies annual average investment of \$1.6 trillion. The shares of this investment in power generation, oil, gas, coal and biofuels are 45%, 27%, 23%, 3% and 1%, respectively.

The shares of the investment in fossil fuels, nuclear, hydro, renewables excluding hydro, and the total of transmission and distribution in power generation are 16%, 6%, 9%, 27% and 43%, respectively. The investment in renewables excluding hydro over 2012-2035 is about \$4.4 trillion which is about \$200 billion per year.

The total investment in renewables excluding hydro in 2012 was \$269 billion, which was five times the level in 2004. Out of this \$143 billion was for solar and \$78 billion for wind power. It was down 11% from a record \$302 billion in 2011 after the governments in industrial nations slashed subsidies for renewables due to the debt crises in the U.S. and Europe and due to a 24 per cent decline in solar panel prices in 2012 (Bloomberg, 2013).

Additional investments required in the energy system are estimated to be \$190 billion to \$800 billion per year in order to limit the temperature increase below 2°C (about 0.27% to 1.14% of current world GDP). The developing countries, witnessing greater increase in energy demands, require more investments than the developed countries (GEA, 2012, chap. 17; IEA, 2012b; h; M. Kainuma et al., 2013).

Investment needs in energy supply sector increase under low GHG scenarios. However, this should be set in the context of the total value of the world's financial stock, which (including global stock market capitalization) stood at more than \$210 trillion at the end of 2010 (Roxburgh et al., 2011). Moreover, the investment needs described above would be offset, to a degree, by the lower operating costs of many low-GHG energy supply sources.

Though only a fraction of the available private-sector capital stock would be needed to cover the costs of low-GHG energy supply even in aggressive GHG reduction scenarios, private capital will not be mobilized automatically for such purposes. For this reason, various measures – such as climate investment funds, carbon pricing, feed-in tariffs, carbon offset markets, and private–public initiatives aimed at lowering barriers for investors – are currently being implemented (United Nations, 2010; World Bank, 2011b). Uncertainty in policies could be a barrier to investment in projects which entail long payback periods.

Investment in LDCs may be a particular challenge given their less-developed capital markets. Multilateral development banks and institutions for bilateral developmental cooperation will have an important role towards increasing levels of confidence for private investors. Innovative insurance schemes to address regulatory and policy barriers could encourage participation of more diverse types of institutional investors (S Patel, 2011). Building capacity in local governments in developing countries for designing and implementing appropriate policies and regulations, including those for efficient and transparent procurement for investment in the infrastructure, is also important (World Economic Forum, 2011; Sudo, 2013).

Rural areas are characterized by a very low population density and very low and often irregular income mainly from agriculture. The vast majority of rural population cannot afford to pay for the initial investment to access low carbon energy technologies despite the sharp decrease of PV prices during this first decade (IPCC, 2011b). Micro finance mechanisms (grants, concessional loans) adapted to the pattern of rural activities (for instance, instalments correlated with income from agriculture) are necessary to lift rural populations out of the poverty energy trap and increase the deployment of low carbon energy technologies.

7.10.3 Cultural, institutional, and legal barriers and opportunities

Managing the transition from fossil fuels to energy systems with a large penetration of low carbon technologies, particularly RES and improved energy efficiency will pose a series of challenges and opportunities particularly in the case of poor countries. Indeed, attitudes towards RE in addition to rationality are driven by emotions and psychological issues. To be successful, RE deployment and information and awareness efforts and strategies need to take this explicitly into account (J. Sathaye et al., 2011a). Depending on the status of the regions and the economies, barriers and opportunities may differ dramatically. A study finds that the apparent disconnect between how electricity is made and how it is socially perceived perpetuates public apathy and misinformation. As a result, wind farms and solar panels (along with other renewable power systems) are often opposed not because they are a poor alternative to fossil fuels, but because people simply do not comprehend why such technologies may be needed (Benjamin Sovacool, 2009).

A huge barrier in the case of poor developing countries is the cultural economic and social gap between rural and urban areas (Khennas, 2012). For instance cooking fuels particularly firewood is widely used in rural areas because it is a suitable fuel for these communities in addition to its access without payment apart from the time devoted to its collection. Indeed values such as time have different perceptions and opportunity costs depending on the social and geographical context. Furthermore legal barriers are often hindering the penetration of modern energy services and distorting the economics of energy systems. For instance, informal settlements in poor peripheral urban areas mean legal barriers to get access to electricity. Land tenancy issues and illegal settlements are major constraints to energy access which are often overcome by illegal power connections with an impact on the safety of the end users and economic loss for the utility due to meter tampering, and vandalism. In addition, in many slums there is a culture of non-payment of the bills (UN Habitat and GENUS, 2009). Orthodox electrification approaches are inefficient in the context of urban slums. Adopting a holistic approach encompassing cultural, institutional and legal issues in the formulation and implementation and implementation of energy policies and strategies is increasingly perceived particularly in sub-Saharan Africa as essential to addressing access to modern energy services. In South Africa, ESKOM, the large utility in Africa, implemented a holistic Energy Losses Management Program (UN Habitat and GENUS, 2009), with strong community involvement to deal with the problem of energy loss management, theft and vandalism. As a result prepayment was successfully implemented as it gives the poor customers a daily visibility of consumption and a different culture and understanding of access to modern energy services.

7.10.4 Human capital capacity building

Lack of human capital is widely recognized as one of the barriers to development, acquisition, deployment, and diffusion of technologies required for meeting the energy-related CO_2 emissions reduction targets. Human capacity is critical in providing a sustainable enabling environment for technology transfer in both the host and recipient countries (Barker et al., 2007; Halsnaes et al., 2007). Human workforce development has thus been identified as an important near-term priority (IEA, 2010b).

Skilled workforce is needed, in particular, in the areas of renewable energy and decentralized energy systems, which form an important part of "green jobs" (Strietska-Ilina et al., 2011). The required skill set differs in detail for different technologies and local context, and people require specific training (W. Moomaw et al., 2011). Developing the skills to install, operate and maintain the renewable energy equipment is exceedingly important for a successful renewable energy project, particularly in developing countries (Martinot, 1998; Wilkins, 2002; UNEP, 2011).

Renewable energy has a high potential for direct employment generation, including R&D, engineering, consultancy, auditing, quality control, and installation and maintenance. Although there are some reports indicating that large scale renewable energy deployment could have offsetting effects on the conventional energy sector and the overall economy, resulting in net job losses (Hillebrand et al., 2006; Frondel et al., 2010), several studies report net positive employment effects (Lehra et al., 2008; del Rio and Burguillo, 2009). In developing economies, particularly in a rural setting, energy access through RE deployment can generate significant employment (Openshaw, 2010; IRENA, 2012), and shortages of teachers and trainers in subjects related to the fast-growing renewable energy sector have been reported (Strietska-Ilina et al., 2011).

In addition to renewable energy, human capital will also be required on other low-carbon energy technologies, particularly CCS and nuclear (Creutzig and D.M. Kammen, 2011). CCS and nuclear power, also could generate more jobs than the fossil fuel sector per unit of energy delivered (M Wei et al., 2010). Moreover, apart from technology-oriented skills, capacity for decision-support and policymaking in the design and enactment stages is also essential, particularly on assessing and choosing technology and policy options, and designing holistic policies that effectively integrate renewable energy with other low-carbon options, other policy goals, and across different but interconnected sectors (e.g. agriculture and water) (Mitchell et al., 2011; Jagger et al., 2013).

To avoid future skill shortages, countries will need to formulate human capital development strategies based on well-informed policy decisions, and adequate information on labour market and skill needs in the context of low carbon transition and green jobs (Strietska-Ilina et al., 2011; Jagger et al., 2013).

7.10.5 Inertia in energy systems physical capital stock turnover

The long life of capital stock in energy supply systems (discussed in section 5.9.3) gives the possibility of path dependant carbon lock-in (Unruh, 2002). Of the 1549 GW investments (from 2000-2010) in the global electricity sector (Davis et al., 2010; EIA, 2011b), 516 GW (33.3%) were coal, 482 GW (31.1%) were natural gas, and 47 GW (3.0%) were oil. 34 GW (2.2%) were nuclear investments. Combined renewable source power plants were 317 GW (20.5%), although this investment share accelerated towards the end of the decade (153 GW (9.9%) were listed as dual-fuel/unclassified).

