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Chapter 7

Energy Systems

Chapter:	7	
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Chapter 7: Energy Systems

Contents

Executive Summary

The *energy systems* chapter addresses issues related to the mitigation of greenhouse gas emissions (GHG) from the *energy supply sector*. The energy supply sector, as defined in this report, comprises all energy extraction, conversion, storage, transmission, and distribution processes that deliver *final energy* to the end-use sectors (industry, transport, and building, agriculture and forestry). Demand side measures in the end-use sectors are discussed in Chapters 8-11.

The energy supply sector is the largest contributor to global greenhouse gas emissions (robust evidence, high agreement). In 2010, the energy supply sector was responsible for approximately 35% of total anthropogenic GHG emissions. Despite the UNFCCC and the Kyoto Protocol, GHG emissions grew more rapidly between 2001 and 2010 than in the previous decade. Growth in sector GHG emissions accelerated from 1.7% per year from 1991-2000 to 3.1% per year from 2001-2010. The main contributors to this trend were a higher energy demand associated with rapid economic growth and an increase of the share of coal in the global fuel mix. [7.2, 7.3]

In the absence of climate change mitigation policies, energy-related CO_2 emissions are expected to continue to increase, with fossil fuel and industrial emissions reaching 55-70 $GtCO_2$ by 2050 (medium evidence, medium agreement). This corresponds to an increase of 80%-130% compared to emissions of about 30 $GtCO_2$ in 2010 (based on the 25th-75th percentile of scenarios). By the end of the 21st century, emissions could grow further, with the 75th percentile of scenarios reaching 90 $GtCO_2$ in 2100. [7.11.1]

Multiple options exist to reduce energy supply sector GHG emissions (robust evidence, high agreement). These include: energy efficiency improvements and fugitive emission reductions in fuel extraction as well as in energy conversion, transmission, and distribution systems; fossil fuel switching; and low GHG energy supply technologies such as renewable energy (RE), nuclear power, and carbon dioxide capture and storage (CCS). [7.5, 7.8.1, 7.11]

The stabilization of greenhouse gas concentrations at low levels requires a fundamental transformation of the energy supply system, and the long-term substitution of unabated[1] fossil fuel conversion technologies by low-GHG alternatives (robust evidence, high agreement). Concentrations of CO_2 in the atmosphere can only be stabilized if global (net) CO_2 emissions peak and decline toward zero in the long term. Improving the energy efficiencies of fossil power plants and/or the shift from coal to gas will not by itself be sufficient to achieve this. Low GHG energy supply technologies are found to be necessary if this goal is to be achieved. [7.5.1, 7.8.1, 7.11]

Integrated assessment modelling studies indicate that decarbonizing electricity supply will play an important role in achieving low CO_{2eq} concentration stabilization levels (medium evidence, high agreement). In the majority of low stabilization scenarios (430-530 ppm CO_{2eq}), the share of low-carbon energy in electricity supply increases from the current share of approximately 30% to more than 80 % by 2050. In the long run (2100), fossil power generation without CCS is phased out almost entirely in these scenarios. [7.11]

Since AR4, many RE technologies have substantially advanced in terms of performance and cost and a growing number of RE technologies have achieved a level of technical and economic maturity to enable deployment at significant scale (robust evidence, high agreement). Some technologies are already economically competitive in various settings. While the levelized cost of photovoltaic systems fell most substantially between 2009 and 2012, a less extreme trend has been observed for many other RE technologies. RE accounted for just over half of the new electricity-generating capacity added globally in 2012, led by growth in wind, hydro and solar power.

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[1] These are those not using carbon capture and storage technologies.

Decentralized RE to meet rural energy needs has also increased, including various modern and advanced traditional biomass options as well as small hydropower, PV, and wind.

Nevertheless many RE technologies still need direct support (e.g., feed-in tariffs, RE quota obligations, and tendering/bidding) and/or indirect support (e.g., sufficiently high carbon prices and the internalization of other externalities), if their market shares are to be increased. Additional enabling policies are needed to address issues associated with the integration of RE into future energy systems (medium evidence, medium agreement). [7.5.3, 7.6.1, 7.8.2, 7.12, 11.13]

There are often co-benefits from the use of RE, such as a reduction of air and water pollution, local employment opportunities, few severe accidents compared to some other forms of energy supply, as well as improved energy access and security (medium evidence, medium agreement). At the same time, however, some RE technologies can have technology and location-specific adverse side-effects, though those can be reduced to a degree through appropriate technology selection, operational adjustments, and siting of facilities. [7.9]

Infrastructure and integration challenges vary by RE technology and the characteristics of the existing background energy system (medium evidence, medium agreement). Operating experience and studies of medium to high penetrations of RE indicate that these issues can be managed with various technical and institutional tools. As RE penetrations increase, such issues are more challenging, must be carefully considered in energy supply planning and operations to ensure reliable energy supply, and may result in higher costs. [7.6, 7.8.2]

Nuclear energy is a low GHG emission technology with specific emissions below approximately 100 gCO_{2eq} per kWh on a life-cycle basis and with currently more than 400 operational nuclear reactors worldwide (robust evidence, high agreement). In recent years, the share of nuclear energy in world power generation has declined. Nuclear electricity represented 11% of the world's electricity generation in 2012, down from a high of 17% in 1993. Pricing the externalities of GHG emissions (carbon pricing) could improve the competitiveness of nuclear power plants. [7.2, 7.5.4, 7.8.1, 7.12]

Barriers to an increasing use of nuclear energy include concerns about operational safety and (nuclear weapon) proliferation risks, unresolved waste management issues as well as financial and regulatory risks (robust evidence, high agreement). New fuel cycles and reactor technologies addressing some of these issues are under development and progress has been made concerning safety and waste disposal (medium evidence, medium agreement). [7.5.4, 7.8.2, 7.9, 7.11]

Carbon dioxide capture and storage (CCS) technologies could reduce the specific CO_{2eq} life-cycle emissions of fossil power plants (medium evidence, medium agreement). Although CCS has not yet been applied at scale to a large, commercial fossil-fired generation facility, all of the components of integrated CCS systems exist and are in use in various parts of the fossil energy chain. A variety of pilot and demonstrations projects have led to critical advances in the knowledge of CCS systems and related engineering, technical, economic and policy issues. CCS power plants will only deploy in the market place if they are either required for fossil fuel facilities by regulation or the cost differential between them and their unabated counterpart is overcome (e.g. via a carbon tax on emissions or subsidies). Beyond economic incentives, well-defined regulations concerning short- and long-term responsibilities for storage are essential for a large-scale future deployment of CCS. [7.5.5, 7.8.1]

Barriers to large-scale deployment of CCS technologies include concerns about the operational safety and long-term integrity of CO_2 storage as well as transport risks (limited evidence, medium agreement). There is, however, a growing body of literature on how to ensure the integrity of CO_2 wells, on the potential consequences of a pressure build-up within a geologic formation caused by CO_2 storage (such as induced seismicity), and on the potential human health and environmental impacts from CO_2 that migrates out of the primary injection zone. [7.5.5, 7.9]

Bioenergy CCS (BECCS) has attracted particular attention since AR4 because it offers the prospect of energy supply with negative emissions (limited evidence, medium agreement). Technological challenges and potential risks of BECCS include those associated with the upstream provision of the biomass that is used in the CCS facility as well as those originating from the capture, transport and long-term underground storage of CO_2 that would otherwise be emitted. BECCS faces large challenges in financing and currently no such plants have been built and tested at scale. [7.5.5, 7.8.2, 7.9, 7.12, 11.13]

Where natural gas is available and the fugitive emissions associated with its extraction and supply are low, near-term GHG emissions from energy supply can be reduced by replacing coal-fired with highly efficient natural gas combined cycle (NGCC) power plants or combined heat and power (CHP) plants (robust evidence, high agreement). Life-cycle assessments indicate a reduction of specific GHG emissions of approximately 50% for a shift from a current world-average coal power plant to a modern NGCC plant depending on natural gas upstream emissions. Substitution of natural gas for renewable energy forms increases emissions. Mitigation scenarios with low GHG concentration targets (430-530 ppm CO_{2eq}) require a fundamental transformation of the energy system in the long term. In most low stabilization scenarios, the contribution of natural gas power generation without CCS is below current levels in 2050, and further declines in the second half of the century (medium evidence, medium agreement). [7.5.1, 7.8, 7.9, 7.12]

Direct GHG emissions from the fossil fuel chain can be reduced through various measures (medium evidence, high agreement). These include the capture or oxidation of coal bed methane, the reduction of venting and flaring in oil and gas systems, as well as energy efficiency improvements and the use of low-GHG energy sources in the fuel chain. [7.5.1]

GHG emission trading and GHG taxes have been enacted to address the market externalities associated with GHG emissions (high evidence, high agreement). In the longer term, GHG pricing can support the adoption of low GHG energy technologies due to the resulting fuel and technology dependent mark up in marginal costs. Technology policies (e.g., feed-in tariffs, quotas and tendering/bidding) have proven successful in increasing the share of RE technologies (medium evidence, medium agreement). [7.12]

The success of energy policies depends on capacity building, the removal of financial barriers, the development of a solid legal framework, and sufficient regulatory stability (robust evidence, high agreement). Property rights, contract enforcement, and emissions accounting are essential for the successful implementation of climate policies in the energy supply sector. [7.10, 7.12]

The energy infrastructure in developing countries, especially in LDCs, is still undeveloped and not diversified (robust evidence, high agreement). There are often co-benefits and positive spill-overs associated with the implementation of mitigation energy technologies at centralized and distributed scales, which include local employment creation, income generation for poverty alleviation, as well as building much needed technical capability and knowledge transfer. There are also risks in that the distributive impacts of higher prices for low carbon energy might become a burden on low income households thereby undermining energy access programmes. [7.9, 7.10]

Although significant progress has been made since AR4 in the development of mitigation options in the energy supply sector, important knowledge gaps still exist that can be reduced with further R&D. These especially comprise the technological challenges, risks and co-benefits associated with the up-scaling and integration of low carbon technologies into future energy systems, and the resulting costs. In addition, research on the economic efficiency of climate-related energy policies and especially concerning their interaction with other policies applied in the energy sector is limited. [7.13]

7.1 Introduction

The energy supply sector is the largest contributor to global greenhouse gas (GHG) emissions. In 2010, approximately 35% of total anthropogenic GHG emissions were attributed to this sector. Despite the UNFCCC and the Kyoto Protocol, annual GHG emissions growth from the global energy supply sector accelerated from 1.7% per year in 1991-2000 to 3.1% in 2001-2010 (Section 7.3). 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 supply sector*, as defined in this chapter (Figure 7.1), comprises all energy extraction, conversion, storage, transmission, and distribution processes with the exception of those that use final energy to provide energy services in the end-use sectors (industry, transport, and building as well as agriculture and forestry). Concerning *energy statistics data* as reported in 7.2 and 7.3, power, heat or fuels which are generated on site for own use exclusively are not accounted for in the assessment of the energy supply sector. Note that many scenarios in the literature do not provide a sectoral split of energy-related emissions. Hence, the discussion of transformation pathways in section 7.11 focuses on aggregated *energy-related emissions* comprising the supply and the end-use sectors.

The allocation of cross-cutting issues among other chapters allows for a better understanding of the Chapter 7 boundaries (see Figure 7.1). The importance of energy for social and economic development is reviewed in Chapters 4 and 5 and to a lesser degree in section 7.9 of this chapter. Chapter 6 presents long-term transformation pathways and futures for energy systems.

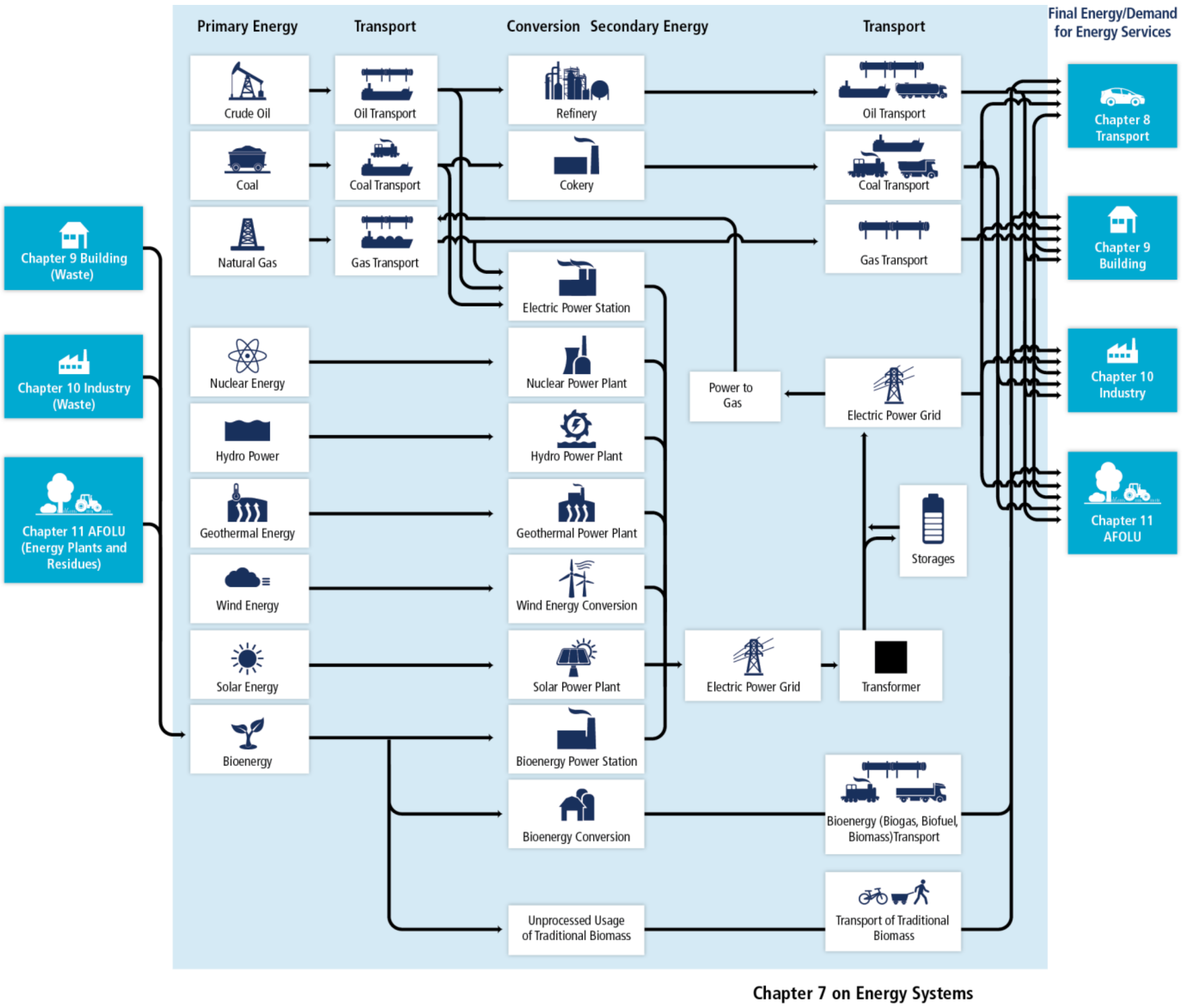

Figure 7.1. Illustrative energy supply paths shown in order to illustrate the boundaries of the energy supply sector as defined in this report. The self-generation of heat and power in the end-use sectors (i.e., transport, buildings, industry and AFOLU) is discussed in Chapter 8-11. AFOLU=Agriculture, Forestry and Other Land Use. Source: own illustration.

Transport fuel supply, use in vehicles, modal choice, and the local infrastructure are discussed in 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. Together with aspects related to bioenergy usage, provision of biomass is discussed in Chapter 11 that covers land uses including agriculture and forestry. Only energy supply sector related policies are covered in Chapter 7 while the broader and more detailed climate policy picture is presented in Chapters 13-15.

The derivation of least-cost mitigation strategies has to take into account the interdependencies between energy demand and supply. Due to the selected division of labor described above, Chapter 7 does not discuss demand side measures from a technological point of view. Trade-offs between demand and supply side options, however, are considered by the integrated assessment models (IAM) that delivered the transformation pathways collected in the AR5 Scenario Database (see Annex II.10 and, concerning energy supply aspects, section 7.11).

Chapter 7 assesses the literature evolution of energy systems from earlier IPCC reports, comprising the IPCC Special Report on Carbon Dioxide Capture and Storage (2005), the IPCC Fourth Assessment Report (AR4) (2007), and the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) (2011a). Section 7.2 describes the current status of global and regional energy markets. Energy related GHG emissions trends together with associated drivers are presented in section 7.3. The next section provides data on energy resources. 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 emission reduction potentials and related costs. Section 7.9 covers issues of co-benefits and adverse side effects of mitigation options. Mitigation barriers are dealt with in section 7.10. The implications of various transformation pathways for the energy sector are covered in section 7.11. Section 7.12 presents energy supply sector specific policies. Section 7.13 addresses knowledge gaps and 7.14 summarizes frequently asked questions (FAQ).

7.2 Energy production, conversion, transmission and distribution

The energy supply sector converts over 75% of total primary energy supply (TPES) 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.

The energy supply sector is itself the largest energy user. 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 TPES 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. Bashmakov (2009) argues that in estimating indirect energy efficiency effects, transformation should be done not only for electricity, for which it is regularly performed, but also for district heating, as well as for any activity in the energy supply sector and even for fuels transportation. According to him global 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.

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 (%)*	*Share in FEC (%)*	*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%*		
Total Primary Energy Supply (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 total 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%*
Combined Heat and Power 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 in TPES by fuels (%)	*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)	**35.72**	**1.44**	**148.02**	**55.19**	**0.00**	**0.00**	**0.92**	**46.14**	**60.35**	**10.60**	**358.37**	***70.20%***	***100.0%***	
Share of energy carriers in TFC (%)	*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: See IEA (2012a) for data, methodology and definitions. IEA data were modified to convert to primary energy by applying the *direct equivalent method* (see Annex II.4). Negative numbers in energy sector reflect energy spent or lost, while positive ones indicate that specific forms of energy were generated. *Only for fossil fuel powered generation. Totals may not add up due to rounding.

In 2001-2010, TPES grew by 27% globally (2.4% per annum), while for the regions it was 79% in Asia, 47% in Middle East and Africa (MAF), 32% in Latin America (LAM), 13% in Economies in Transition (EIT), and it was nearly stable for OECD90 (IEA, 2012a)(For regional aggregation see Annex II.7). After 2010, global TPES grew slower (close to 2% per annum over 2011-2012) with Asia, MAF and LAM showing nearly half their 2001-2010 average annual growth rates and declining energy use in EIT and OECD90 (BP, 2013; Enerdata, 2013). Thus all additional energy demand after 2000 was generated outside of the OECD90 (Figure 7.2). The dynamics of the energy markets evolution in Asia differs considerably from the other markets. This region accounted for close to 70% of the global TPES increment in 2001-2010 (over 90% in 2011-2012), for all additional coal demand, about 70% of additional oil demand, over 70% of additional hydro, and 25% of additional wind generation (IEA, 2012a; BP, 2013; Enerdata, 2013). In 2001-2010 China alone more than doubled its TPES and contributed to over half of the global TPES increment making it now the leading energy-consuming nation.

Led by Asia, global coal consumption grew in 2001-2010 by over 4% per annum and a slightly slower rate in 2011-2012. Coal contributed 44% of the growth in energy use and this growth alone matched the total increase in global TPES for 1991-2000 (Figure 7.2). Power generation remains the main global coal renaissance driver (US DOE, 2012). China is the leading coal producer (47% of world 2012 production), followed by the USA, Australia, Indonesia and India (BP, 2013). Competitive power markets flexible to gas and coal price spreads are creating stronger links between gas and coal markets driving recent coal use down in the US, but up in EU (IEA, 2012b).

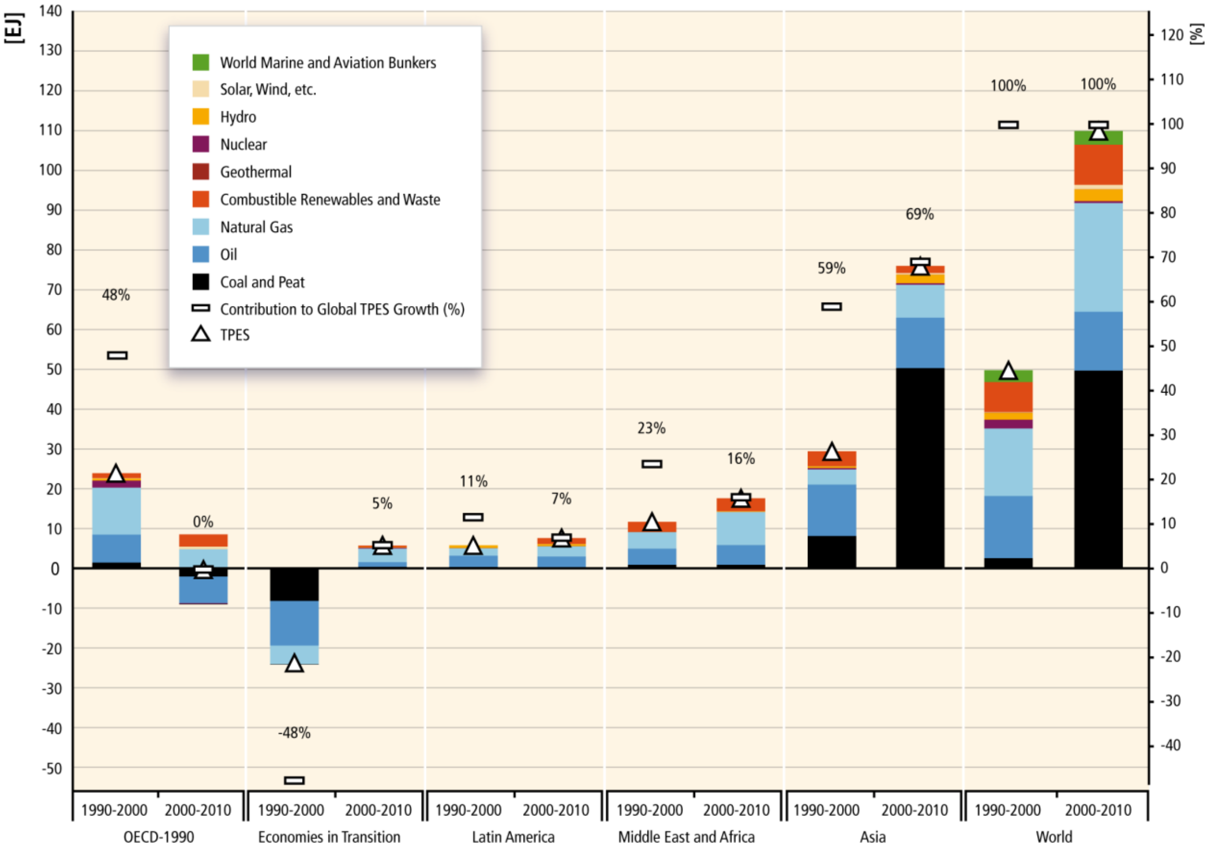

Figure 7.2. Contribution of energy sources to global and regional primary energy use *increments*. Notes: Modern biomass contributes 40% of the total biomass share. Underlying data from IEA (2012a) for this figure have been converted using the direct equivalent method of accounting for primary energy (see Annex.II.4). Legend: OECD 1990 (OECD90), Asia (Asia), Economies in Transition (EIT), Middle East and Africa (MAF), and Latin America (LAM).

Although use of liquid fuels has grown in non-OECD countries (mostly in Asia and the MAF), falling demand in the OECD90 has seen oil's share of global energy supply continue to fall in 2001-2012. Meeting demand has required mobilization of both conventional and unconventional liquid supplies. 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 (Table 7.1). OPEC in 2012 provided 43% of the world's total oil supply keeping its share above its 1980 level; 33% came from the Middle East (BP, 2013). The most significant non-OPEC contributors to production growth since 2000 were Russia, Canada, US, Kazakhstan, Brazil, and China (GEA, 2012; IEA, 2012b; US DOE, 2012; BP, 2013). Growing reliance on oil imports raises concerns of Asia and other non-OECD regions about oil prices and supply security (IEA, 2012b).

In the global gas balance, the share of unconventional gas production (shale gas, tight gas, coal-bed methane and biogas) grew to 16% in 2011 (IEA, 2012c). The shale gas revolution put the U.S. (where the share of unconventional gas more than doubled since 2000 and reached 67% in 2011) on top of the list of major contributors to additional (since 2000) gas supply, followed by Qatar, Iran, China, Norway and Russia (BP, 2013; US DOE, 2013a). Although the 2001-2010 natural gas consumption increments are more widely distributed among the regions than for oil and coal, gas increments in Asia and the MAF dominate. 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 2012 (BP, 2013) has however created greater flexibility and opened the way to global trade in gas (MIT, 2011). Growth in U.S. natural gas production and associated domestic gas prices decline have resulted in the switching of LNG supplies to markets with higher prices in South America, Europe, and Asia (IEA, 2012b). Nevertheless natural gas supply by pipelines still delivers the largest gas volumes in North America and in Europe (US DOE, 2012; BP, 2013).

Renewables contributed 13.5% of global TPES in 2010 (Table 7.1). The share of renewables in global electricity generation approached 21% in 2012 (BP, 2013; Enerdata, 2013) making them the third largest contributor to global electricity production just behind coal and gas, with large chances to become the second well before 2020. Greatest growth during 2005-2012 occurred in wind and solar with generation from wind increasing 5-fold, and from solar photovoltaic which grew 25-fold. By 2012, wind power accounted for over 2% of world electricity production (gaining 0.3% share each year since 2008). Additional energy use from solar and wind energy was driven mostly by two regions: OECD90, and Asia, with a small contribution from the rest of the world (IEA, 2012d). In 2012 hydroelectricity supplied 16.3% of world electricity (BP, 2013).

New post-2000 trends were registered for nuclear's role in global energy systems: In recent years, the share of nuclear energy in world power generation has declined. Nuclear electricity represented 11% of the world's electricity generation in 2012, down from a high of 17% in 1993; its contribution to global TPES is declining since 2002 (IEA, 2012b; BP, 2013). Those trends were formed well before the incident at the Fukushima nuclear plant in March 2011 and following revision of policies towards nuclear power by several governments (IEA, 2012e). Growing nuclear contribution to TPES after 2000 was observed only in EIT and Asia (mostly in Russia and China).

Additional information on regional total and per-capita energy consumption and emissions, historic emissions trends and drivers, embedded (consumption based) emissions is reported in Chapter 5.

7.3 New developments in emission trends and drivers

In 2010 the energy supply sector accounts for 49% of all energy-related GHG emissions[2] (JRC/PBL, 2012) and 35% of anthropogenic GHG emissions, up 13% from 22% in 1970 making it the largest

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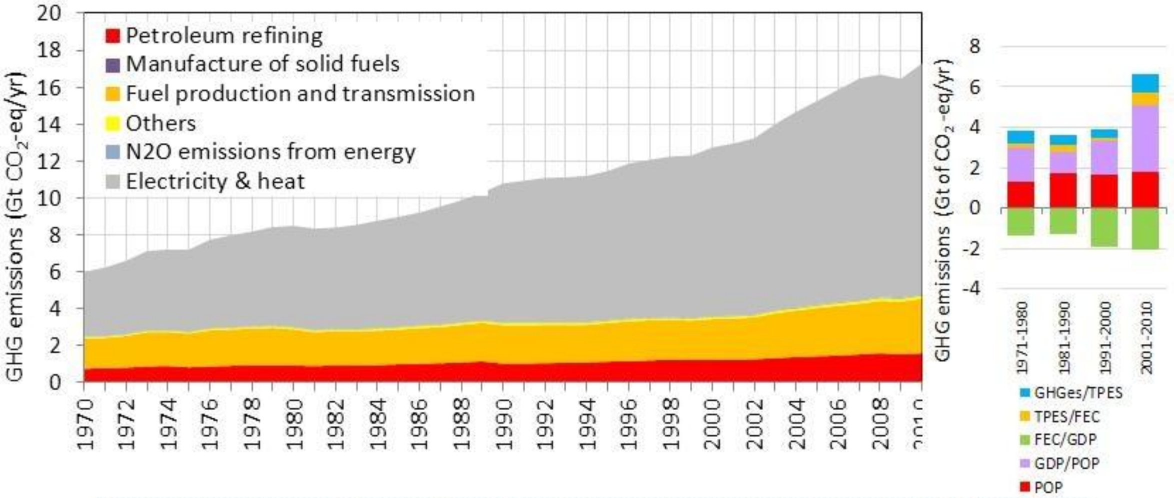
[2] The remaining energy-related emissions occur in the consumer sectors (see Figure 7.1). The IEA reports energy sector share at 46% (IEA, 2012f).

sectoral contributor to global emissions. According to the Historic Emission Database EDGAR/IEA dataset, 2001-2010 global energy supply sector GHG emissions increased by 35.7% and grew on average nearly 1% per year faster than global anthropogenic GHG emissions. Despite the UNFCCC and the Kyoto Protocol, GHG emissions grew more rapidly between 2001 and 2010 than in the previous decade. Growth in the energy supply sector GHG emissions accelerated from 1.7% per year from 1991-2000 to 3.1% per year from 2001-2010 (Figure 7.3). In 2012, the sector emitted 6% more than in 2010 (BP, 2013), or over 18 Gt CO_2-eq. In 2010, 43% of CO_2 emissions from fuel combustion were produced from coal, 36% from oil and 20% from gas (IEA, 2012f).

Emissions from electricity and heat generation contributed 75% of the last decade increment followed by 16% for fuel production and transmission and 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]



Annual average growth rates					Shares (%)		
	70s	80s	90s	00s	1970	1990	2010
Electricity & heat	4,51%	3,22%	1,96%	3,19%	58,9	69,9	72,6
Petroleum refining	2,09%	1,11%	1,88%	2,58%	12,3	9,4	9,1
Manufacture of solid fuels	4,26%	8,26%	1,16%	5,05%	0,0	0,0	0,0
Fuel production and transmission	1,78%	0,59%	0,60%	2,94%	27,5	19,3	17,1
Others	3,77%	2,00%	-0,48%	3,72%	1,1	1,0	0,9
N2O emissions from energy	4,74%	2,19%	2,17%	2,66%	0,3	0,3	0,3
Total energy sector	**3,53%**	**2,43%**	**1,68%**	**3,10%**	**100,0**	**100,0**	**100,0**

Figure 7.3. Energy supply sector GHG emissions by subsectors.Table shows average annual growth rates of emissions over decades and the shares (related to absolute emissions) of different emission sources. Right hand graph displays contribution of different drivers (POP – population, FEC- final energy consumption) to energy supply sector GHG (GHGs) decadal emissions increments. It is based on IEA (IEA, 2012a). The large graph and table are based on the Historic Emission Database EDGAR/IEA dataset (IEA, 2012g; JRC/PBL, 2012).