Therefore high carbon energy capital stock is currently being heavily invested in and this – combined with earlier fossil plant capacity – will be still in place for decades to come.

Long-living fossil energy system investments represent an *effective* (high carbon) lock-in. Typical lifetime of central fossil fuelled power plants are between 30 and 40 years; those of electricity and gas infrastructures between 25-50 years (Philibert and Pershing, 2002).

Although such capital stock is not an irreversible investment, premature retirement (or retrofitting with CCS if feasible) is expensive. Furthermore, removal of existing fossil plant must overcome inertia from existing providers, and consider wider physical, financial, human capital and institutional barriers.

Explicit analysis of path dependency from existing energy fossil technologies (450ppm scenario, IEA, 2011a) illustrates that if current trends continue, by 2015 at least 90% of the available "carbon budget" will be allocated to existing energy and industrial infrastructure, and in a small number of subsequent years there will be no room for manoeuvre at all (IEA, 2011a, Figure 6.12).

Effective lock-in from long-lived energy technologies is particularly relevant for future investments by developing economies – that are projected to account for over 90% of the increase in primary energy demand by 2035 (IEA, 2011a). The relative lack of existing energy capital in many developing countries bolsters the potential opportunities to develop a low carbon energy system, and hence reduce the effective carbon lock-in from broader energy infrastructures (e.g., electricity lines, road transport) (Guivarch and Hallegatte, 2011), or the very long lived capital stock embodied in buildings and urban patterns (Jaccard and Rivers, 2007).

FAQ 7.4 What barriers need to be overcome in the energy supply sector to enable a transformation to low GHG emissions?

The combined global technical potential of low carbon technologies is sufficient to enable the deep cuts in GHG emissions necessary to achieve the global mean temperature change of less than 2°C established by the Cancun Agreement.

Despite this, financial barriers as well as integration issues act to constrain the scale and speed of their implementation. Many RE technologies are still not competitive with market energy prices. Further direct or indirect financial support is required to increase their market share.

The same is and will be true for CCS plants because of the additional equipment they require and their decreased efficiency.

For nuclear power, the assessment of their economics post Fukushima is mixed. Beyond financial and technical ones, additional barriers exist in the field of technology transfer, capacity building and in some cases public perception.

For least developed countries, deep penetration of low carbon technologies will require financial support coupled to sustainable technology transfer. The biggest barrier, however, is the lack of a coherent global climate policy that is committed to the deep emission reductions needed to obey the Cancun Agreement. Central elements of such a policy would be a global carbon pricing scheme supplemented by technology support and regulation where necessary in order to overcome market failures.

7.11 Sectoral implication of transformation pathways and sustainable development

This section reviews long-term integrated assessment scenarios and transformation pathways with regard to their implication for the global energy system. Focus is given to energy-related CO_2

emissions and the required changes to the energy system needed to achieve emissions reductions compatible with a range of long-term climate targets.[17]

The assessment builds upon more than 800 greenhouse gas emissions scenarios, which were collated by Chapter 6 in the AR5 scenario database.[18,19] The scenarios were grouped into baseline or reference scenarios and GHG mitigation scenarios, which in turn are further grouped by levels of ambition to reduce GHG emissions. The most stringent mitigation scenarios (category 1) correspond to a long-term total radiative forcing targets of 2.3 to 2.9 W/m^2 (425 to 475 ppm CO_2e), which is broadly compatible with stated objective of the Cancun Agreement to limit global average temperature change to below 2°C. As described in more detail in Chapter 6, category 2 scenarios correspond to stabilization of total radiative forcing between 2.9-3.4 W/ m^2, category 3: 3.4-3.9 W/ m^2, category 4: 3.9-5.1 W/ m^2, and category 5: 5.1-6.8 W/ m^2. Scenarios in the highest category (6) correspond to modest mitigation efforts leading to radiative forcing levels greater than 6.8 W/m^2 (1000 ppm CO_2e) with temperature outcomes of approximately 4°C (See Chapter 6 for details).

7.11.1 Energy-related greenhouse gas emissions

In absence of climate change mitigation policies, energy-related CO_2 emissions are expected to continue to increase from current levels with fossil fuel and industrial emissions reaching 55-70 $GtCO_2$ by 2050 (25th-75th percentile of the scenarios in the AR5 database, see Figure 7.15)[20] This corresponds to an increase of between 80 and 130 per cent compared to emissions of about 30 $GtCO_2$ in the year 2010. By the end of the 21st century emissions could grow further, the 75th percentile of scenarios reaching 90 $GtCO_2$.[21,22]

The stabilization of GHG concentrations requires fundamental change in the global energy system relative to a business as usual pathway.[23] As discussed in Section 7.11.4, unlike traditional pollutants, CO_2 concentrations can only be stabilized if global emissions peak and in the long term, decline toward zero. The lower the concentration at which CO_2 is to be stabilized, the sooner and lower is the peak. For example, in scenarios compatible with a long-term target of below 2.9 W/m^2 (475 ppm CO_2e, category 1) energy-related emissions peak between 2020 and 2030, and decline to about 10-15 $GtCO_2$ by 2050 (Figure 7.15). This corresponds to emissions reductions by 2050 of 50-70% compared to the year 2010, and 75-90% compared to the business as usual (25th-75th percentile).

[17] Other non-CO_2 greenhouse gases (eg, CH4 and N2O) are primarily emitted by other sectors than energy supply and transformation. Their share is thus relatively small in the energy supply and transformation sectors.
[18] AR5 database: https://secure.iiasa.ac.at/web-apps/ene/AR5DB
[19] The analysis in this section focuses on CO_2 emissions only, since the transformation scenarios in the AR5 database do not provide sufficient detail for energy-related emissions of non-CO_2 gases.
[20] Note that energy & industry emissions are mostly dominated by energy-related emissions. A split of this category is not available in the AR5 scenario database. Some models do include in this category emissions from fossil fuel feedstocks for industrial processes (fossil fuel use, for example, lubricants, asphalt, cement production, etc.).
[21] The full uncertainty range of the AR5 databases includes high emissions scenarios approaching 80 $GtCO_2$ by 2050, and almost 120 GtCO2 by 2100.
[22] If not otherwise mentioned, ranges refer to the 25-75 percentile of the AR5 database.
[23] "Baseline" or "reference" scenarios are scenarios which by construction assume no policies or measures are implemented explicitly to limit anthropogenic climate change, beyond those in force at present. Non-climate policies including policies to improve local air quality and/or enhance energy security are considered. They are not intended to be predictions of the future, but rather counterfactual constructions that can serve to highlight implications of climate-motivated policies and measures.