Decomposition analysis (Figure 7.3), shows that population growth contributed 39.7% of additional sector emissions in 2001-2010, with GDP per capita 72.4%. Over the same period, energy intensity decline (final energy consumption (FEC) per unit of GDP) reduced the emissions increment by 45.4%. Since electricity production grew by 1% per year faster than TPES, the ratio of TPES/FEC

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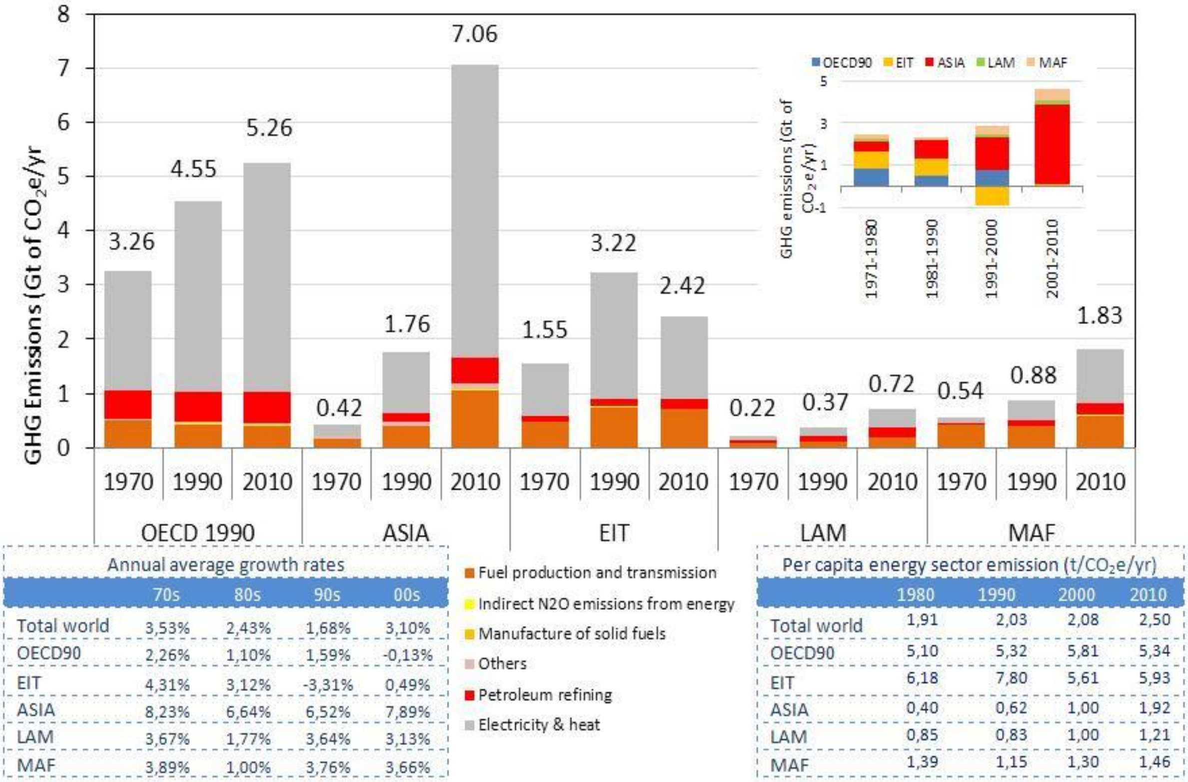
[3] As in the case with energy, there is some disagreement on the historical level of global energy related GHG emissions (See Andres et al., 2012). Moreover, emission data provided by IEA or EDGAR often do not match data from national communications to UNFCCC. For example, Bashmakov and Myshak (2012) 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.

increased contributing 13.1% of the additional emissions. Sector carbon intensity relative to TPES was responsible for 20.2% of additional energy supply sector GHG emissions.

In addition to the stronger TPES growth, the last decade was marked by a lack of progress in the decarbonisation of the global fuel mix. With 3.1% annual growth in energy supply sector emissions, the decade with the strongest ever carbon emission mitigation policies was the one with the strongest emissions growth in the last 30 years.

Carbon intensity decline was fastest in OECD90 followed closely by EIT in 1991-2000, and by LAM in 2001-2010 (IEA, 2012a; US DOE, 2012); most developing countries show little or no decarbonization. Energy decarbonization progress in OECD90 (-0.4% per annum in 2001-2010) was smaller than the three previous decades, but enough to compensate their small TPES increment keeping 2010 emissions below 2000 levels. In non-OECD90 countries, energy-related emissions increased on average from 1.7% per year in 1990-2000 to 5.0% in 2001-2010 due to TPES growth accompanied by a 0.6% per annum growth in energy carbon intensity, driven largely by coal demand in Asia (IEA, 2012b). As a result, in 2010 non-OECD90 countries' energy supply sector GHG emissions were 2.3 fold that for OECD90 countries.



Annual average growth rates

	70s	80s	90s	00s
Total world	3,53%	2,43%	1,68%	3,10%
OECD90	2,26%	1,10%	1,59%	-0,13%
EIT	4,31%	3,12%	-3,31%	0,49%
ASIA	8,23%	6,64%	6,52%	7,89%
LAM	3,67%	1,77%	3,64%	3,13%
MAF	3,89%	1,00%	3,76%	3,66%

Per capita energy sector emission (t/CO$_2$e/yr)

	1980	1990	2000	2010
Total world	1,91	2,03	2,08	2,50
OECD90	5,10	5,32	5,81	5,34
EIT	6,18	7,80	5,61	5,93
ASIA	0,40	0,62	1,00	1,92
LAM	0,85	0,83	1,00	1,21
MAF	1,39	1,15	1,30	1,46

Figure 7.4. Energy supply sector GHG emissions by subsectors and regions - OECD90, ASIA countries, transition economies (EIT), Africa and the Middle East (MAF), and Latin America (LAM). Right hand graph shows contribution of different regions to decadal emissions increments. Source: Historic Emission Database EDGAR/IEA (IEA, 2012g; JRC/PBL, 2012).

In 1990, OECD90 was the world's highest emitter of energy supply sector GHGs (42% of the global total), followed by the EIT region (30%). By 2010, Asia had become the major emitter with 41% share, and China's emissions surpassed those of the U.S., and India's surpassed Russia's (IEA, 2012f). Asia accounted for 79% of additional energy supply sector emissions in 1991-2000 and 83% in 2001-2010, followed well behind by the MAF and LAM regions (Figure 7.4). The rapid increase in energy supply 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 GHGs emissions in developing countries are below the global average, but the gap is shrinking especially for Asia (Figure 7.4). The per capita energy supply sector CO_2 emissions of Asia (excluding China) in 2010 was only 0.75 tCO_2, against the world average of 2.06, while the 2010 Chinese energy supply sector CO_2 emissions per capita of 2.86 exceeded the 2.83 of OECD-Europe (IEA, 2012f).

Another region with large income-driven energy supply sector GHG emissions in 2001-2010 was EIT, although neutralized by improvements in energy intensity there. This region was the only one that managed to decouple economic growth from energy supply sector emissions; its GDP in 2010 being 10% above the 1990 level while energy supply sector GHG emissions declined by 29% over the same period. Additional information on regional total and per-capita emissions, historic emissions trends and drivers, embedded (consumption based) emissions is reported in Chapter 5.

7.4 Resources and resource availability

7.4.1 Fossil fuels

Table 7.2 provides a summary of fossil fuel resource estimates in terms of energy and carbon contents. Fossil fuel resources are not fixed; they are a dynamically evolving quantity. The estimates shown span quite a range reflecting the general uncertainty associated with limited knowledge and boundaries. Changing economic conditions, technological progress and environmental policies may expand or contract the economically recoverable quantities altering the balance between future reserves and resources.

Coal reserve and resource estimates are subject to uncertainty and ambiguity, especially when reported in mass units (tonnes) and without a clear distinction of their specific energy contents, which can vary considerably. For both reserves and resources, the quantity of hard (black) coal significantly out numbers the quantity of lignite (brown coal) and despite resources being far greater than reserves, the possibility for resources to cross over to reserves is expected to be limited since coal reserves are likely to last around 100 years at current rates of production (Rogner et al., 2012).

Cumulative past production of *conventional* oil falls between the estimates of the remaining reserves suggesting that the peak in conventional oil production is imminent or has already been passed (Höök et al., 2009; Owen et al., 2010; Sorrell et al., 2012). Including resources extends "conventional" oil availability considerably. However, depending on such factors as demand, the depletion and recovery rates achievable from the oil fields (IEA, 2008a; Sorrell et al., 2012), even the higher range in reserves and resources will only postpone the peak by about two decades, after which global "conventional" oil production is expected to begin to decline leading to greater reliance on unconventional sources.

Unconventional oil resources are larger than those for conventional oils. Large quantities of these in the form of shale oil, heavy oil, bitumen, oil (tar) sands and extra-heavy oil are trapped in sedimentary rocks in several thousand basins around the world. Oil prices in excess of $80(2010) per barrel are probably needed to stimulate investment in unconventional oil development (Engemann and Owyang, 2010; Rogner et al., 2012; Maugeri, 2012).

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, shale gas, deep formation and tight gas are now estimated to be larger than conventional reserves and resources combined. In some parts of the world, supply of unconventional gas now represents a significant proportion of gas withdrawals, see 7.2.

For climate change, it is the carbon dioxide emitted to the atmosphere from the burning of fossil fuels that matters. When compared to the estimated CO_2 budgets of the emission scenarios presented in Chapter 6 (Table 6.2) as part of the transformation pathways analysis, the estimate of the total fossil fuel reserves and resources contains sufficient carbon if released to yield radiative forcing above that required to limit global mean temperature change to less than 2°C as established by the Cancun Agreement. Transformaion scenarios are further discussed in Section 7.11 and Chapter 6.

Table 7.2: Estimates of fossil reserves and resource, and their carbon content.
Source: (Rogner et al. 2012)[1]

	Reserves		Resources	
	[EJ]	[Gt C]	[EJ]	[Gt C]
Conventional oil	4 900 - 7 610	98 - 152	4 170 - 6 150	83 - 123
Unconventional oil	3 750 - 5 600	75 - 112	11 280 - 14 800	226 - 297
Conventional gas	5 000 - 7 100	76 - 108	7 200 - 8 900	110 - 136
Unconventional gas	20 100 - 67 100	307 - 1 026	40 200 - 121 900	614 - 1 863
Coal	17 300 - 21 000	446 - 542	291 000 - 435 000	7 510 - 11 230
Total	51 050 - 108 410	1 002 - 1 940	353 850 - 586 750	8 543 - 13 649

[1] Reserves are those quantities able to be recovered under existing economic and operating conditions (BP, 2011); resources are those where economic extraction is potentially feasible (UNECE, 2010a).

7.4.2 Renewable energy

For the purpose of AR5, renewable energy (RE) is defined as in (IPCC, 2011a) to include bioenergy, direct solar energy, geothermal energy, hydropower, ocean energy, and wind energy.[4] 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, but 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; Jacobson and Archer, 2012; Adams and Keith, 2013). Finally, it should be emphasized that technical potential estimates do not seek to address all practical or economic limits to deployment; many of those additional limits are noted at the end of this section, and are discussed elsewhere in Chapter 7.

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, (IPCC, 2011a) concludes that the aggregated global technical potential for RE as a whole is significantly higher than global energy demands. Figure 7.12 (shown in Section 7.11) summarizes the ranges of global technical potentials as estimated in the literature for the different RE sources, as reported in IPCC (2011a). The technical potential for solar is shown to be the largest by a large magnitude, but sizable potential exists for many forms of RE. 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.

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[4] Note that, in practice, the RE sources as defined here are sometimes extracted at a rate that exceeds the natural rate of replenishment (e.g., some forms of biomass and geothermal energy). Most, but not all, RE sources impose smaller GHG burdens than do fossil fuels when providing similar energy services (see 7.8.1).

Considering all RE sources *together*, the estimates reported by this literature suggest that global and regional technical potentials are unlikely to pose a physical constraint on the combined contribution of RE to the mitigation of climate change (also see GEA (2012)). Additionally, 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 some *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 such as hydrogen 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) as well as materials demands (cf. Annex Bioenergy in Chapter 11; de Vries et al., 2007; Kleijn and van der Voet, 2010; Graedel, 2011). In other cases, economic factors, environmental concerns, public acceptance, and/or the infrastructure required to manage system integration (e.g., investments needed to accommodate variable output or transmit renewable electricity to load centres) are likely to limit the deployment of individual RE technologies before absolute technical resource potential limits are reached (IPCC, 2011a).

7.4.3 Nuclear energy

The average uranium (U) 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 (Bunn et al., 2003). The theoretically available uranium in the Earth's crust is 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 (Bunn et al., 2003). Without substantial R&D efforts to develop vastly improved and less expensive extraction technologies, these occurrences do not represent practically extractable uranium. Current market and technology conditions limit extraction of conventional uranium resources to concentrations above 100 ppm U.

Altogether, there are 4200 EJ (or 7.1 MtU) of identified conventional uranium resources available at extraction costs of less than 260 $/kg U (current consumption amounts to about 53 760 t U per year). Additional conventional uranium resources (yet to be discovered) estimated at some 4400 EJ can be mobilized at costs larger than 260 $/kg U (NEA and IAEA, 2012). Present uranium resources are sufficient to fuel existing demand for more than 130 years, and if all conventional uranium occurrences are considered, for more than 250 years. Reprocessing of spent fuel and recycling of uranium and plutonium in used fuel doubles the reach of each category (IAEA, 2009). Fast breeder reactor technology can theoretically 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 competitive below uranium prices of 425 $$_{(2010)}$/kgU (Bunn et al., 2003). Thorium is a widely distributed slightly radioactive metal. Although the present knowledge of the world's thorium resource base is poor and incomplete, it is three to four times more abundant than uranium in the Earth's outer crust (NEA, 2006). Identified thorium resource availability is estimated at more than 2.5 Mt at production costs of less than 82 $$_{(2010)}$ /kg Th (NEA, 2008).

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

Climate change can only be mitigated and global temperature be stablilized when the total amount of CO_2 emissions is limited and emissions eventually approach zero (Allen et al., 2009; Meinshausen et al., 2009). Options to reduce GHG emissions in the energy supply sector reduce the life-cycle GHG-emissions intensity of a unit of final energy (electricity, heat, fuels) supplied to end users. Section 7.5 therefore addresses options to replace unabated fossil fuel usage with technologies without direct GHG emissions, such as renewable and nuclear energy sources, and options to mitigate GHG emissions from the extraction, transport, and conversion of fossil fuels through increased efficiency, fuel switching, and GHG capture. In assessing the performance of these options, life-cycle emissions have to be considered. Appropriate policies need to be in place to ensure that the adoption of such options leads to a reduction and ultimate phase-out of freely emitting (i.e., unabated) fossil technologies and not only to reduced additional energy consumption, as indicated in section 7.12.