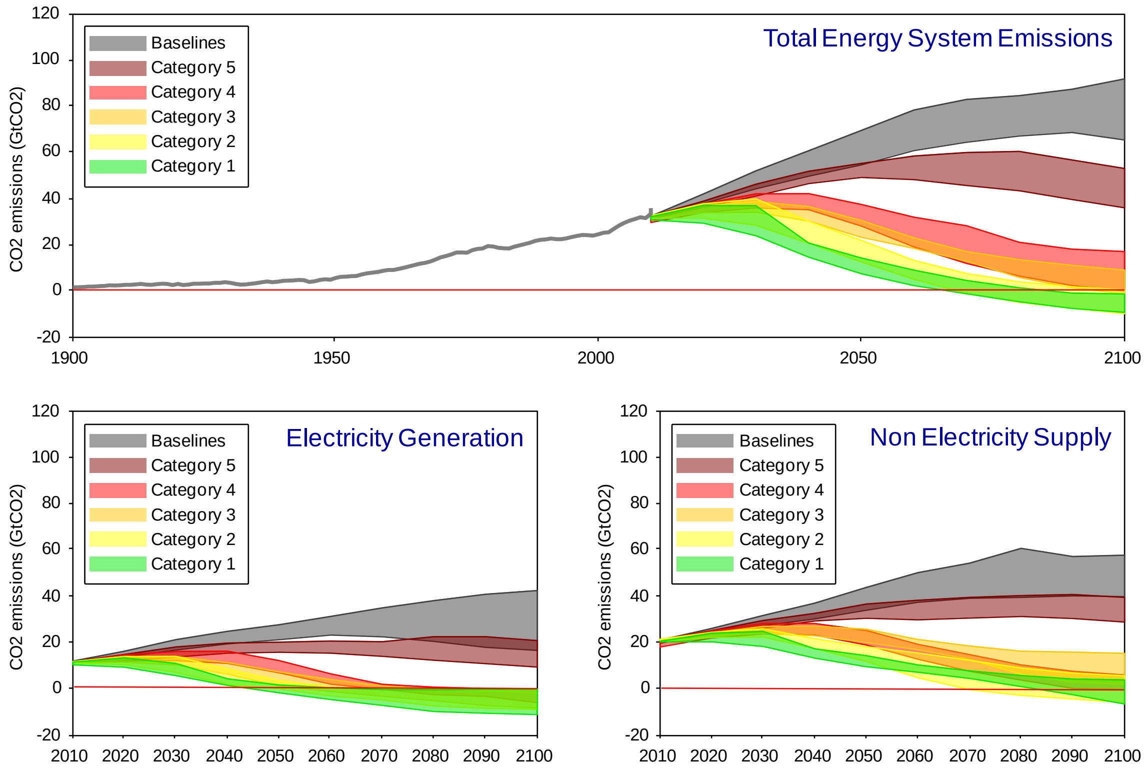


Figure 7.15 Global development of global CO2 emissions in the total energy system (upper panel) and in the electricity and non-electric sectors (lower panels). The baseline emissions range (grey) is compared to the range of emissions from mitigation scenarios grouped according to their long-term target (C1 to C5). Shaded areas correspond to the 25th-75th percentile across scenario categories of the AR5 scenarios database (see Chapter 6 for details). Source: AR5 scenario database (Chapter 6). Note: Some scenarios report industrial process emissions as part of the energy system.

7.11.2 Energy supply in low stabilization scenarios

While stabilizing GHG concentrations requires fundamental changes to the global energy system, a portfolio of measures is available including the reduction of final energy demand through enhanced efficiency or behavioural changes as well as fuel switching from coal to oil and gas and the introduction of low-carbon supply options such as renewables, nuclear, CCS, in combination with fossil or biomass energy conversion processes, and finally, improvements in the efficiency of fossil fuel use. These are discussed in Section 7.5 as well as in chapters 8 through 10.

Figure **7.16** shows examples of alternative energy system transformation pathways that are consistent with Category 1 mitigation levels.

The scenarios from three selected models shown in Figure 7.16 are broadly representative of different strategies for the transformation of the energy system to achieve the stabilization of GHG concentrations at low levels (category 1: 2.7 W/m^2 (460 ppm) by the end of the century). In absence of policies to reduce GHG emissions, the energy supply portfolio of the scenarios continues to be dominated by fossil fuels. Global energy supply in the three scenarios increases from present levels to 900-1200 EJ by 2050 (left-hand panel of Figure 7.16). Stabilization at low levels requires the rapid and pervasive replacement of fossil fuel without CCS (right-hand panel of Figure 7.16). Between 60 and 300 EJ of fossil fuels are replaced across the three scenarios over the next two decades (by

2030). By 2050 fossil energy use is 230-770 EJ lower than in non-climate-policy reference scenarios.[24]

While the pace of the transformation differs across the scenarios (and depends also on the carbon-intensity and energy demand development in the baseline), all three illustrative scenarios show the importance of measures to reduce energy demand over the short term. For instance by 2030, between 40-90% of the emissions reductions are achieved through energy demand saving, thus reducing the need for fossil fuels. The long-term contribution of energy demand savings differs, however, significantly across the three scenarios. For instance, in MESSAGE more than 1200 EJ of fossil fuels are replaced through efficiency and demand-side improvements by 2100, compared to about 400 EJ in the GCAM scenario.

Achieving the stabilization of GHG concentrations at low levels (category 1) requires significant up-scaling of low-carbon energy supply options including the use of CCS with fossil fuels, but with greater energy demand reduction requiring less pervasive and rapid up-scaling of supply side options (see right-side panel of Figure 7.16). Figure 7.17 compares scenarios with low and “moderately high” reference scenario global energy demands. The relatively higher energy demand scenarios are generally accompanied by higher deployment rates for low-carbon options and reduced use of fossil fuels without CCS. The exception to the generally observed reduced use of fossil fuels in Category 1 scenarios with higher reference scenario energy systems is oil production. Note also that even at very low stabilization levels a significant fraction of energy supply in 2050 may be provided by freely emitting fossil energy (without CCS).

[24] The numbers refer to the replacement of freely emitting fossil fuels without CCS. The contribution of fossil fuels with CCS is increasing its contribution in the stabilization scenarios.