Options discussed here put some emphasis on electricity production, but many of the same options could be used to produce heat or transport fuels or deliver heating and transportation services through electrification of those demands, while the dedicated provision of transport fuels is treated in chapter 8, of heat for buildings in chapter 9, and of heat for industrial processes in chapter 10. Options to reduce final energy demand are addressed in Chapters 8–12. Options covered in this section mostly address technology solutions; behavioural issues in the energy supply sector often concern the selection of and investment in technology, and these issues are addressed in sections 7.10, 7.11, and 7.12. Costs and emission-reduction potentials associated with the options are discussed in section 7.8, whereas co-benefits and risks are addressed in section 7.9.

7.5.1 Fossil fuel extraction, conversion and fuel switching

Several important trends shape the opportunity to mitigate emissions associated with the extraction, transport and conversion of fossil fuels: (1) new technologies that make accessible substantial reservoirs of shale gas and unconventional oil; (2) a renewed focus on fugitive methane emissions, especially those associated with gas production; (3) increased effort required to find and extract oil; and (4) improved technologies for energy efficiency and the capture or prevention of methane emissions in the fuel supply chain. Carbon capture technologies are discussed in 7.5.5.

A key development since AR4 is the rapid deployment of hydraulic-fracturing and horizontal-drilling technologies, which has increased and diversified the gas supply and allows for a more extensive switching of power and heat production from coal to gas (IEA, 2012b); this is an important reason for a reduction of GHG emissions in the United States. At the same time, the increasing utilization of gas has raised the issue of fugitive emissions of methane from both conventional and shale gas production. While some studies estimate that around 5% of the produced gas escapes in the supply chain, other analyses estimate emissions as low as 1% (Stephenson et al., 2011; Howarth et al., 2011; Cathles et al., 2012). Central emission estimates of recent analyses are 2% - 3% (+/-1%) of the gas produced, where the emissions from conventional and unconventional gas are comparable (Jaramillo et al., 2007; O'Sullivan and Paltsev, 2012; Weber and Clavin, 2012). Fugitive emissions depend to a significant degree on whether low emission practices, such as the separation and capture of hydrocarbons during well completion and the detection and repair of leaks throughout gas extraction and transport, are mandated and how they are implemented in the field (Barlas, 2011; Wang et al., 2011; O'Sullivan and Paltsev, 2012). Empirical research is required to reduce uncertainties and to better understand the variability of fugitive-gas emissions (Jackson et al., 2013) as well as to provide a more global perspective. Recent empirical research has not yet resolved these uncertainties (Levi, 2012; Petron et al., 2012). The main focus of the discussion has been drilling, well completion and gas product, but gas grids (Ryerson et al., 2013) and liquefaction (Jaramillo et al., 2007) are also important.

There has also been some attention to fugitive emissions of methane from coal mines (Su et al., 2011; Saghafi, 2012) in connection with opportunities to capture and utilize or treat coal-seam gas (Karacan et al., 2011). Emission rates vary widely based on geological factors such as the age of the coal and previous leakage from the coal seam (Moore, 2012).

Taking into account revised estimates for fugitive-methane emissions, recent lifecycle assessments indicate that specific GHG emissions are reduced by one half (on a per-kWh basis) when shifting from the current world-average coal-fired power plant to a modern natural gas combined-cycle (NGCC) power plant, evaluated using the 100-year GWP (Burnham et al., 2012), as indicated in Figure 7.6 (section 7.8). This reduction is the result of the lower carbon content of natural gas (15.3 gC/MJ compared to, e.g., 26.2 gC/MJ for sub-bituminous coal) and the higher efficiency of combined-cycle power plants (IEA, 2011a). A better appreciation of the importance of fugitive emissions in fuel chains since AR4 has resulted in a downward adjustment of the estimated benefit from fuels switching. More modest emissions reductions result when shifting from current average coal plants to the best available coal technology or less advanced gas power plants. Climate mitigation consistent with the Cancun Agreement requires a reduction of emissions rates below that of NGCC plants by the middle of this century (Figure 7.7, Section 7.8.2 and Figure 7.9, section 7.11), but natural gas may play a role as a transition fuel in combination with variable renewable sources (Levi, 2013).

Combined heat and power plants (CHP) are capable to recover a share of the waste heat that is otherwise released by those power plants that generate only electricity. The global average efficiency of fossil fueled power plants is 37%, whereas the global average efficiency of CHP units is 58% if power and the recovered heat are both accounted for (see Table 7.1 in 7.2). State of the art CHP plants are able to approach efficiencies over 85% (IEA, 2012b). The usefulness of decentral cogeneration units is discussed in (Pehnt, 2008). Further emissions reductions from fossil fuel systems are possible through CO_2 capture and storage (7.5.5).

Producing oil from unconventional sources and from mature conventional oil fields requires more energy than producing it from virgin conventional fields (Brandt and Farrell, 2007; Gagnon, Luc et al., 2009; Lechtenböhmer and Dienst, 2010). Literature indicates that the net energy return on investment has fallen steadily for conventional oil to less than 10 GJ/GJ (Guilford et al.; Brandt et al., 2013). For oil sands, the net energy return ratio of the product delivered to the customer is about 3 GJ/GJ invested (Brandt et al., 2013), with similar values expected for oil shale (Dale et al., 2013). As a result, emissions associated with synthetic crude production from oil sands are higher than those from most conventional oil resources (Charpentier et al., 2009; Brandt, 2011). These emissions are related to extra energy requirements, fugitive emissions from venting and flaring (Johnson and Coderre, 2011), and land use (Rooney et al., 2012). Emissions associated with extraction of oil sands and refining to gasoline are estimated to be 35–55 $gCO_{2\text{-eq}}$ per MJ(LHV) fuel, compared to emissions of 20 $gCO_{2\text{-eq}}$ /MJ for the production and refining of regular petroleum and 70 $gCO_{2\text{-eq}}$ /MJ associated with combusting this fuel (Burnham et al., 2012). Overall, fossil fuel extraction and distribution are currently estimated to contribute 5%–10% of total fossil-fuel-related GHG emissions (Alsalam and Ragnauth, 2011; IEA, 2011a; Burnham et al., 2012). Emissions associated with fuel production and transmission 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, the reduction of venting and flaring from oil and gas production (IPIECA and API, 2009; Johnson and Coderre, 2011), and leak detection and repair for natural gas systems (Goedbloed, 2011; Wilwerding, 2011).

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, and that currents and thus losses are lower at high voltages. These losses are due to a combination of cable or line losses and transformer losses and vary with the nature of the power system and in particular its geographical layout. Losses as a fraction of power generated vary considerably between countries with developed countries tending to have lower losses and a number of developing countries having losses of over 20% in 2010 according to IEA online data (IEA, 2010a). 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). 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 (Méndez Quezada et al., 2006; Thomson and Infield, 2007), 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 renewables into power systems would be expected to increase the bulk transfer of power over considerable distances and thus the losses (see 7.6.1). High voltage DC transmission (HVDC) has the potential to reduce transmission losses and is cost effective for very long above ground lines. However, sub-sea, HVDC has lower losses over 55 to 70 kms (Barberis Negra et al., 2006) and will most likely be used for the connection of large offshore wind farms due to the adverse reactive power 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 consuming process if it is not effectively performed (PetroMin Pipeliner, 2010). Pipelines are the most efficient means to transport fluids. Additives can ease the flow of oil and reduce the energy used (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.

Finally, it is worth noting that the decarbonisation of heat through heat pumps and transport through an increased use of electric vehicles (EVs), could require major additions to generation capacity and aligned with this, an 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 (see 8.3.4.2 for more detail).

7.5.3 Renewable energy technologies

Only a small fraction of the renewable energy (RE) technical potential has been tapped so far (see Section 7.4.2; IPCC 2011a), and most—but not all—forms of RE supply have low life-cycle GHG emissions in comparison to fossil fuels (see 7.8.1). 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 (Sathaye et al., 2011; Sims et al., 2011; REN21, 2013). 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.

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 may experience the largest incremental growth. The mix of RE technologies suited to a specific location, however, will depend on local conditions, with hydropower and geothermal playing a significant role in certain countries.

Because some forms of RE are primarily used to produce electricity (e.g., Armaroli and Balzani, 2011), 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; Jacobson and Delucchi, 2011; see also other chapters of AR5).

The performance and cost of many RE technologies have advanced substantially in recent decades and since IPCC's AR4 (e.g., IPCC, 2011a; Arent et al., 2011). For example, improvements in photovoltaic (PV) technologies and manufacturing processes, along with changed market conditions (i.e., manufacturing capacity exceeding demand) and reduced non-hardware costs, have substantially reduced PV costs and prices. Continued increases in the size and therefore energy capture of individual wind turbines have reduced the levelised cost of land-based wind energy and improved the prospects for future reductions in the cost of offshore wind energy. Concentrated solar thermal power (CSP) technologies, some together with thermal storage or as gas/CSP hybrids, have been installed in a number of countries. Research, development, and demonstration of enhanced geothermal systems has continued, enhancing the prospects for future commercial deployments. Performance improvements have also been made in cropping systems, logistics, and multiple conversion technologies for bioenergy (see 11.13). IPCC (2011a) provides further examples from a broader array of RE technologies.

As discussed in IPCC (2011a), a growing number of RE technologies have achieved a level of technical and economic maturity to enable deployment at significant scale (with some already being deployed at significant scale in many regions of the world), while others are less mature and not yet widely deployed. Most 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 many lignocellulose-based transport fuels are at a pre-commercial stage (see 11.13). The maturity of solar energy ranges from the R&D stage (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); however, even the technologies that are more technically mature have not all reached a state of economic competitiveness. Geothermal power and heat technologies that rely on hydrothermal resources use mature technologies (though reservoir risks remain substantial), whereas enhanced geothermal systems continue to undergo R&D with some limited demonstration plants now deployed. Except for certain types of tidal barrages, ocean energy technologies are also at the demonstration phase and require additional R&D. Traditional land-based wind technologies are mature, while the use of wind energy in offshore locations is increasing but is typically more costly than land-based wind.

With regard to traditional biomass, the conversion of wood to charcoal in traditional kilns results in low conversion efficiencies. A wide range of interventions have tried to overcome this challenge by promoting more efficient kilns, but the adoption rate has been limited in many countries, particularly in sub-Saharan Africa (Chidumayo and Gumbo, 2013). Although not yielding large GHG savings in global terms, increasing the efficiency of charcoal production offers local benefits such as improved charcoal delivery and lower health and environmental impacts (FAO, 2010).

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, 2013). 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—though 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.

RE currently constitutes a relatively small fraction of global energy supply, especially if one excludes traditional biomass. However, RE provided almost 21% of global electricity supply in 2012, and RE deployment has increased significantly since the IPCC's AR4 (see Section 7.2). In 2012, RE power capacity grew rapidly: REN21 (2013) reports that RE accounted for just over half of the new electricity-generating capacity added globally in 2012.[5] As shown in Figure 7.5, the fastest-growing sources of RE power capacity included wind power (45 GW added in 2012), hydropower (30 GW), and PV (29 GW).[6]

In aggregate, the growth in cumulative renewable electricity capacity equalled 8% from 2010 to 2011 and from 2011 to 2012 (REN21, 2013). Biofuels accounted for 3.4% of global road transport fuel demand in 2012 (REN21, 2013); though growth was limited from 2010 to 2012, growth since the IPCC's AR4 has been substantial. By the end of 2012, the use of RE in hot water/heating markets included 293 GWth of modern biomass, 255 GWth of solar, and 66 GWth of geothermal heating (REN21, 2013).

Collectively, developing countries host a substantial fraction of the global renewable electricity generation capacity, with China adding more capacity than any other country in 2012 (REN21, 2013). Cost reductions for 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 through 2012 coming from Europe (and to a lesser degree Asia and North America) but with manufacturing shifting to Asia (REN21, 2013; see also Section 7.8). The USA and Brazil accounted for 61% and 26%, respectively, of global bioethanol production in 2012, while China led in the use of solar hot water (REN21, 2013).

Decentralized RE to meet rural energy needs, particularly in the less developed countries, has also increased, including various modern and advanced traditional biomass options as well as small hydropower, PV and wind, thereby expanding and improving energy access (IPCC, 2011a; REN21, 2013).

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[5] A better metric 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 2012, however, are not available.

[6] REN21 (2013) estimates that biomass power capacity increased by 9 GW in 2012, CSP by 1 GW, and geothermal power by 0.3 GW.

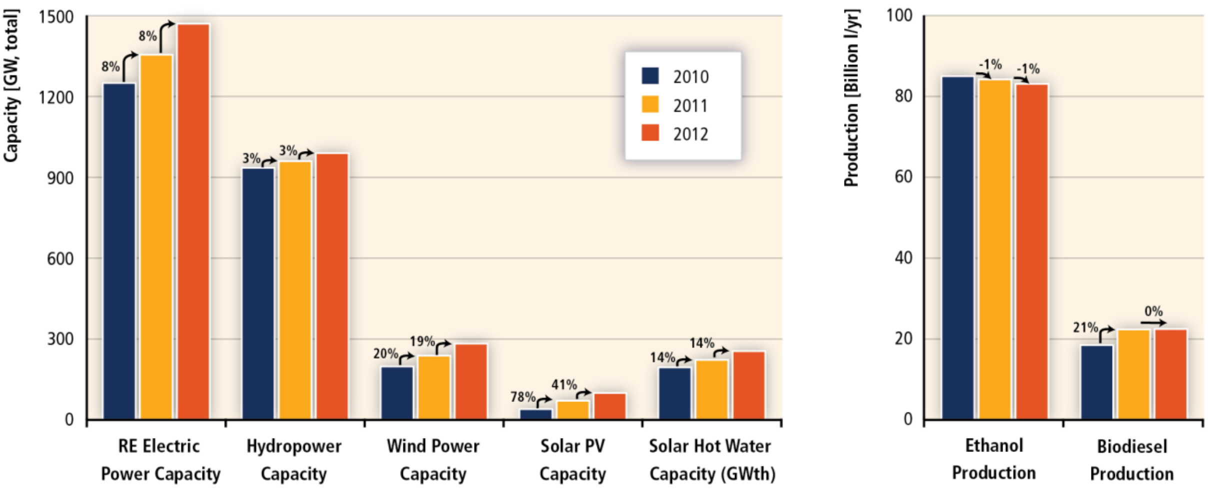

Figure 7.5. Selected indicators of recent global growth in RE deployment (**REN21, 2013**). Note: A better metric of the relative contribution of RE would be based on energy supply, not installed capacity, especially because of the relatively low capacity factors of some RE sources. Energy supply statistics 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 30 countries around the world (IAEA, 2013a). There are 434 operational nuclear reactors with a total installed capacity of 371 GWe as of September 2013 (IAEA, 2013a). Nuclear electricity represented 11% of the world's electricity generation in 2012, with a total generation of 2346 TWh (IAEA, 2013b). The 2012 share of global nuclear electricity generation is down from a high of 17% in 1993 (IEA, 2012b; BP, 2013). The USA, France, Japan, Russia, and Korea (Rep. of)—with 99, 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 September 2013 (IAEA, 2013a). The majority of the world's reactors are based on light-water technology of similar concept, design and fuel cycle. Of the reactors worldwide, 354 are light-water reactors (LWR), of which 270 are pressurized water reactors (PWR) and 84 are boiling water reactors (BWR) (IAEA, 2013a). 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, 2013a). The choice of reactor technologies has implications for safety, cost and nuclear fuel cycle issues.