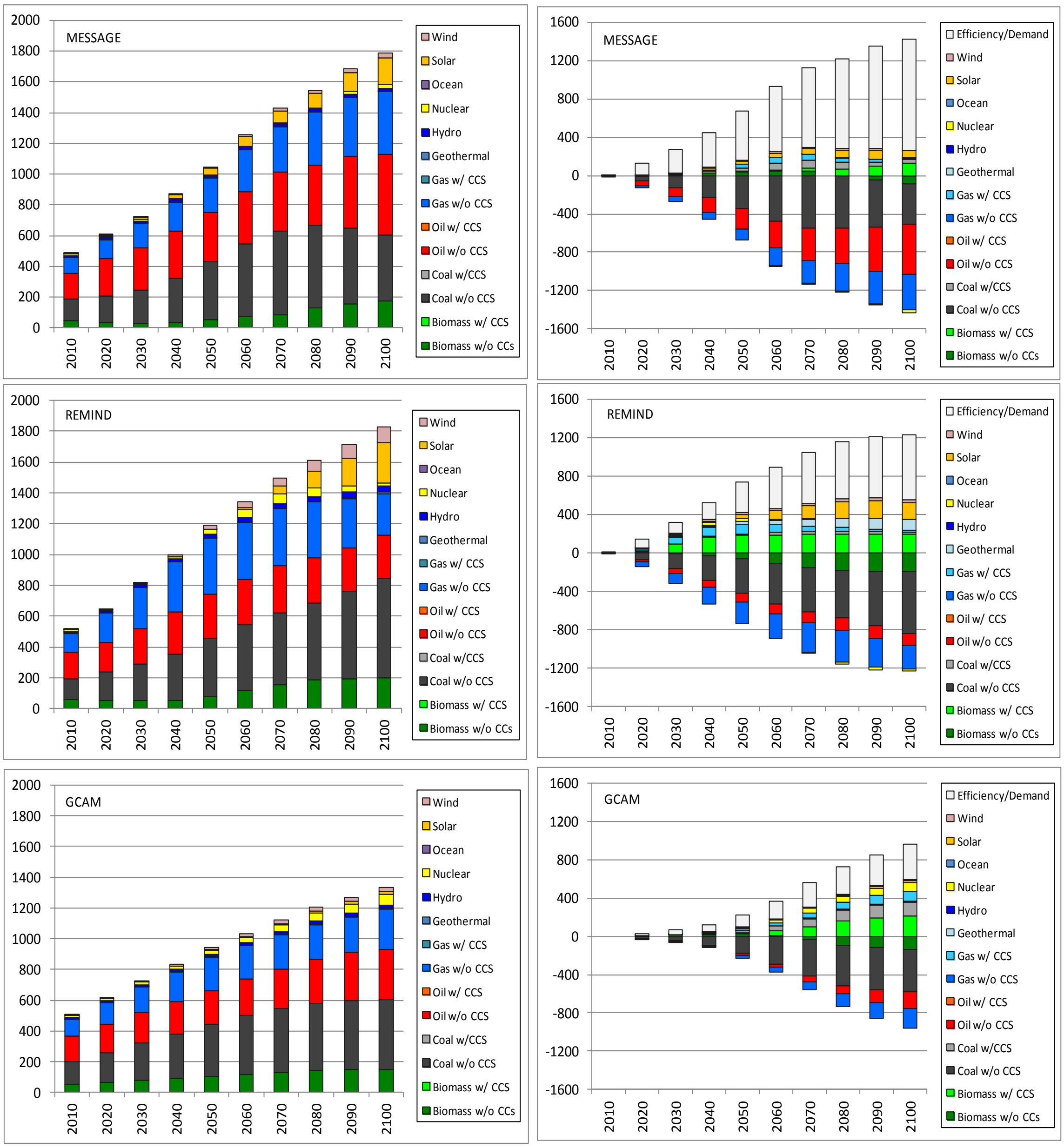


Figure 7.16 Development of primary energy (EJ) in three illustrative baseline scenarios (left-hand panel); and the change in primary energy compared to the baseline in order to meet 450 ppm CO2eq stabilization target (selected scenarios of category 1 of the AR5 scenario database). Data based on chapter 6 scenario database, and three illustrative models: ReMIND (Rose: Kriegler et al, (2013), forthcoming); GCAM (AME: Calvin et al, (2012)); MESSAGE (GEA: Riahi et al, (2012))[25].

[25] Note that "Savings" is calculated as the residual reduction in total primary energy.

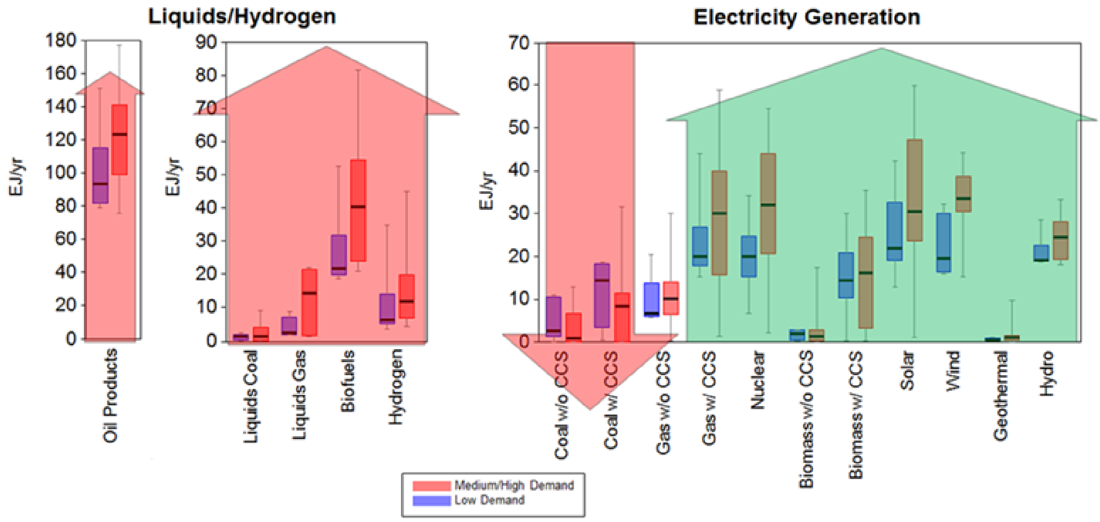


Figure 7.17 Influence of energy demand on the deployment of energy supply technologies in low stabilization scenarios (category 1) in 2050. Green arrows indicate increasing contribution of low-carbon electricity options due to higher demand with the exception of coal-CCS. Red bars show the impact of higher demand on other groups of technologies. Bars show the 25th-75th percentile of individual technology groups (Source: AR5 scenario database).

Energy system response to a prescribed climate policy varies across models and regions. There are multiple alternative transition pathways, for both the global energy system as a whole, and for individual regional energy systems. In fact the special circumstances encountered by individual regions imply greater regional variety in energy mitigation portfolios than in the global portfolio (K Calvin et al., 2012; N. Bauer et al., 2013).

7.11.3 The role of the electricity sector in emissions mitigation

Electrification of the energy system has been a major driver of the historical energy transformation from an originally biomass dominated energy system in the 19th century to a modern system with high reliance on coal and gas (the major sources of electricity generation today). Many emissions mitigation studies (J. Edmonds et al., 2006; as well as the AR5 database) has three generic components: 1. Decarbonize power generation, 2. Substitute electricity for direct use of fossil fuels in buildings and industry (see Chapters 7 and 8), and sometimes transportation, and 3. Reduce aggregate energy demands through technology and other substitutions.

Most integrated assessment scenarios in the AR5 data base report a continuation of the global electrification trend in the future. The share of electricity in final energy more than doubles in some reference scenarios, Figure 7.18. In reference scenarios without climate policy most of the demand for electricity continues to be in the residential, commercial and industry sectors (see Chapters 7 and 8), while transport sectors rely predominantly on liquid fuels (Chapter 9). Bioenergy and electricity both have the potential to provide transport services without fossil fuel emissions. The relative contribution of each depends at least in part on the character of technologies that evolve to provide transport services with each fuel.

Power production is the largest single sector emitting fossil fuel CO_2 at present and in reference scenarios of the future. A variety of mitigation options exist in the electricity sector, including renewables (wind, solar energy, biomass, hydro, geothermal), nuclear and the possibility of fossil or biomass with CCS. The electricity sector plays a major role in transformation scenarios with deep cuts of GHG emissions. Many mitigation studies report an acceleration of the electrification trend in emissions mitigation scenarios (Figure 7.18).

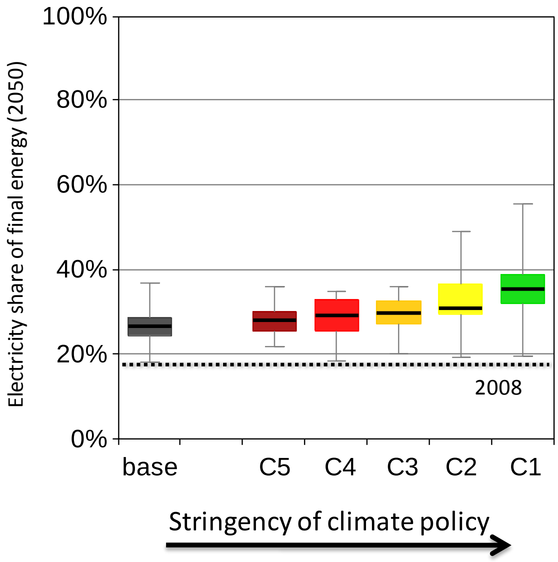


Figure 7.18 Share of electricity in total final energy for the year 2050 in baseline scenarios and three different levels of emissions mitigation stringency. Ranges correspond to the 25th-75th percentile of baseline and stabilization scenario categories of the AR5 scenario database (see chapter 6 and Table 7.5 for more details). Dashed horizontal lines show the electricity share for the year 2008.

Mitigation studies indicate that the decarbonisation of the electricity sector may be achieved at much higher pace than in the rest of the energy system (Figure 7.19). In stringent stabilization scenarios (category 1 & 2), the share of low-carbon energy increases from presently about 30% to more than 80% by 2050. In the long term (2100) fossil-based electricity generation without CCS is phased out entirely in these scenarios.

Integrated assessment models (see Chapter 6) tend to agree that at about 100-150 $/tCO2 the electricity sector is largely decarbonized with a significant fraction being from CCS deployment (V. Krey and K. Riahi, 2009; P Luckow et al., 2010; M. Wise et al., 2010). This is an important insight as at about an 100$/tCO2 price threshold the large-scale utilization of bioenergy with CCS (BECCS) is in many scenarios well underway (V. Krey and K. Riahi, 2009; Azar et al., 2010; P Luckow et al., 2010; JA Edmonds et al., 2013), which would allow for net removal of CO_2 from the atmosphere while simultaneously producing electricity.

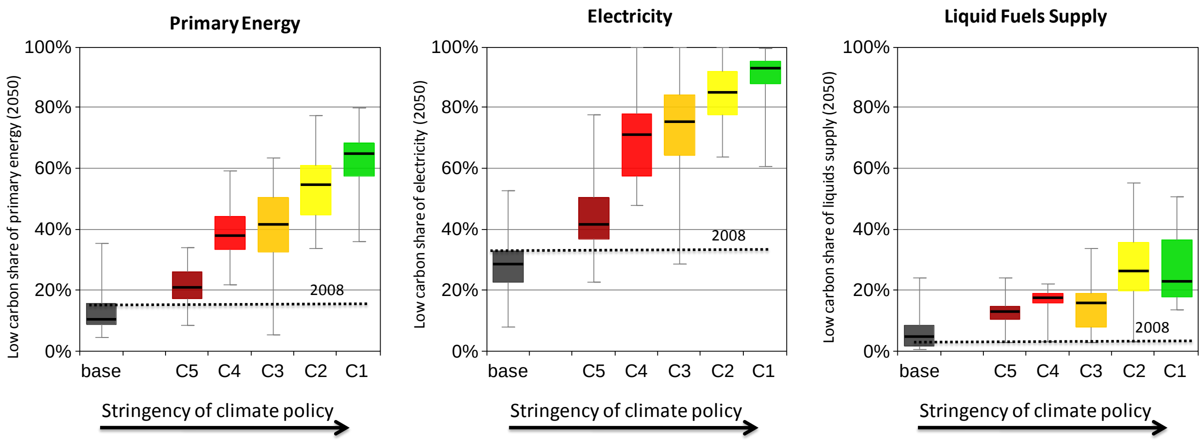


Figure 7.19 Share of low-carbon energy in total primary energy, electricity and liquid supply sectors for the year 2050. Ranges indicate the 25th-75th percentile of the full set of IAM scenarios in the AR5 scenario database (see chapter 6 for more details). Dashed horizontal lines show the low-carbon share for the year 2008. Low-carbon energy includes nuclear, renewables, and fossil fuels with CCS.

Figure 7.20 shows the evolution over time of transformation pathways for primary energy supply, electricity supply, and liquid fuels supply for reference scenarios and Category 1 stabilization scenarios. The effect of climate policy plays out differently in each of these three domains. In aggregate emissions mitigation leads to a reduction in primary energy demands. However, two distinctly different mitigation portfolios emerge—one in which bioenergy (and fossil fuel) with CCS plays a prominent role and the other where, taken together, non-biomass renewables and nuclear power take center stage. In both instances the share of fossil energy without CCS declines to less than 20 per cent of the total. Note that in the scenarios examined here, the major branch point occurs in the post-2050 period, while the foundations are laid in the 2030 to 2050 period.

Power generation is a somewhat different story. While as previously noted, power generation decarbonizes rapidly and completely (in many scenarios emissions actually become negative), taken together, non-biomass renewables and nuclear power always play an important role. The role of biomass and particularly biomass with CCS varies greatly, but even when BECCS becomes extremely important to the overall emissions mitigation strategy, this individual technology never exceeds half of power generation. In contrast to the overall scale of primary energy supply, which fell in carbon policy scenarios relative to reference scenarios, the scale of power generation can be either higher or lower in the presence of climate policy depending on whether the pace of electrification proceeds more or less rapidly than the rate of end-use energy demand reductions.

Liquid fuels are presently supplied by refining petroleum. Many scenarios report increasing shares for liquids derived from other primary energy feedstocks such as bioenergy, coal, and natural gas. Like aggregate primary energy supply the supply of liquid fuels is reduced in climate policy scenarios compared with reference scenarios. In addition, the primary feedstock shifts from petroleum and other fossil fuels to bioenergy.

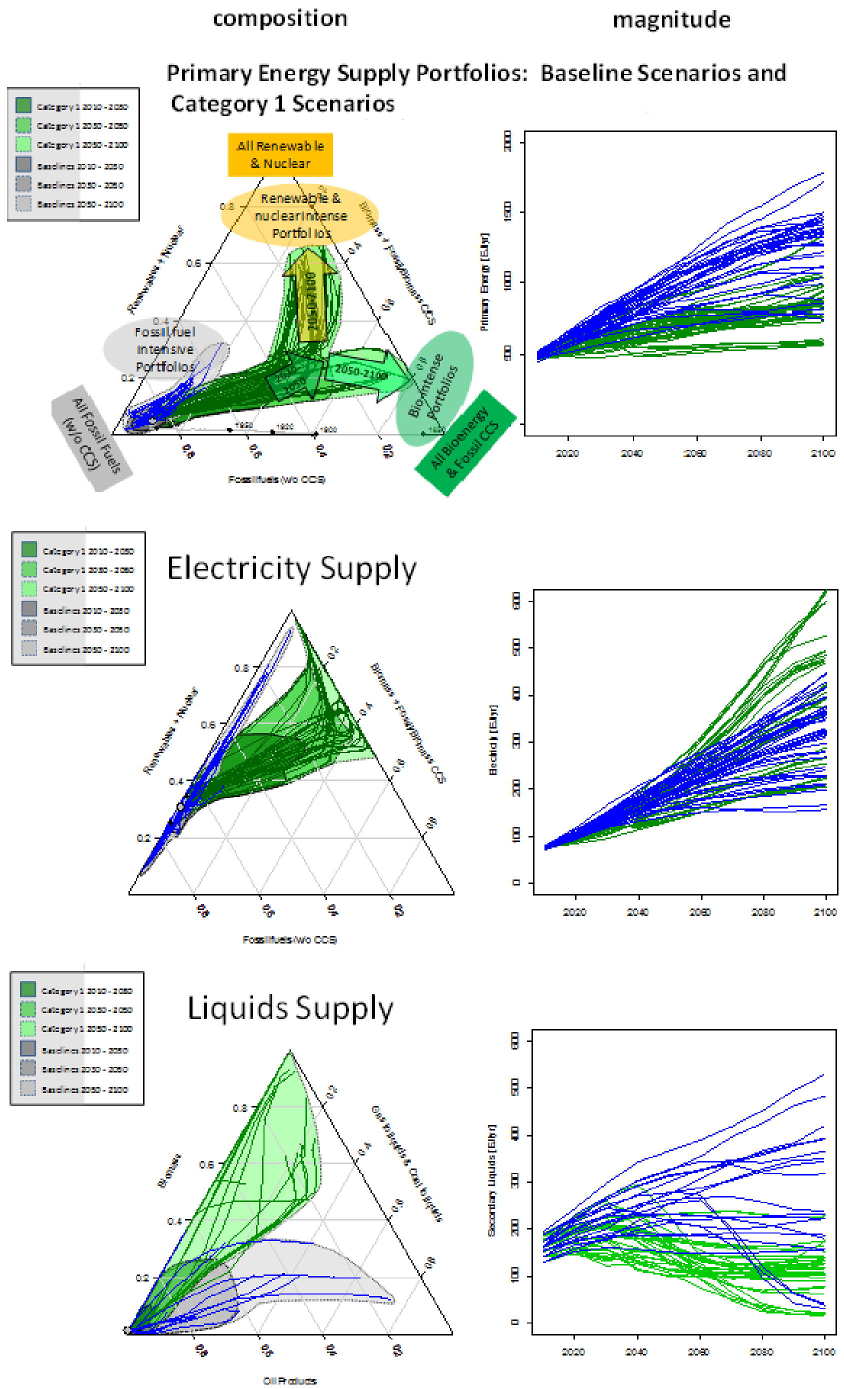


Figure 7.20 Transition Pathways for the Aggregate Energy Supply and Transformation System, Electricity Supply, and the Supply of Liquid Fuels: 2010 to 2100 for Reference and Category 1 Scenarios

7.11.4 The relationship between short-term action and long-term targets

The relationship between near-term actions and long-term goals is complex and has received a great deal of attention in the research literature. Unlike short-lived species (e.g. CH_4, CO, NO_x, and SO_2) for which stable concentrations are associated with stable emissions, stable concentrations of CO_2 ultimately in the long term require emissions to decline to zero (Kheshgi et al., 2005). Two important implications of that biophysics follow directly.