Growing demand for electricity, energy diversification and GHG-emissions mitigation motivate the construction of new nuclear reactors. The electricity from nuclear power does not contribute to direct GHG emissions. There are 69 reactors, representing 67 GWe of capacity, currently under construction in 14 countries (IAEA, 2013a). The bulk of the new builds are in China, Russia, India, Korea (Rep. of), and the USA—with 28, 10, 7, 5, and 3 reactors under construction, respectively (IAEA, 2013a). New reactors consist of 57 PWR, 5 PHWR, 4 BWR, 2 FBR, and one high-temperature gas-cooled reactor (HTGR) (IAEA, 2013a).

Commercial reactors currently under construction—such as the Advanced Passive-1000 (AP-1000, USA-Japan), Advanced Boiling Water Reactor (ABWR, USA-Japan), European Pressurized Reactor (EPR, France), Water-Water Energetic Reactor-1200 (VVER-1200, Russia), and Advanced Power Reactor-1400 (APR-1400, Rep. of Korea)—are Gen III and Gen III+ reactors that have evolutionary designs with improved active and passive safety features over the previous generation of reactors (Cummins et al., 2003; IAEA, 2006; Kim, 2009; Goldberg and Rosner, 2011).

Other more revolutionary small modular reactors (SMR) with additional passive safety features are under development (Rosner and Goldberg, 2011; IAEA, 2012a; Vujic et al., 2012; World Nuclear

Association, 2013). The size of these reactors is typically less than 300 MWe, much smaller than the 1000 MWe or larger size of current LWRs. The idea of a smaller reactor is not new, but recent SMR designs with low power density, large heat capacity, and heat removal through natural means have the potential for enhanced safety (IAEA, 2005a, 2012a). Additional motivations for the interest in SMRs are economies of manufacturing from modular construction techniques, shorter construction periods, incremental power capacity additions, and potential for improved financing (Rosner and Goldberg, 2011; Vujic et al., 2012; World Nuclear Association, 2013). Several SMR designs are under consideration. 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; Zhang et al., 2009). A 210 MWe demonstration high-temperature pebble-bed reactor (HTR-PM) is under construction in China (Zhang et al., 2009). While several countries have interest in the development of SMRs, their widespread adoption remains uncertain.

The choice of the nuclear fuel cycle has a direct impact on uranium resource utilization, nuclear proliferation and waste management. The use of enriched uranium fuels for LWRs in a once-through fuel cycle dominates the current nuclear energy system. In this fuel cycle, only a small portion of the uranium in the fuel is utilized for energy production, while most of the uranium remains unused. The composition of spent or used LWR fuel is approximately 94% uranium, 1% plutonium and 5% waste products (ORNL, 2012). The uranium and converted plutonium in the spent fuel can be used as new fuel through reprocessing. While the ultimate availability of natural uranium resources is uncertain (see 7.4.3), dependence on LWRs and the once-through fuel cycle implies greater demand for natural uranium. Transition to ore grades of lower uranium concentration for increasing uranium supply could result in higher extraction costs (Schneider and Sailor, 2008). Uranium ore costs are a small component of nuclear electricity costs, however, so higher uranium extraction cost may not have a significant impact on the competitiveness of nuclear power (IAEA, 2012b).

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, with some nations electing to recycle plutonium for use in new fuels and others electing to leave it intact within the spent fuel (IAEA, 2008a). 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 (NRC, 1996), which require final waste-disposal strategies to address safety of waste disposal on such great timescales. Alternative strategies to isolate and dispose of fission products and their components apart from actinides could have significant beneficial impact on waste-disposal requirements (Wigeland et al., 2006). Others have argued that separation and transmutation of actinides would have little or no practical benefit for waste disposal (NRC, 1996; 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, 2013). The thorium fuel cycle is an alternative to the uranium fuel cycle, and the abundance of thorium resources motivates its potential use (see 7.4.3). Unlike natural uranium, however, thorium does not contain any fissile isotopes. An external source of fissile material is necessary to initiate the thorium fuel cycle, and breeding of fissile U-233 from fertile Th-232 is necessary to sustain the fuel cycle (IAEA, 2005b).

Ultimately, full recycling options based on either uranium or thorium fuel cycles that are combined with advanced reactor designs—including fast and thermal neutron spectrum reactors—where only fission products are relegated as waste can significantly extend nuclear resources and reduce high-level wastes (GIF, 2002, 2009; IAEA, 2005b). Current drawbacks include higher economic costs, as well as increased complexities and the associated risks of advanced fuel cycles and reactor technologies. 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.

There is no final geologic disposal of high-level waste from commercial nuclear power plants currently in operation, but Finland and Sweden are the furthest along in the development of geologic disposal facilities for the direct disposal of spent fuel (Posiva Oy, 2011, 2012; SKB, 2011). In Finland, construction of the geologic disposal facility is in progress and final disposal of spent fuel is to begin in early 2020 (Posiva Oy, 2012). 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 of fission products and other actinides in a geologic repository (OECD and NEA, 2007; Butler, 2010). 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 USA, waste-disposal options are currently under review with the termination of the Yucca Mountain nuclear waste repository in Nevada (CRS, 2012). Indefinite dry cask storage of high-level waste at reactor sites and interim storage facilities are to be pursued until decisions on waste disposal are resolved.

The implementation of climate change mitigation policies increases the competiveness of nuclear energy technologies relative to other technology options that emit GHG emissions (See 7.11, Nicholson et al., 2011). The choice of nuclear reactor technologies and fuel cycles will affect the potential risks associated with an expanded global response of nuclear energy in addressing climate change.

Nuclear power has been in use for several decades. 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 expansion of nuclear energy worldwide as a response to climate change mitigation require greater efforts to address the safety, economics, uranium utilization, waste management, and proliferation concerns of nuclear energy use (IPCC, 2007, Chapter 4; GEA, 2012).

Research and development of the next-generation nuclear energy system, beyond the evolutionary LWRs, is being undertaken through national and international efforts (GIF, 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 and co-benefits, deployment barriers, and policy aspects can be found in Sections 7.4.3, 7.8.2, 7.9, 7.10, and 7.12.

7.5.5 Carbon dioxide capture and storage (CCS)

As of mid-2013, CCS has not yet been applied at scale to a large, commercial fossil-fired power generation facility. However, all of the components of integrated CCS systems exist and are in use today by the hydrocarbon exploration, production and transport; and petrochemical refining sectors.

A “complete end-to-end CCS system” captures CO_2 from large (e.g., typically larger than 0.1 $MtCO_2$/year) stationary point sources (e.g., hydrocarbon-fuelled power plants, refineries, cement plants, steel mills), transports and injects the compressed CO_2 into a suitable deep (typically more than 800 m below the surface) geologic structure, and then applies 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; Herzog, 2011). As of mid-2013, five large end-to-end commercial CCS facilities were in operation around the world. Collectively they have stored more than 30 $MtCO_2$ over their lifetimes (Eiken et al., 2011; Whittaker et al., 2011; MIT, 2013). All of them capture a high-purity CO_2 stream from industrial (i.e., non-electricity-generating) facilities such as natural gas processing plants. The near-term deployment of CCS is likely to arise in just these kinds of industrial facilities that produce high-purity (which connotes relatively inexpensive to capture) CO_2 waste streams that would otherwise be vented to the atmosphere and/or in situations where the captured CO_2 can be used in a value-added manner as is the case with CO_2-driven tertiary hydrocarbon recovery (IPCC, 2005; Bakker et al., 2010; Vergragt et al., 2011). In the long term, the largest market for CCS systems is most likely found in the electric power sector, where the cost of deploying CCS (measured on a $/$tCO_2$ basis) will be much higher and, as a result, will be done solely for the purpose of isolating anthropogenic CO_2 from the atmosphere - which is unlikely to occur without sufficiently stringent limits on GHG emissions to make it economic to incur these additional costs, regulatory mandates that would require the use of CCS (for example, on new facilities), or sufficient direct or indirect financial support (IPCC, 2005; Herzog, 2011).

Research aimed at improving the performance and cost of CO_2 capture systems for the electric power sector is significant across three broad classes of CO_2 capture technologies: pre-combustion (Rubin et al., 2007; Figueroa et al., 2008), post-combustion (Lin and Chen, 2011; Padurean et al., 2011; Versteeg and Rubin, 2011) and oxyfuel capture (Scheffknecht et al., 2011; Wall et al., 2011).

The risks associated with a large-scale deployment of CCS technologies include concerns about the life-cycle toxicity of some capture solvents (IEAGHG, 2010; Korre et al., 2010; M. Corsten et al., 2013), the operational safety and long-term integrity of CO_2 storage sites (Birkholzer et al., 2009; Oruganti and Bryant, 2009; Juanes et al., 2010, 2012; Morris et al., 2011; Mazzoldi et al., 2012) as well as risks associated with CO_2 transport via dedicated pipelines (Aines et al., 2009; Mazzoldi et al., 2012).

There is, however, a growing body of literature on how to minimize capture risks and to ensure the integrity of CO_2 wells (Carey et al., 2007, 2010; Jordan and Benson, 2009; Crow et al., 2010; Zhang and Bachu, 2011; Matteo and Scherer, 2012) as well as on using detailed measurement, monitoring and verification data to lower the threshold for detecting any leakage out of the intended injection zone (Hovorka et al., 2006; Gilfillan et al., 2009; Jordan and Benson, 2009; Eiken et al., 2011). The literature is also quantifying potential consequences of a pressure build-up within a formation caused by CO_2 storage such as induced seismicity (Juanes et al., 2012; Mazzoldi et al., 2012; NAS, 2013a), the potential human health impacts (Roberts et al., 2011; de Lary et al., 2012; Atchley et al., 2013) and environmental consequences from CO_2 that might migrate out of the primary injection zone (Gaus, 2010; Romanak et al., 2012; Zheng et al., 2012) as well as mechanisms for actively managing the storage formation such as withdrawing formation waters to reduce pressure build-up (Esposito and Benson, 2012; Réveillère et al., 2012; Sullivan et al., 2013).

The deployment of CCS at a scale of 100s of $GtCO_2$ over the course of this century (which is consistent with the stabilization scenarios described in Chapter 6 and in Section 7.11) would imply that large, regional, deep geologic basins would have to accommodate multiple large-scale CO_2 injection projects (Bachu, 2008; Nicot, 2008; Birkholzer and Zhou, 2009; Juanes et al., 2010) while taking into account other industrial activities in the region that could impact the integrity of CO_2 storage reservoirs (Elliot and Celia, 2012). The peer reviewed literature that has looked at these large CCS deployment scenarios stress the need for good CO_2 storage site selection that would explicitly address the cumulative far-field pressure effects from multiple injection projects in a given basin.

A considerable body of practical engineering and scientific knowledge has been generated from the first five large-scale, complete CCS deployments as well as from numerous smaller-scale CCS field experiments and technology demonstrations (Cavanagh et al., 2010; IEAGHG, 2011; NETL, 2012). In particular, a key advance has been the field testing of MMV technologies to monitor injected CO_2 in a variety of settings. These real-world MMV deployments are the beginnings of a broader portfolio of MMV technologies that can be matched to site-specific geology and project- and jurisdiction-specific MMV needs (Mathieson et al., 2010; Vasco et al., 2010; Sato et al., 2011). The value of high-quality MMV data is becoming clearer as these data allow for the active management of a geologic CO_2 storage formation and can provide operators and regulators with the ability to detect possible leakage out of the target formation at low levels, which, in turn, can reduce the probability and magnitude of adverse events (Dooley et al., 2010; Torvanger et al., 2012; Buscheck et al., 2012; Schloemer 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 over time. The accumulated knowledge from the five commercial CCS facilities mentioned above, from many smaller field experiments and technology demonstrations, and from laboratory-based research suggests a declining long-term risk profile for CO_2 stored in deep geologic reservoirs once active CO_2 injection into the reservoir has ceased (Hovorka et al., 2006; Gilfillan et al., 2009; Jordan and Benson, 2009). Torvanger et al. (2012) builds upon this accumulated knowledge and concludes, "only in the most unfortunate conditions could such CO2 escape [from deep geologic CO_2 storage reservoirs and] compromise [humanity's ability to not exceed a] maximum 2.5 °C warming."

Further information concerning transport risks, costs, deployment barriers and policy aspects can be found in Sections 7.6.4, 7.8.2, 7.10, and 7.12, respectively. The use of CCS in the industrial sector is described in Section 10.4.

The direct CO_2 emissions from biogenic feedstock combustion broadly correspond to the amount of atmospheric CO_2 sequestered through the growth cycle of bioenergy production.[7] A net removal of atmospheric CO_2 therefore would result, once the direct emissions are captured and stored using CCS technologies (see 11.13). As a consequence, a combination of bio-energy and CCS (called BECCS) generally will result in net negative emissions (see IEA, 2011c, 2012c; IEAGHG, 2011). Currently two small scale examples of commercial precursors to BECCS capture CO_2 emissions from ethanol production facilities for enhanced oil recovery in close proximity facilities (DiPietro and Balash, 2012).

BECCS is one of the few technologies that are capable to remove past CO_2 emissions remaining in the atmosphere. As this enhances the "when" (i.e. temporal) flexibility during the design of mitigation scenarios considerably, BECCS plays a prominent role in many of the low stabilisation pathways discussed in Chapter 6 and 7.11. Potential risks associated with BECCS technologies are related to those associated with the upstream provision of the used biomass[8] (see 11.13) as well as those originating from the capture, transport and long-term underground storage of CO_2 that would be emitted otherwise (see above).

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[7] Non-vanishing life cycle emissions originate from fossil fuels used during the planting, regrowth and harvesting cycle and potential emissions from land-use and management change, among others. The lifecycle emissions depend on the type of feedstock, specific location, scale and practices of biomass production, and on the dynamics and management of land use. In some cases, if biomass growth accumulates carbon in the soil until reaching equilibrium, additional carbon sequestration can occur but these may be short term effects. Indirect emissions relate more directly to the use of food crops for energy than to the utilization of lignocellulosic biomass (see 11.13). Short rotation species, herbaceous plants, wastes have near zero net emissions cycles.

[8] BECCS costs can be reduced by using large-scale biomass conversion facilities which, in turn require the development of cost-effective and low emitting large-scale feedstock and supply logistics.

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 – these will both depend on the mitigation technologies employed. The fundamental reliability constraints that underpin this process are the requirements that power supply and electricity demand remain in balance at all times (system balancing), that adequate generation capacity is installed to meet (peak) residual demand (capacity adequacy)[9], and that transmission and distribution network infrastructure is sufficient to deliver generation to end-users (transmission and distribution). Studies of high variable RE penetration (Mason et al., 2010; Delucchi and Jacobson, 2011; Denholm and Hand, 2011; Huva et al., 2012; Elliston et al., 2012; Haller et al., 2012; Rasmussen et al., 2012; Budischak et al., 2013) and the broader literature (summarized in Sims et al., 2011) suggest that integrating significant GHG mitigation generation technology is technically feasible, though economic and institutional barriers may hinder uptake. Integrating high penetrations of RE resources, particularly those that are intrinsically time variable, alongside operationally inflexible generation is expected to result in higher system balancing costs. Compared to other mitigation options variable renewable generation will contribute less to capacity adequacy, and, if remote from loads, will also increase transmission costs. The determination of least cost portfolios of those options which facilitate the integration of fluctuating power sources is a field of active and ongoing research (Haller et al., 2012; Steinke et al., 2013).