First, to a first approximation it is cumulative emissions over the entire century that determines the CO_2 concentration at the end of the century, and therefore no individual year's emissions are critical (for cumulative CO_2 emissions consistent with different targets see chapter 6, and Meinshausen et al (2009)).

Second, minimization of global social cost implies an immediate, initiation of global emissions mitigation, relative to a reference, no-climate-policy scenario, with a marginal value of carbon which rises exponentially (Hotelling, 1931; Peck and YS Wan, 1996). The consequence of this latter feature is that emissions mitigation and the deployment of mitigation technologies grows over time. The challenge to technology deployment is typically large (see for example L Clarke et al., 2007).

When only a long-term state, e.g. a fixed level of radiative forcing in a specific year such as 2.6 Wm^{-2} in 2100, is prescribed, the interim path can theoretically take on any value before the target year. "Overshoot scenarios" are scenarios for which target values are exceeded during the period before the target date. They are possible because carbon is removed from the atmosphere by the oceans over an extended period of time, and can be further extended by the ability of society to create negative emissions through sequestration in terrestrial systems (section 7.5, Chapter 11), production of bioenergy in conjunction with CCS technology, and/or direct air capture (DAC). See for example, Edmonds, et al. (2013).

Even so, the bounded nature of the cumulative emissions associated with any long-term CO_2 limit creates a derived limit on near-term emissions. Beyond some point, the system cannot adjust sufficiently to achieve the goal. Early work linking near-term actions with long-term goals was undertaken by researchers such as Swart, et al. (1998), the "safe landing" concept, and Bruckner, et al., (1999), the "tolerable windows" concept. O'Neill, et al., (2010) assessed the relationship between emissions levels in 2050 and the probability of meeting different 2100 targets. They identified "emissions windows" through which global energy systems would need to pass in order to achieve various atmospheric composition goals.

Figure 7.21 shows the time path of decarbonization of primary energy supply for two Category 1 emissions mitigation scenarios. While major changes occur in the post-2050 period, transformation scenarios reported the largest change in the global energy system occurring in the period between 2030 and 2050. Cumulative emissions consistent with Category 1 stabilization levels were largely exhausted by 2030. When near-term policies had less-than-optimal emissions mitigation in the 2010 to 2030 period, emissions mitigation was accelerated in the 2030 to 2050 period in order to meet the long-term goal.

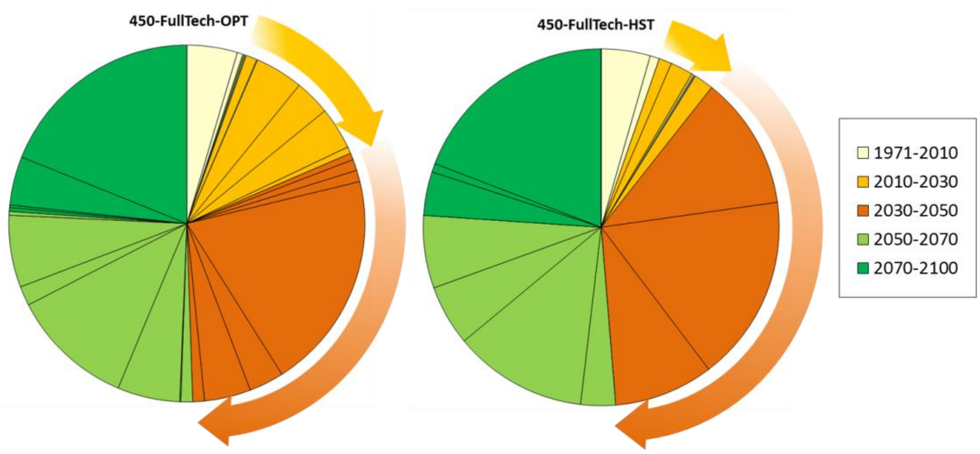


Figure 7.21 Share of Non-emitting Fuels in Primary Energy Supply over time for Category 1 optimal scenarios and scenarios with less-than-optimal emissions mitigation before 2030. (Source: AMPERE modelling intercomparison project: Eom et al, (2013); Riahi et al, (2013)

7.11.5 Energy investments in low stabilization scenarios

The longevity of energy sector physical capital stock can translate into high inertia in energy supply systems, which impedes rapid transformation. There is significant cost to society to allocate resources to the creation of one capital stock and then abandoning it before the end of its useful life (see section 7.10.5). The energy investment decisions of the next several years are thus of central importance, since they will have long-lasting implications and will critically shape the direction of the energy transition path for years to come.

The transition to a low-emissions global energy system requires shifts in the composition of the investment portfolio as well as an increase in its overall magnitude. Studies focusing on the estimation of future energy investment (IEA, 2012b; K. Riahi et al., 2012; World Bank, 2012; LD McCollum et al., 2013) indicate the need to accelerate the pace of energy sector investments over the next decades in order to achieve the stabilization of GHG concentrations at low levels (category 1). There is considerable uncertainty about the required investments in specific technology options needed to achieve low stabilization goals. The present investment portfolio is neither sufficient nor compatible in structure with the required investment portfolio in order to achieve stabilization of GHGs at low levels (category 1) (K. Riahi et al., 2012). The transition to a low-emissions global energy system will require shifts in the composition of the investment portfolio as well as an increase in its overall magnitude.

Table 7.5 compares the present investment intensity with future investment needs from two major recent studies: the Global Energy Assessment (K. Riahi et al., 2012) and the LIMITS modelling comparison project (E. Kriegler et al., 2013; LD McCollum et al., 2013). The table compares investment requirements of important mitigation options to achieve stabilization at low levels (category 1) with investments in baseline scenarios without new climate policies. Despite uncertainties, both studies indicate the need of substantial increases of energy investments into efficiency, nuclear, renewables, CCS as well as electricity transmission and distribution in order to reach the low targets. For many options the average investments between 2010 and 2050 tend to increase by more than a factor of two compared to today. Mobilizing the necessary financial resources will thus be critical in order to transform the energy system. As illustrated by Table 7.5, the higher investment intensity across all options leads to significant contributions of the different mitigation options, both in terms of absolute deployment and overall share in the energy system.

Table 7.5 Energy investments across 41 low stabilization scenarios (category 1), and illustrative policy mechanisms to mobilize the necessary resources. Source: Riahi et al, (2012) and McCollum et al, (2013).

	Average annual investments (billions of US$/yr)		Technology deployment & demand		Related scenario Indicators	
	2010	2010–2050	2010	2050	2010	2050
End-use Efficiency	n.a.[a]	*Baseline scenario:* 35-150 *Category 1:* 140–650[b] (LIMITS) 290-800 (GEA)	**Final Energy Demand (EJ)** 343	*Baseline scenario:* 590-680 *Category 1:* 440–530 (LIMITS) 360-550 (GEA)	**Final Energy Intensity (MJ/$)** 9.5	*Baseline scenario:* 4.3-8.1 *Category 1:* 3.1–7.2 (LIMITS) 3.0-5.2 (GEA)
Nuclear	5-40[b]	*Baseline scenario:* 12-190 *Category 1:* 60–320 (LIMITS) 15-210 (GEA)	**Nuclear Deployment (PWh)** 3	*Baseline scenario:* 1-8 *Category 1:* 5–15 (LIMITS) 1-16 (GEA)	**Nuclear power as share in electricity (%)** 14%	*Baseline scenario:* 2-17% *Category 1:* 11–36% (LIMITS) 2-23% (GEA)
Renewables	190	*Baseline scenario:* 170–390 *Category 1:* 230– 940 (LIMITS) 260-1010 (GEA)	**Renewable Deployment (EJ)** 60	*Baseline scenario:* 90-160 *Category 1:* 150–350 (LIMITS) 171-340 (GEA)	**Renewable share of total primary energy (%)** 13%	*Baseline scenario:* 10-21% *Category 1:* 28–54% (LIMITS) 31-61% (GEA)
Carbon Capture and Storage (CCS)	<1	*Baseline scenario:* 0-5 *Category 1:* 0–30 (LIMITS) 0-64(GEA)	**Total CO_2 captured and stored ($GtCO_2$)** ~0	*Baseline scenario:* 1-3 *Category 1:* 6–18 (LIMITS) 0-19 (GEA)	**CCS share of total energy sector emissions (%)** 0%	*Baseline scenario:* 2-6% *Category 1:* 22–69% (LIMITS) 0-55% (GEA)
Electricity Infrastructure[c]	260	*Baseline scenario:* 330–420 *Category 1:* 280–590 (LIMITS) 310-500 (GEA)	**Total Electricity Generation (PWh)** 20	*Baseline scenario:* 46-61 *Category 1:* 37–63 (LIMITS) 40-70 (GEA)	**Share of electricity in final energy (%)** 18%	*Baseline scenario:* 27-33% *Category 1:* 30–46% (LIMITS) 31-46% (GEA)