7.6.1.1 System balancing - flexible generation and loads

Variable RE resources may increase the need for system balancing beyond that required to meet variations in demand. Existing generating resources can contribute to this additional flexibility. An IEA assessment 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 above 40% in two regions and one country (IEA, 2011d). Higher RE penetrations will require additional flexible resources (De Vos et al., 2013). Surplus renewable supply can be curtailed by switching off unwanted plant or through regulation of the power output, but with corresponding economic consequences (Brandstätt et al., 2011; Jacobsen and Schröder, 2012).

Some low carbon power technologies (such as nuclear) have relatively high up-front and low operating costs, making them attractive for base-load operation rather than providing flexible generation to assist in system balancing. Depending on the pattern of electricity demand, a relatively high share of energy can be provided by these base-load technologies but at some point, further increases in their penetration will require part-loaded operation,[10] load following, time shifting of demand (via load management or demand response), and/or deployment of storage where it is cost effective (Knapp, 1969; Johnson and Keith, 2004; Chalmers et al., 2009; Pouret et al., 2009).

Part-load operation of nuclear plant is possible as in France, though in other regions may be restricted by institutional barriers (Perez-Arriaga and Batlle, 2012). Load following by nuclear power plants is more challenging and must be considered at the design stage (NEA, 2011a, 2012; Greenblatt et al., 2012). Flexible operation of CCS fitted generation plant is also an active area of research (Chalmers and Gibbins, 2007; Nord et al., 2009; Cohen et al., 2011). Operational flexibility of combined heat and power (CHP) plant may be constrained by heat loads, though thermal storage and complementary heat sources can mitigate this effect (e.g., Lund and Andersen, 2005; Christidis et al., 2012; Blarke, 2012; Nuytten et al., 2013), however the capital intensity of CHP will favor high load factors. Reservoir hydropower can be useful in balancing due to its flexibility.

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[9] Sometimes called resource adequacy.

[10] In the field of RE this is called „curtailment".

Certain combinations may present further challenges (Ludig et al., 2011): high shares of variable RE power for example may not be ideally complemented by nuclear, CCS, and CHP plant (without heat storage). If those plants cannot be operated in a flexible manner, additional flexibility is required and 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). Obtaining flexibility from fossil generation has a cost (see 7.8.2) and can affect the overall GHG reduction potential of variable RE (Pehnt et al., 2008; Fripp, 2011; Wiser et al., 2011; Perez-Arriaga and Batlle, 2012). Demand response[11] is of increasing interest due to its potentially low cost (see chapter 9 and 10; IEA, 2003b; Depuru et al., 2011; Cook et al., 2012; Joung and Kim, 2013; Procter, 2013), albeit some emphasize its limitation compared to flexible conventional supply technologies (Cutter et al., 2012). Smart meters and remote controls are key components of the so called smart grid where information technology is used to improve the operation of power systems, especially with resources located at the distribution level (IEA, 2011e).

Energy storage might play an increasing role in the field of system balancing (Zafirakis et al., 2013). Today pumped hydro storage is the only widely deployed storage technology (Kanakasabapathy, 2013). Other storage technologies including compressed air energy storage (CAES) and batteries may be deployed at greater scale within centralized power systems in the future (Pickard, Hansing, et al., 2009; Pickard, Shen, et al., 2009; Roberts and Sandberg, 2011), and the latter can be decentralized. These short-term storage resources can be used to compensate the day-night cycle of solar and short term fluctuation of wind power (Denholm and Sioshansi, 2009; Chen et al., 2009; Loisel et al., 2010; Beaudin et al., 2010). With the exception of pumped-hydro storage, full (levelised) storage costs are still high, but storage costs are expected to decline with technology development (IEA, 2009b; Deane et al., 2010; Dunn et al., 2011; EIA, 2012). “Power to heat” and “Power to gas” (H2 or methane) technologies might allow for translating surplus renewable electricity into other useful final energy forms (see 7.6.2 and 7.6.3).

7.6.1.2 Capacity 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 the availability of sufficient generation is called the capacity credit or capacity value (Keane et al., 2011). The capacity credit of nuclear, thermal plants with CCS, geothermal, and large hydro is expected to be higher than 90% (i.e. within 10% of the plant nameplate capacity) as long as fuel supply and cooling water is sufficient and maintenance is scheduled outside critical periods. Variable RE will generally have a lower capacity credit that depends on the correlation between generation availability and periods of high demand. The capacity credit of wind power, for instance, ranges from 5% to 40% of the nameplate capacity (Mason et al., 2010; Holttinen et al., 2011); ranges of capacity credits for other 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 (defined as the ratio of the sum of the nameplate capacity of all generation to peak demand) to ensure the same degree of system reliability. If specifically tied to RE generation, energy storage can increase the capacity credit of that source; for example, the capacity credit of CSP with thermal storage is greater than without thermal storage (Madaeni et al., 2011).

7.6.1.3 Transmission and Distribution

Due to the geographical diversity of RE resources, connecting RE sources to the existing transmission system may require the installation of additional transmission capacity and strengthening the existing system if significantly greater power flows are required across the system (Sims et al., 2011). Increased interconnection and strengthened transmission systems provide power system operators

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[11] Demand response is load-management triggered by power price signals derived from the spot market prices or other control signals (IEA, 2003b).

the capability to move surplus generation in one region to meet otherwise unmet demand in another, exploiting the geographical diversity of both loads and generation (Rasmussen et al., 2012). Although there will be a need for additional transmission capacity, its installation often faces institutional challenges, and it can be visually intrusive and unpopular in the affected areas. Infrastructure challenges are particularly acute for RE deployment in developing countries which is why stand-alone decentralized generation, such as with solar home systems, is often favored.

Transmission considerations applied to CCS plants have to reflect the trade-off between the cost of electrical transmission and the cost of pipeline transport of CO_2 to final depositories (Svensson et al., 2004; Benson et al., 2005; Herzog et al., 2005; Spiecker et al., 2011). Transmission investments may also be needed for future nuclear plant if these are located at some distance from load centers due to public perceptions of health and safety, access to cooling water, or other factors.

Distributed generation (DG), where small generating units (often renewable technologies, cogeneration units, or fuel cells) are connected directly to the electricity distribution system and near loads, may 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 to have increased visibility and controllability of DG to ensure overall system reliability. Smart grids might include components to facilitate the integration of various DG technologies, allow for more active control of the distribution network, and improve the market value of DG through aggregation into virtual power plants (Pudjianto et al., 2007; Clastres, 2011; IEA, 2011e; Wissner, 2011; Ardito et al., 2013; Hashmi et al., 2013).

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[12] of district heat for sale at CHP (44%) and heat-only boilers (56%) (Table 7.1). After a long decline in the 1990's, district heat returned to a growing trajectory in the last decade rising by about 21% above the 2000 level (IEA, 2012a). 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 intelligent 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 facilitates additional opportunities for low carbon technologies (CHP, waste heat use, heat pumps, solar heating and cooling) (IEA, 2012a). In addition, excess renewable electricity can be converted into heat to replace what otherwise would have been produced by fossil fuels (Meibom et al., 2007).

Statistically reported average global efficiency of heat generation by heat-only boilers is 83%, while it is possible to improve it to 90-95% depending on fuel used. About 6.9% of globally generated heat for sale 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 (Bashmakov, 2009).

The promotion of district heating and cooling system should also account for future technology developments that impact the district heating sector (building heat demand reduction, high efficiency single housing boilers, heat pump technology, cogeneration reciprocating engines or fuel cells, etc.), which may allow switching to more efficient decentralized systems (GEA, 2012). District heating and cooling systems could be more energy and economically efficient when heat or coldness load density is high through the development of tri-generation, the utilization of waste heat by

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[12] UNES reports lower number. For 2008 this sources assess the total production of district heat equal to 10.7 EJ (UNES, 2011).

communities or industrial sites, if heat (cooling) and power loads show similar patterns, and if heat loss control systems are well designed and managed (see 9.4.1.1).

7.6.3 Fuel supply systems

As noted in 7.5.1, fossil fuel extraction and distribution contributes around 5-10% of total fossil fuel related GHG emissions. It has also been noted that specific emissions from this sector will increase due to 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 fuel supply system supporting this sector does however provide opportunities to reduce GHG emissions by enabling the delivery of low carbon fuels (such as biofuels, or biogas, renewable H2 or renewable methane).

Opportunities for delivery of liquid fuels are likely limited to fuels such as biodiesel and ethanol at points in the system that enable either storage or blending before transport to distribution nodes, this is 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, e.g. “power to methane” (Sterner, 2009; Arvizu et al., 2011), from other renewable sources such as biomass and waste, or via coal when combined with CCS; CCS can be added to gas production from biomass 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 (Hagen et al., 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 (Naturalhy 2004). Limiting factors are gas quality standard and equipment compliance, pipeline integrity (failure, fire and explosion) and end user safety (Naturalhy, 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 reduce energy flow, unless gas pressure can be increased. If required, hydrogen separation is possible via a range of existing technologies.

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 (Yang and Ogden, 2007). Hydrogen can be produced from renewable sources such as wind and solar (IEA, 2006; Moriarty and Honnery, 2007; Gahleitner, 2013) as well as biomass. Its production from intermittent renewable sources can provide greater system flexibility; drawbacks are the additional cost and reduced overall efficiency in energy delivery (Mason and Zweibel, 2007; Honnery and Moriarty, 2009; IPCC, 2011a).

7.6.4 CO_2 transport

There are more than 6,300 km of existing CO_2 pipeline in the U.S and much has been learnt from the decades of operational experience obtained from these existing CO_2 pipeline systems (Dooley et al., 2011). There is a growing body of research that describes the magnitude and region-specific nature of future CO_2 transport systems. Specifically, there are a growing number of bottom-up studies that examine spatial relationships between where CO_2 capture units might be located and the very heterogeneous distribution, capacity and quality of candidate geologic storage reservoirs. For example, the work of Dahowski et al., (2005, 2012) suggests that more than 90% of the large stationary CO_2 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 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; 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; Ozaki and Ohsumi, 2011; Yoo et al., 2011).

The U.S. oil and gas industry has more than 40 years of experience associated with transporting large volumes of CO_2 via dedicated commercial pipelines (IPCC, 2005; Meyer, 2007). Available data suggests that these CO_2 pipelines have safety records that are on par with or better than large interstate natural gas pipelines, their closest industrial analogue (Gale and Davison, 2004; IPCC, 2005; Cole et al., 2011). There is also a growing body of work combining pipeline fluid flow, pipeline engineering models, and atmospheric dispersion models suggesting that the hazard associated with potential ruptures in CO_2 pipelines is likely to be small for most plausible releases to the atmosphere (Aines et al., 2009; Koornneef et al., 2010; Mazzoldi et al., 2011). Although much can be learnt from existing CO_2 pipeline systems, 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; Cole et al., 2011) with particular importance given to limiting the amount of water in the gas stream at its source 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 Section 7.8.2. Options for CO_2 geologic storage are presented in 7.5.5 and a discussion of the cost of CO_2 capture is presented 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; Arent et al., 2014), thereby also influencing energy supply needs. The effect on overall energy demand will vary geographically (Mideksa and Kallbekken, 2010; Pilli-Sihvola et al., 2010; 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 (Isaac and van Vuuren, 2009; Akpinar-Ferrand and Singh, 2010; Arent et al., 2014). Peak electricity demand could also increase, especially as a result of extreme events, requiring a disproportionate increase in energy infrastructure (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 (US EPA, 2008; Aromar and

Sattherhwaite, 2014). As another example, reductions or changes to surface water flows could increase energy demand for desalination (Boyé, 2008; Scholes and Settele, 2014).

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 (Arent et al., 2014).

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 they may vary substantially on regional and local levels (IPCC, 2011a; Schaeffer et al., 2012; Arent et al., 2014). 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.”

A decline in renewable resource potential in one area could lead to a shift in the location of electricity-generation technologies over time to areas where the resource has not degraded. Long-lived transmission and other 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 (Kumar et al., 2011; Schaeffer et al., 2012).

Climate change may also impact the design and operation of energy sourcing and delivery facilities (e.g., US DOE, 2013b). Offshore infrastructure, including gas and oil wells but also certain RE facilities such as offshore wind power plants, are vulnerable to extreme weather events (Karl et al., 2009; Wiser et al., 2011; World Bank, 2011a; Rose et al., 2012; Arent et al., 2014). 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 (Schaeffer et al., 2012; Sathaye et al., 2013). Some power-generation facilities will also be impacted by changes in access to and the temperature of cooling water, while both power-generation facilities and energy-delivery infrastructures can be impacted by sea-level rise and extreme weather events (Kopytko and Perkins, 2011; Schaeffer et al., 2012; Arent et al., 2014). Adaptation strategies include infrastructure relocation and reinforcement, cooling-facility retrofit, and proactive water-resource management (Rübbelke and Vögele, 2011; Arent et al., 2014).

Finally, interdependencies between the energy supply 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 2014; 11.13). 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 (Kumar et al., 2011; Arent et al., 2014; Cisneros and Oki, 2014).

7.8 Costs and potentials

7.8.1 Potential emission reduction from mitigation measures

When assessing the potential of different mitigation opportunities, it is important to evaluate the options 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 life cycle GHG emissions associated with different energy supply technologies per unit of final energy delivered, with a focus on electricity generation (Figure 7.6).

The largest life-cycle GHG emissions are associated with the combustion of coal. For life cycle assessments reviewed in SRREN, a range of 675-1689 gCO_{2eq} per kWh electricity was identified. Corrsponding ranges for oil and gas were 510-1170 and 290-930 gCO_{2eq}/kWh[13]. For the AR5, the performance of prospective, new fossil fuel power plants was assessed, taking into account a revised assessment of fugitive methane emission from coal mining and natural gas supply (Section 7.5.1)., According to this assessment, modern to advanced hard coal power plants show a range of 710-950 gCO_{2eq}/kWh, while natural gas combined cycle plants have emissions in the range of 410-650 gCO_{2eq}/kWh, with high uncertainty and variability associated with methane emissions from gas production (section 7.5.1) (Annex II.10.1). Compared to a separate provision of heat, cooling, and power from stand-alone fossil fuel based facilities, combined heat, cooling and power plants reduce emissions by one quarter (Pehnt, 2008). The transformation pathways which achieve a stabilization of the global temperature that is consistent with the Cancun Agreement (Chapter 6, Section 7.11, Figure 7.7), however, are based on emissions intensities approaching zero in the second half of this century, so that the employment of technologies with even lower emissions (than the one mentioned for gas-fired power and combined heat and power plants) is called for if these goals are to be achieved.

A number of power supply technologies offer very low life-cycle GHG emissions(Figure 7.6). CCS is expected to reduce emission to 70-290 gCO_2e/kWh for coal (98-396 in SRREN). For gas power, the literature specifies 120-170 gCO_2e/kWh assuming a leakage of 1% of natural gas (Koorneef et al., 2008; Singh et al., 2011; Mariëlle Corsten et al., 2013), while SRREN specified 65-245 gCO_2e/kWh. According to the literature, natural gas leakage is between 0.8-5.5% (Burnham et al., 2012) (see 7.5.1 for a discussion and more references), resulting in emissions between 90 and 370 gCO_2e/kWh (Fig. 7.6). Most of these assessments assume that 90% of the CO2 in the flue gas is captured, while the remaining emissions are mainly connected to the fuel chain. The upper range of emissions for CCS based power plants is flexible as plants can be designed to capture less, something that results in lower cost and less equipment required. A higher capture rate can be most easily be achieved for oxyfuel based plants (Fig. 7.6).

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[13] All reported SRREN numbers are from Table A.II.4 in Moomaw et al.(2011)

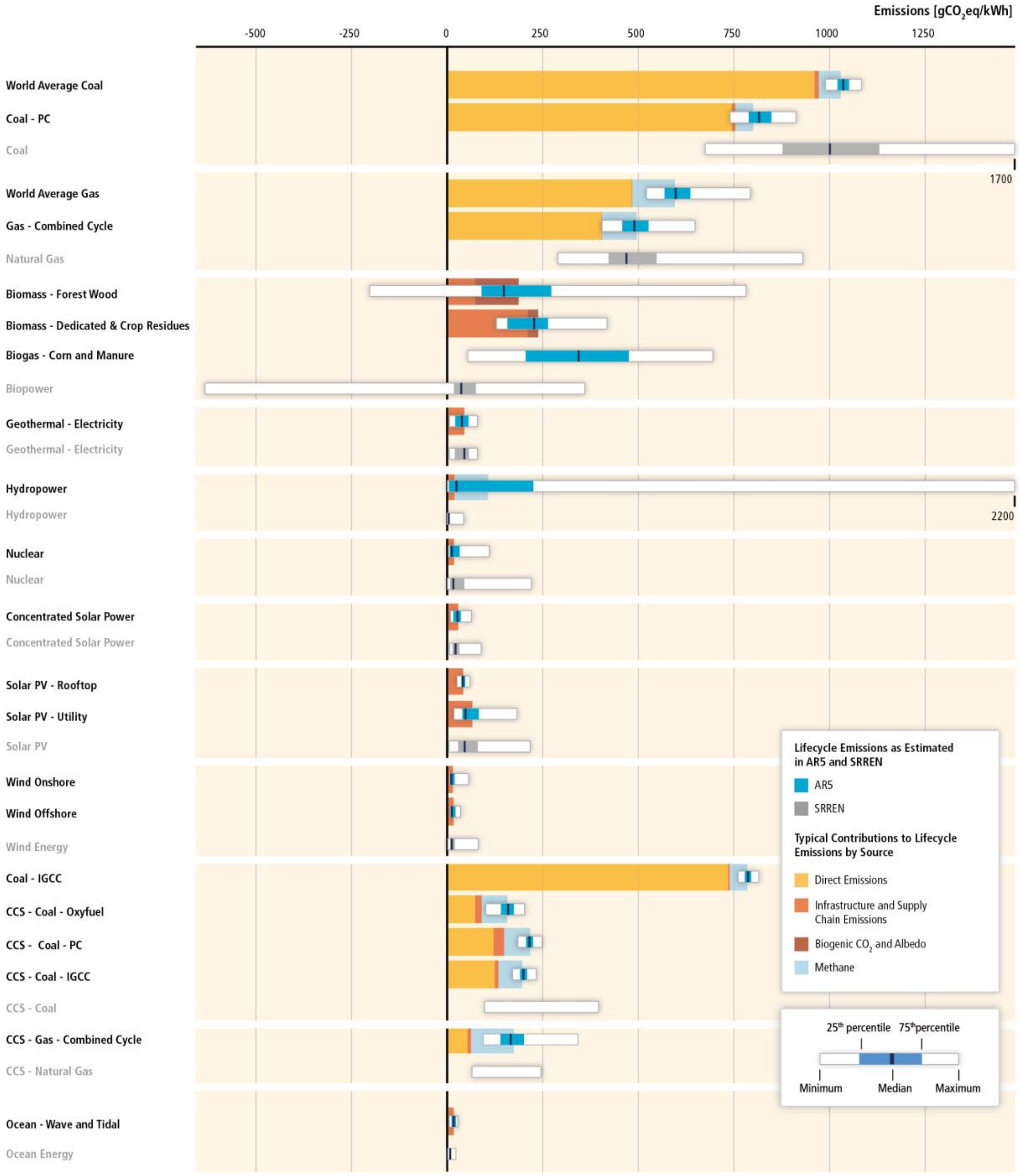

Figure 7.6. Comparative lifecycle greenhouse gas emissions from electricity supplied by currently commercially available technologies (fossil fuels, renewable, and nuclear power) and pre-commercial technologies (advanced fossil systems with CCS and ocean energy). The figure shows distributions of lifecycle emissions (based on WGIII AR5 Report and WGIII SRREN Report for comparison) and typical contributions to lifecycle emissions by source (cf. figure legend). For fossil technologies, fugitive emissions of methane from the fuel chain are the largest indirect contribution and hence shown separately. For hydropower, biogenic methane emissions are the main cause of the large range.

Abbreviations: AR5 – IPCC WG III Fifth Assessment Report, CCS – CO2 capture and storage, IGCC – integrated coal gasification combined cycle, PC – pulverized hard coal, PV – photovoltaic, SRREN – IPCC WGIII Special Report on Renewable Energy Sources and Climate Change Mitigation. Sources: SRREN (IPCC, 2011), Wind (Arvesen and Hertwich, 2012), PV (Kim et al., 2012; Hsu et al., 2012), CSP (Burkhardt et al., 2012), ocean and wave (Walker and Howell, 2011; Kelly et al., 2012), geothermal power (Sathaye et al., 2011), hydropower (Sathaye et al., 2011; Hertwich, 2013), nuclear power (Warner and Heath, 2012), bioenergy (Cherubini et al., 2012). Harmonized values have been used where available. For the fossil fuel technologies, all fugitive methane emissions were calculated based on the range provided by (Burnham et al., 2012), infrastructure and supplies are based on (Singh et al., 2011), and direct emissions are based on (Singh et al., 2011; Corsten et al., 2013b). For bioenergy, ranges include global climate impacts of CO2 emissions from combustion of regenerative biomass (i.e., biogenic CO2) and the associated changes in surface albedo following ecosystem disturbances, quantified according to the IPCC framework for emission metrics (see the 4th IPCC Assessment Report, (Forster et al., 2007)) and using global warming potentials (GWP) with TH = 100 years as characterization factors (Cherubini et al., 2012). These impacts are site-specific and generally more significant for long rotation species. The category "Biogas" includes cases where manure, dedicated crops (e.g., maize), or a mixture of both are used as feedstocks. In addition to the variability in the substrates, the large range in the results reflects different degrees of CH4 emissions from leakage and digestate storage, with the latter that can be reduced in closed storage systems (Boulamanti et al., 2013). For more detail, see Annex II.10.1 and 11.13.4.

Renewable heat and power generation and nuclear energy can bring more significant reductions in GHG emissions. The information provided here has been updated from the data provided in SRREN, taking into account new findings and reviews, where available. The ranges of harmonized life-cycle greenhouse gas emissions reported in the literature are 18-180 gCO_{2eq}/kWh for PV (Kim et al., 2012; Hsu et al., 2012), 9-63 for CSP (Burkhardt et al., 2012), and 4-110 gCO_2e/kWh for nuclear power (Warner and Heath, 2012). The harmonization has narrowed the ranges down from 5-217 for PV, 7-89 for CSP, and 1-220 for nuclear energy. A new literature review for wind power published since 2002 reports 7-56 gCO_2e/kWh, where the upper part of the range is associated with smaller turbines (<100 kW) (Arvesen and Hertwich, 2012), compared to 2-81 reported in SRREN. 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. SRREN reported 6-79 gCO_2e/kWh for geothermal power and 2-23 gCO_2e/kWh for ocean energy (Moomaw et al. 2012). For ocean power, Fig. 7.6 shows only the results of newer assessments, which range between 10-30 gCO_2e/kWh for tidal barrages, marine current turbines, and wave power(Walker and Howell, 2011; Kelly et al., 2012). For RE, emissions are associated with the manufacturing and installation of the power plants, but for nuclear power uranium enrichment can be significant (Warner and Heath, 2012). Generally, the ranges are quite wide reflecting differences in local resource conditions, technology, and methodological choices of the assessment. The lower end of estimates often reflects incomplete systems while the higher end reflects poor local conditions or outdated technology.

Life-cycle direct global climate impacts of bioenergy in Figure 7.6 come from the peer-reviewed literature from 2010 to 2012 (reviewed in 11.13.4) and are based on a range of electric conversion efficiencies of 30-50%. The category “Biomass - dedicated and crop residues” includes perennial grasses, like switchgrass and miscanthus, short rotation species, like willow and eucalyptus, and agricultural byproducts, like wheat straw and corn stover. “Biomass – forest wood” refers to sustainably harvested forest biomass from long rotation species in various climate regions. The range in “Biomass - forest wood” is representative of various forests and climates, e.g., aspen forest in Wisconsin (US), mixed forest in Pacific Northwest (US), pine forest in Saskatchewan (Canada), and spruce forest in Southeast Norway. Impacts from biogenic CO_2 and albedo are included in the same manner as the other GHGs, i.e. converted to g $CO_{2\text{-}eq}$. after characterization of emissions from combustion with case specific GWPs (Cherubini et al., 2012). In areas affected by seasonal snow cover, the cooling contribution from the temporary change in surface albedo can be larger than the warming associated with biogenic CO_2 fluxes and the bioenergy system can have a net negative impact (i.e., cooling). Change in soil organic carbon can have a substantial influence on the overall GHG balance of bioenergy systems, especially for the case “Biomass – dedicated and crop residues”, but are not covered here due to their high dependence on local soil conditions and previous land use (Don et al., 2012; Gelfand et al., 2013).

The climate effect of hydropower is very project specific. Life-cycle emissions from fossil fuel combustion and cement production related to the construction and operation of hydropower stations reported in the literature fall in the range of up to 40 $gCO_{2\text{-}eq}$/kWh for the studies reviewed in the SRREN (Kumar et al, 2011) and 3-7 $gCO_{2\text{-}eq}$ /kWh for studies reviewed in (Dones et al., 2007). Emissions of biogenic CH_4 resulting from the degradation of organic carbon primarily in hydropower reservoirs are a serious concern (Tremblay et al., 2005; Barros et al., 2011; Demarty and Bastien, 2011). Recent work indicates that CH_4 emissions are log-normally distributed, with the majority of measurements being below 20 $gCO_{2\text{-}eq}$/kWh (Hertwich, 2013), but emissions of ca. 2 $kgCO_{2\text{-}eq}$ /kWh coming from a few large reservoirs (Abril et al., 2005; Kemenes et al., 2007) (Kemenes et al., 2011).

New research suggest a global average of 70 $gCO_{2\text{-}eq}$ /kWh (Maeck et al., 2013; Hertwich, 2013). Ideas for mitigating existing methane emissions have been presented (Ramos et al., 2009; Stolaroff et al., 2012).

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 hydro power in suitable locations. In the future, further reductions of life-cycle emissions on these technologies could be attained through performance improvements (Caduff et al., 2012; Dale and Benson, 2013) and as a result of the a cleaner energy supply in the manufacturing of the technologies (Arvesen and Hertwich, 2011).

7.8.2 Cost assessment of mitigation measures

Though there are limits to its use as a tool for comparing the competitiveness of energy supply technologies, the concept of "levelized costs of energy" (LCOE, also called levelized unit costs or levelized generation costs)[14] is frequently applied (IEA, 2005, 2010b, 2011a; GEA, 2012).

Figure 7.7 shows a current assessment of the private cost[15] of various low carbon power supply technologies in comparison to their conventional counterparts.

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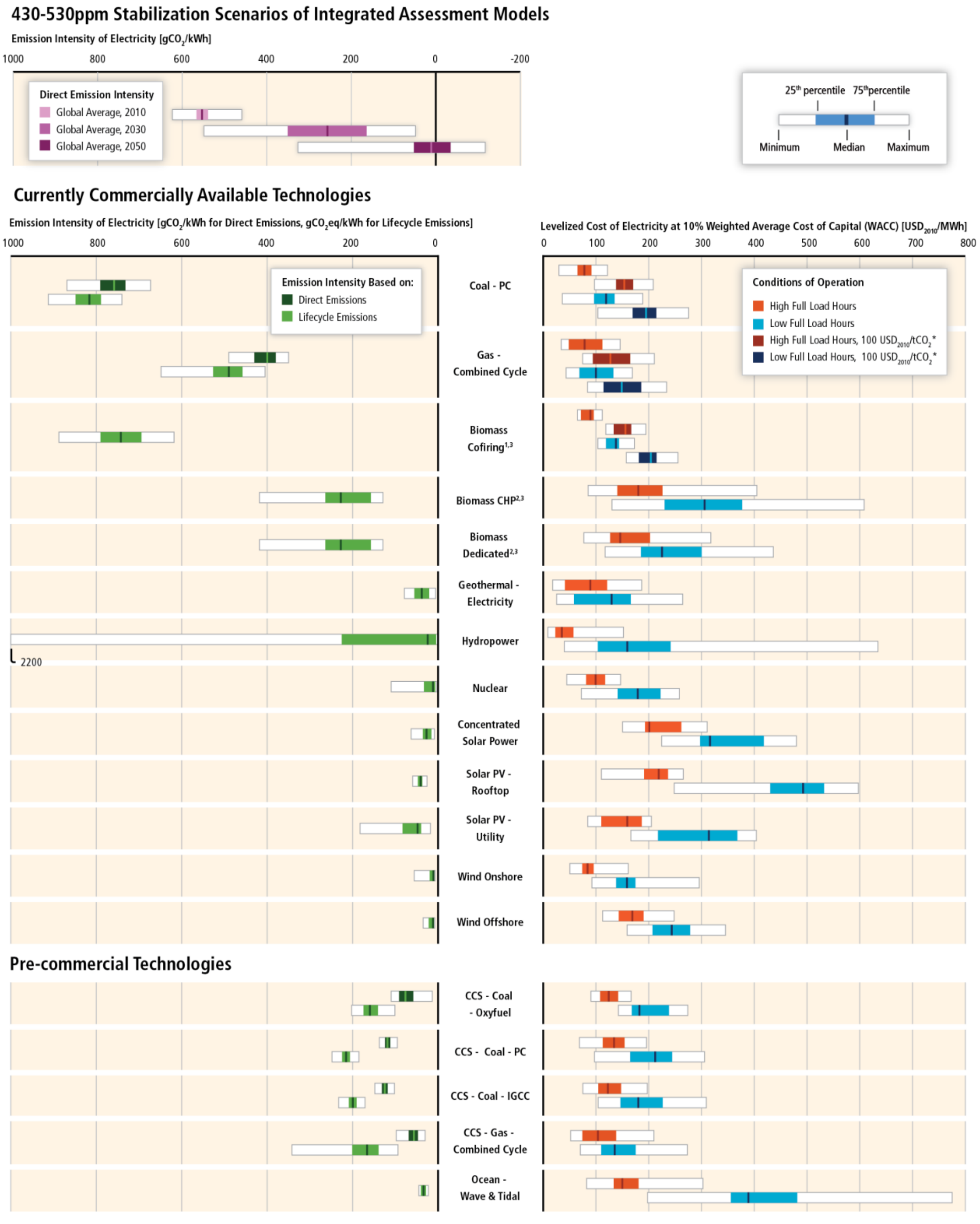
[14] A basic description of this concept, including its merits and shortcomings, can be found in the Methodology Annex of this report.