a. Global investments into end-use efficiency improvements for the year 2010 are not available. However, as a point of comparison, the best-guess estimate from Chapter 24 of the Global Energy Assessment (Grubler et al. 2012) indicates that investments into energy components of demand-side devices are about US$300 billion per year. This includes, for example, investments into the engines in cars, boilers in building heating systems, and compressors, fans, and heating elements in large household appliances. The uncertainty range is between US$100 billion/yr and US$700 billion/yr for investments in components. Accounting for the full investment costs of end-use devices would increase demand-side investments by about an order of magnitude.

b. Lower-bound estimate includes only traditional deployment investments in about 2 GW capacity additions in 2010. Upper-bound estimate includes, in addition, investments for plants under construction, fuel reprocessing, and estimated costs for capacity lifetime extensions.

c. Overall electricity grid investments, including investments for operations and capacity reserves, back-up capacity, and power storage.

7.12 Sectoral policies

Concerns about climate change, local air pollution, energy security and energy poverty have triggered a renewed interest in energy sector policies designed to address these challenges (DECC, 2009). As discussed in Chapter 15, energy policies can be roughly divided into three categories: policies which use financial measures to price in the externality costs of GHG emissions, technology policies including direct investments and regulatory or financial measures for their subsequent deployment, and a range of wider enabling policies (US DOE, 1989). Recent major studies on projecting emissions (BP, 2011b; IEA, 2011a; US DOE, 2011a) include aggregated GHG emission reduction policies up to legislated measure as of mid-2011. Studies (e.g., C Carraro and Massetti, 2011; IEA, 2011a; M. den Elzen et al., 2011) that have analysed the impact of current policies plus the emission reduction pledges under the Cancun Agreement, finding that global GHG emissions will continue to grow, starkly contrasting with the substantive deviation from current trends by 2020 as required for most 450ppmv CO2eq pathways. As a consequence, beyond those already existing, additional policies must be enacted and the coverage and stringency of the existing ones must be increasded if the Cancun agreement is to be fulfilled.

7.12.1 GHG pricing policies

GHG pricing policies, such as tradable emission permits (EP) and emission taxes (e.g. carbon taxes) have been frequently proposed to address the market externalities associated with GHG emissions (see chapters 3 and 13 - 15). In the power sector, GHG pricing is primarily pursued through emission trading mechanisms and, to a lower extent by carbon taxes. Following the European Emission Trading System (EU ETS), which started in 2005 (YJ Zhang and YM Wei, 2010), such schemes are now also in place in Alberta (Canada), New Zealand, in ten north-eastern US states (namely those forming the Regional Greenhouse Gas Initiative - RGGI) and in California (IEA, 2010d; Bushnell and Y Chen, 2012; OECD, 2012). Australia (Nelson et al., 2012), South Korea and China (M Lee and N Zhang, 2012) have taken steps to implement emission trading mechanisms.

Emissions trading schemes have effects on investment and operational choices in the power sector along mainly three channels:

(1) Emission trading schemes translate political commitments to climate policy into tangible emission trajectories that can serve as a basis for corporate strategy choices (Neuhoff, 2011; LaBelle, 2012). In this way, opportunities arising from using low-carbon technologies (Coria, 2009; Rogge et al., 2011) and risks associated with fossil fuel power plants (Blyth et al., 2007; Abadie and Chamorro, 2009) can be identified. In principle, GHG pricing policies should reduce the profitability of *investments* in carbon intensive generation technologies. As the experience of EU ETS illustrates, this effect can be muted if new power station get an allocation of free allowances in the past. EU ETS rules of that type encouraged continued investment in coal power stations (Grubb et al., 2006; Pahle et al., 2011). This has been corrected and from 2013 onwards, all allowances are auctioned to the power sector in most European countries.

(2) As the EU ETS phase I has shown, the GHG prices observed in the markets were effective in changing *operating choices* in a way that allowed the fulfilment of greenhouse gas reduction goals even in periods of economic growth (Ellerman et al., 2010).

(3) GHG pricing policies increase the marginal cost of electricity from fossil fuelled power plants, which (with the exception of some so-called super-peak hours (see PL Joskow, 2008) determines the market clearing price in deregulated markets (Sijm et al., 2006; Zachmann, 2013). For systems with non-negligible price elasticity, the price increase results in lower electricity demand s all other things being equal (IEA, 2003b).

The short-term impact of the power price increase for industrial and private consumers has been widely discussed (Parry, 2004; Hourcade et al., 2007). In order to address the associated distributional impacts various compensation schemes have been proposed (Burtraw et al., 2012; EU Commission, 2012). The impact of an emission trading scheme on the profitability of power generation is ambivalent. If allowances are allocated for free and not linked to output, then all generators will profit (Keats and Neuhoff, 2005; IEA, 2010d, p. 8). With full auctioning, the impact on profitability can vary between different power stations. Generators with a portfolio of generation assets often benefit due to increased infra-marginal rents (Keppler and Cruciani, 2010). Some modelling work points to the risk of distortions between the use of electricity and other fuel inputs, if electricity prices increase with an emission trading scheme while other fuel inputs are not covered (J. Edmonds et al., 2006).

The emissions credits generated by the Clean Development Mechanism (CDM) have been a significant incentive for the expansion of renewable energy (Michaelowa et al., 2006; Purohit and Michaelowa, 2007; Restuti and Michaelowa, 2007; Bodas Freitas et al., 2012; Hultman et al., 2012) Lokey (2009) discusses the barriers faced by renewable energy CDM projects. Energy efficiency improvement projects have faced much more difficulties under the CDM, such as slow approval of baseline and monitoring methodologies (Michaelowa et al., 2009) and problems in proving additionality of projects. Figure 7.22 illustrates the share of energy systems in key CDM indicators. While over 75% of all projects relate to energy systems – mainly renewables, the share of projected credits reaches about 60% and the share of issued credits only 28%. While the latter indicators are likely to increase, they show that the energy systems-related projects are slower in their implementation than projects in the industrial sector (see Chapter 9).

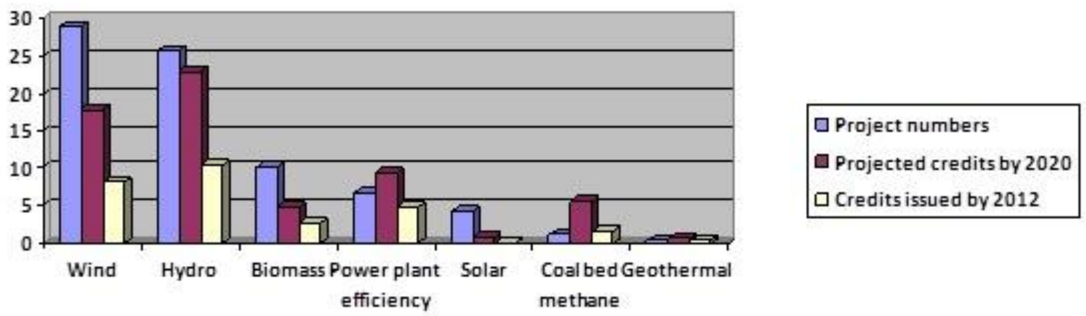


Figure 7.22 Share of energy-related project types (%) in key CDM indicators. Data source: UNEP Riso Centre 2012 (Current data November 2012, to be updated as per latest data available at time of final draft). Power plant efficiency includes captive power in industrial sites.

7.12.2 Technology policies to complement carbon pricing

Many low carbon supply side mitigation options (e.g. most RE) are not yet competitive on the basis of market electricity prices – even if these are increased by GHG pricing schemes (IPCC, 2005, 2011a). Additional support schemes therefore are needed if the usage of these technologies is to be increased. In order to achieve this goal, technology policies (e.g., (1) low carbon technology targets, (2) R&D policies, and (3) deployment policies) are enacted in a growing number of countries (REN21, 2012). Taken together these policies have been successful in driving an escalated growth of RE energies (IPCC, 2011a).

(1) The formulation of low carbon technologies goals can help technology companies to anticipate the scale of the market and to identify opportunities for their products and services (Lester and Neuhoff, 2009), thus, motivating investments in innovation and production facilities while reducing costs for low carbon technologies. Currently, for instance, about 120 countries have renewable targets in place. More than half of them are developing countries (REN21, 2012, p. 14).

(2) While public energy-related R&D expenditures in the IEA countries peaked in 2009 as a result of economic stimulus packages, they have declined substantially afterwards. Although the R&D spending is now again rising, the energy-related expenditures still account for less than 5% of the total government R&D spending – compared to 11% that was observed in 1980 (IEA, 2012b, p. 11). Although private RD&D expenditures are seldom disclosed, they are estimated to represent a large share of the overall spending for RD&D activities (IEA, 2012j, p. 15). Private RD&D investments are not only stimulated by RD&D policies. Additional policies (e.g., market entry programs) addressing other parts of the innovation chain, as well as broad GHG pricing policies might assist in triggering private investments in RD&D (IPCC, 2011a, p. 851; Rogge et al., 2011).

(3) Price-based mechanisms (such as feed-in-tariffs, FITs) and quantity-based systems (such as quotas or renewable portfolio standards, RPS) are the most common deployment policies in the power sector. In 2012, more than 65 countries and 27 states used FIT policies; quotas or RPS were in place in 18 countries and in more than 53 other jurisdictions (REN21, 2012). With respect to their success and efficiency, the SRREN (IPCC, 2011a, p. 869) notes the following: “A number of studies have concluded that FITs have consistently delivered new supply, from a variety of technologies, more effectively and at lower cost than alternative mechanisms, including quotas, although they

have not succeeded in every country that has enacted them (Ragwitz et al., 2005; Stern, 2007; de Jager and Rathmann, 2008)".

While nuclear has received significant support in many countries, RDD&D support for CSS is only available in some countries (Global CCS Institute, 2012).

7.12.3 Enabling policies

The success of energy policies and measures depends at least in part on the development of an efficient system to facilitate their implementation. Property rights, contract enforcement, and emissions accounting are essential to successful policy implementation. For example, a well-defined emissions mitigation crediting environment and long-term responsibility for storage is essential to the deployment of CCS. The energy policy framework requires a solid legal foundation, as well as regulatory stability so that participants must know how the system works, its administrative requirements, the time delays, and the implementation and changes in the process. Governmental or nongovernmental regulatory agencies can successfully play this role. For example, a rural electrification agency – with a good appreciation of the country specific characteristics and cost implications (Reiche et al., 2006) – can function as a "de facto" regulator of tariffs and technical quality in return for giving grants or subsidized loans.

In order to facilitate a least cost integration of fluctuating renewable energies, further issues are to be addressed. These comprise (1) the enhancement of the currently rather low price elasticity of demand by technical means (IEA, 2003b), (2) the inclusion of local price elements to reveal network constraints (Neuhoff et al., 2011), and (3) the requirement of back-up power plants to capture their investment costs (Bode and Groscurth, 2009; Hood, 2011).

Demand response measures, nodal pricing schemes, ancillary services markets, and capacity markets (PL Joskow, 2008) have been proposed to address these challenges. Increasing demand response is generally seen as clearly beneficial (IEA, 2003b), although the role of regulation in achieving efficient, reliable and environmentally responsible electricity "smart grids" is still under debate (Pérez-Arriaga, 2009).

At a beginning of the transition to a low GHG energy supply system, a wide array and an accelerating number of climate change mitigation policy initiatives have been initiated at the regional (e.g., EU), national and sub-national levels (IEA, 2012k; MURE, 2012; REN21, 2012). Recent studies have emphasized the problem of policy coordination and potentially adverse consequences such as lock-in, carbon leakage and rebound effects. A better coherence among the range of policies and their instruments therefore is sought (IPCC, 2011a, Chapter 11, and references therein).

It is an open question as to whether existing policies will deliver their desired quantitative reductions in GHG emissions. Crucially, the impacts of existing initiatives or legislation represent a future cost, and existing policies may be revised or scrapped as iterative policy making occurs. The relatively few studies that undertook ex-post verification of energy model baselines (e.g., Pilavachi et al., 2008; N Strachan, 2011; US DOE, 2011b), showed the evolution and inclusion of current policies was a key determinant of projected energy supply, demand, and prices.

The effectiveness of current policies may be further limited by "2nd best implementation" in terms of delayed timing, regional cooperation, technology innovation failures, and behavioural barriers (Edenhofer et al., 2010).

Finally, energy policies are not isolated instruments. The phase-out of fossil fuel consumption subsidies (i.e., via the G20 commitment made in 2009) would reduce global energy-related carbon emissions by about 6% (Bruvoll et al., 2011; IEA, 2011e). Policies on energy security and local air pollution are also important for climate mitigation. More broadly, the emerging evolutionary economic growth literature emphasizes the need to overcome vested interests to enable economic and structural change in new technologies and industries (Moe, 2010).

The biggest barrier, however, is the lack of a coherent global climate policy that is committed to the deep emission reductions needed to obey the Cancun Agreement. Central elements of such a policy would be a global carbon pricing scheme supplemented by technology support and regulation where necessary in order to overcome market failures.

7.13 Gaps in knowledge and data

Gaps in knowledge and data are addressed to identify the limitations of research. Chapter 7 is confronted by various gaps in knowledge primary those related to methodologies and availability of data. On one hand, the diversity of energy balances construction and GHG emission accounting methodologies leads to some disagreement among statistical sources. Furthermore, a significant knowledge gap arises through the several years of delay of the availability of comprehensive data not only just on CO_2, but as well on global GHG emissions [7.2,7.3]. Although, the terms reserves, resources and occurrences are routinely used in the resource industry, there is no consensus on their exact meanings. Many countries and institutions have developed their own expressions and definitions, and different authors have different meanings for the same terms. Moreover, resource deposits are often located several kilometers below the surface. The estimates are based on inherently limited information and geological analogies. The data derived from exploration activities are subject to interpretation and judgment. In addition, the realizable technical potential for RE and the availability of CCS storage sites is uncertain as well [7.4]. Operational, proliferation and supply chain risks of nuclear power plants and the safety of CCS storage sites are hard to quantify [7.5]. There is limited research on the integration issues associated with high levels of low carbon technology shares [7.6]. Furthermore further knowledge gaps pertain to the regional and local impacts of climate change on the technical potential for renewable energy and appropriate adaptation, design, and operational strategies to minimize the impact of climate change on energy infrastructure [7.7]. Moreover, the current literature provides a limited number of comprehensive studies on the economic, environmental, social, and cultural implications that are associated with low carbon emission paths [7.8, 7.9, 7.10]. In addition, integrated decision making support requires further development of integrated analysis tools and modeling frameworks, accounting for the range of possible co-benefits and trade-offs of different policies in energy sector that tackle access, security and/or environmental concerns, as well as institutional and human capacity for the use of such tools and frameworks [7.12]. Finally, research on the effectiveness and efficiency of climate policies and their interaction with other policies in the energy sector is limited.

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