[15] Beyond variations in carbon prices, additional external costs are not considered in the following. Although the term 'private' will be omitted in the remainder of this section, the reader should be aware that all costs discussed here are private costs. An extended discussion of external costs is given in Fischedick et al., (2011).



[1] Assuming biomass feedstocks are dedicated energy plants and crop residues and 80-95% coal input

[2] Assuming feedstocks are dedicated energy plants and crop residues

[3] On-Site emissions for electricity from biomass are not shown. Indirect emissions include albedo effect.

* Carbon price levied on direct emissions. Effects shown where significant.

Figure 7.7. Specific direct and life-cycle emissions (gCO_2/kWh and gCO_2eq/kWh, respectively) and levelized cost of electricity (LCOE in USD_{2010}/MWh) for various power generating technologies (cf. Annex III, section A.III.2 for data and assumptions and Annex II, section A.II.3.1 and section A.II.10.1 for methodological issues). The upper left graph shows global averages of specific direct CO_2 emissions (gCO_2/kWh) of power generation for the set of 430-530ppm scenarios that are contained in the AR5 database (cf. Chapter 6).

Figure notes: (1) Assuming biomass feedstocks are dedicated energy plants and crop residues and 80 – 95% coal input. (2) Assuming feedstocks are dedicated energy plants and crop residues. (3) On-site emissions for electricity from biomass are not shown. Indirect emissions include albedo effect. (*) Carbon price is levied on direct emissions only. Carbon price effects are only shown where significant. Additional notes: Transport and storage costs of CCS are set to 10 USD_{2010}/tCO_2. LCOE of nuclear include front and back-end fuel costs as well as decommissioning costs. Remarks: The inter-comparability of LCOE is limited. For details on general methodological issues and interpretation related to LCOE see Annex II (Section A.II.3.1). Additional assumptions with respect to emission intensities are summarized in Annex II (Section A.II.10.1). For details on specific methodology, input data and assumptions for LCOE and emission intensities see Annex III (Section A.III.2).

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 and site specific projected costs of investment, and operation and maintenance. Investment decisions therefore should not be based on the LCOE data provided here; instead, site-, project- and investor-specific conditions are to be considered. Integration costs, time dependent revenue opportunities (especially in the case of intermittent renewables) and relative environmental impacts (e.g., external costs) play an important role as well (Heptonstall, 2007; Fischedick et al., 2011; Joskow, 2011; Borenstein, 2012; Edenhofer et al., 2013; Hirth, 2013).

The LCOE of many low carbon technologies changed considerably since the release of the IPCC AR4. Even compared to the numbers published in the SRREN (IPCC, 2011a), the decline of LCOE of some renewable energy (RE) technologies have been significant.[16] The LCOE of (crystalline silicon) photovoltaic systems, for instance, fell by 57% since 2009. Compared to PV a similar, albeit less extreme trend towards lower LCOE (from the second quarter of 2009 to the first quarter of 2013) has been observed for onshore wind (-15%), land fill gas (-16%), municipal solid waste (-15%), and biomass gasification (-26%) (BNEF and Frankfurt School-UNEP Centre, 2013).

Due to their rapid cost decline, some RE sources have become an economical solution for energy supply in an increasing number of countries (IRENA, 2013). Under favourable conditions (see Figure 7.7), large-scale hydropower (IEA, 2008b), larger geothermal projects (>30 MWe) (IEA, 2007), and wind onshore power plants (IEA, 2010c) are already competitive. The same is true for selected off-grid PV applications (IEA, 2010d, 2011b). As emphasized by the IPCC, SRREN (2011a) and IEA (IEA, 2008b, 2011b, 2012h) support policies, however, are still necessary in order to promote the deployment of many RE in most regions of the world.

Continuous cost reductions are not always a given (see BNEF and Frankfurt School-UNEP Centre, 2013), as illustrated by the recent increase in costs of offshore wind (+44%) and technologies in an early stage of their development (marine wave and tidal, binary plant geothermal systems). This however, does not necessarily imply that technological learning has stopped. As observed for PV and wind onshore (see SRREN,IPCC, 2011a), phases characterized by an increase of the price might be followed by a subsequent decline, if, for instance, a shortage of input material is eliminated or a “shake out” due to increasing supplier competition is happening (Junginger et al., 2005, 2010). In contrast, a production overcapacity as currently observed in the PV market might result in system prices that are temporarily below production costs (IEA, 2013a). A critical discussion of the solar photovoltaic grid-parity issue can be found in (IEA, 2013a).

While nuclear power plants, which are capable to deliver base-load electrical energy with low life-cycle emissions, have low operating costs (NEA, 2011b), investments in nuclear power are characterized by very large up-front investment costs, and significant technical, market and regulatory risks (IEA, 2011a, p. 455). Potential project and financial risks are illustrated by the significant time and cost over-runs of the two novel European Pressurized Reactors (EPR) in Finland and France (Kessides, 2012). Without support from governments, investments in new nuclear power plants are currently generally not economically attractive within liberalized markets which have access to relatively cheap coal and/or gas (IEA, 2012b). Carbon pricing could improve the

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[16] The subsequent % values in LCOE data refer to changes between the second quarter (Q2) of 2009 and the first quarter (Q1) of 2013 (BNEF and Frankfurt School-UNEP Centre, 2013). Although the IPCC SRREN was published in 2011, the cost data base used there refers to 2009.

competitiveness of nuclear power plants (NEA, 2011b). The post Fukushima assessment of the economics and future fate of nuclear power is mixed. According to the IEA, the economic performance and future prospects of nuclear power might be significantly affected (IEA, 2011a, 2012b). Joskow and Parsons (2012) assesses that the effect will be quite modest at the global level, albeit based on a pre-Fukushima baseline evolution which is a moderate one itself.

As there is still no commercial large-scale 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 (Yeh and Rubin, 2010; Rubin, 2012). CCS technologies applied in the power sector will only become competitive with unabated technologies if the additional equipment attached to the power plant and their decreased efficiency as well as the additional cost for CO_2 transport and storage is compensated by sufficiently high carbon prices or direct financial support (Lohwasser and Madlener, 2011; IEA, 2013b). BECCS faces large challenges in financing and currently no such plants have been built and tested at scale.

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 of transport and storage (excluding capture costs) are unlikely to exceed \$15/ton-CO_2 for the majority of CCS deployment scenarios (Herzog et al., 2005; Herzog, 2011; ZEP, 2011b) and some estimates are below \$5/ton-CO_2 (McCoy and Rubin, 2008; Dahowski et al., 2011). Figure 7.7 relies on an assumed cost of \$10/ton-CO_2.

System integration costs (cf. 7.6.1, and not included in Figure 7.7) typically increase with the level of deployment and are dependent on the mitigation technology and the state of the background energy system. From the available evidence, these costs appear to be greater for variable renewable technologies than they are for dispatchable power plants (Hirth, 2013). The costs comprise (1) balancing costs (originating from the required flexibility to maintain a balance between supply and demand), (2) capacity adequacy costs (due to the need to ensure operation even at peak times of the residual load), and (3) transmission and distribution costs.

(1) Based on assessments carried out for OECD countries, the provision of additional balancing reserves increases the system costs of wind energy by approximately \$1 to \$7 USD/MWh for wind energy market shares of up to approximately 30% of annual electricity demand (IEA, 2010e, 2011d; Wiser et al., 2011; Holttinen et al., 2011). Balancing costs for PV are in a similar range (Hoke and Komor, 2012).

(2) As described in 7.6.1, the contribution of variable renewables like wind, solar, and tidal energy to meeting peak demand is less than the resources’ nameplate capacity. Still, 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, 2010e, 2011d; Wiser et al., 2011). Because of the coincidence of solar generation with air conditioning loads, solar at low penetration levels can in some regions 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, 2010e, 2011d; 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.[17]

7.8.3 Economic potentials of mitigation measures

Quantifying the economic potential of major GHG mitigation options 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 Chapters 3.4.3 and 3.7.1 for a general discussion). Three major approaches to reveal the economic potentials of mitigation measures are discussed in the literature:

One approach is to use energy supply cost curves, which summarize energy resource estimates (GEA, 2012) 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 second and broader approach are marginal abatement cost (MAC) curves. MAC curves (discussed in chapter 3.9.3) discretely rank mitigation measures according to their (GHG) emission abatement cost (in US$/t$CO_2$) for a given amount of emission reduction (in million tCO_2). MAC curves have become a standard policy communication tool in assessing cost-effective emissions reductions (Kesicki and Ekins, 2011). There is wide heterogeneity (discussed in detail in Chapter 3.9.3) 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 (van Vuuren et al., 2004; IEA, 2008c; Clapp et al., 2009; Nauclér and Enkvist, 2009) give overall mitigation potentials ranging from 20% - 100% of the baseline for costs up to $100/t$CO_2$. MACS can be a useful summary mechanism but improved treatment of interactions between mitigation measures and the path-dependency of potential cost reductions due to technological learning (e.g., Luderer et al., 2012), as well as more sophisticated modelling of interactions throughout the energy systems and wider economy are required.

A third approach – utilised in the IPCC AR5 – overcomes these shortcomings through integrated assessment modeling exercises in order to calculate the economic potential of specific supply-side mitigation options. These models are able to determine the economic potential of single options within the context of (other) competing supply-side and demand-side mitigation options by taking their interaction and potential endogenous learning effects into account. The results obtained in this way are discussed in Chapter 6; the different deployment paths of various supply-side mitigation options as part of least-cost climate protection strategies are shown in section 7.11.

7.9 Co-benefits, risks and spillovers

Besides economic cost aspects, the final deployment of mitigation measures will depend on a variety of additional factors, including synergies and trade-offs across mitigation and other policy objectives. The implementation of mitigation policies and measures can have positive or negative effects on these other objectives – and vice versa. To the extent these side-effects are positive, they can be

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[17] 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; Thomson and Infield, 2007; Hernández et al., 2008; 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).

deemed ‘co-benefits’; if adverse and uncertain, they imply risks.[18] Co-benefits, adverse side effects, technical risks and uncertainties associated with alternative mitigation measures and their reliability (7.9.1-7.9.3) as well as public perception thereof (7.9.4) can affect investment decisions, individual behaviour as well as priority setting of policymakers. Table 7.3 provides an overview of the potential co-benefits and adverse side-effects of the main mitigation measures that are assessed in this chapter. In accordance with the three sustainable development pillars described in chapter 4, the table presents effects on objectives that may be economic, social, environmental and health related.

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[18] Co-benefits and adverse side-effects describe effects in non-monetary units without yet evaluating the net effect on overall social welfare. Please refer to the respective sections in the framing chapters as well as to the glossary in Annex I for concepts and definitions – particularly 2.4, 3.6.3, and 4.8. The extent to which co-benefits and adverse side-effects will materialize in practice as well as their net effect on social welfare 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 measures.

Table 7.3. Overview of potential co-benefits (green arrows) and adverse side-effects (orange arrows) of the main mitigation measures in the energy supply sector. Arrows pointing up/down denote positive/negative effect on the respective objective/concern; a question mark (**?**) denotes an uncertain net effect. Please refer to sections 11.7 and 11.13.6 for possible upstream effects of biomass supply on additional objectives. Co-benefits and adverse side-effects depend on local circumstances as well as on the implementation practice, pace and scale (see section 6.6). For an assessment of macroeconomic, cross-sectoral effects associated with mitigation policies (e.g., on energy prices, consumption, growth and trade), see Sections 3.9, 6.3.6, 13.2.2.3 and 14.4.2. Numbers correspond to references listed below table.

Mitigation measures	**Effect on additional objectives/concerns**			
	Economic	**Social**	**Environmental**	**Other**
Nuclear replacing coal power	↑ Energy security (reduced exposure to fuel price volatility)[1] ↑ Local employment impact (uncertain net effect)[2] ↑ Legacy cost of waste and abandoned reactors[3]	Health impact via ↓ Air pollution[4], coal mining accidents[5] ↑ Nuclear accidents[6] and waste treatment, U mining and milling[7] ↑ Safety and waste concerns[8]	Ecosystem impact via ↓ Air pollution[9], coal mining[10] ↑ Nuclear accidents[11]	Proliferation risk[12]
RE (Wind, PV, CSP, hydro, geothermal, bioenergy) replacing coal	↑ Energy security (resource sufficiency, diversity in the near/medium term)[13] ↑ Local employment impact (uncertain net effect)[14] ↑ Irrigation, flood control, navigation, water availability (for some hydro)[15] ↑ Extra measures to match demand (for PV, wind and some CSP)[16]	Health impact via ↓ Air pollution (except bioenergy)[17] ↓ Coal mining accidents[18] ↑ Contribution to (off-grid) energy access[19] ? Project-specific public acceptance concerns (e.g., visibility of wind)[20] ↑ Threat of displacement (large hydro)[21]	Ecosystem impact via ↓ Air pollution (except bioenergy)[22] ↓ Coal mining[23] ↑ Habitat impacts (for some hydro)[24] ↑ Landscape/wildlife impact (for wind)[25] ↓ Water use (for wind and PV)[26] ↑ Water use (for bioenergy, CSP, geothermal and reservoir hydro)[27]	Higher use of critical metals for PV, direct drive wind turbines[28]
Fossil CCS replacing coal	↑↑ Preservation vs lock-in of human and physical capital in the fossil industry[29]	Health impact via ↑ Risk of CO_2 leakage[30] ↑ Upstream supply-chain activities[31] ↑ Safety concerns (CO_2 storage and transport)[32]	↑ Ecosystem impact via upstream supply-chain activities[33] ↑ Water use[34]	Long-term monitoring of storage[35]
BECCS replacing coal	*See fossil CCS where applicable. For possible upstream effect of biomass supply, see sections 11.7 and 11.13.6*			
Methane leakage prevention, capture or treatment	↑ Energy security (potential to use gas in some cases)[36]	↑ Occupational safety at coal mines[37] ↑ Health impact via reduced air pollution[38]	↓ Ecosystem impact via reduced air pollution[39]	

Legend: [1]Adamantiades and Kessides (2009); Rogner (2010, 2012a; b). For the low share of fuel expenditures in LCOE, see IAEA (2008b) and Annex III. For the energy security effects of a general increase in nuclear power, see NEA, (2010) and Jewell , (2011a). [2]Cai et al., (2011); Wei et al., (2010); Kenley et al., (2009); McMillen et al., (2011). [3]Marra and Palmer, (2011); Greenberg, (2013a); Schwenk-Ferrero, (2013a); Skipperud et al., (2013); Tyler et al., (2013). [4]Smith and Haigler, (2008); Smith et al., (2012); Smith et al., (2013); Gohlke et al., (2011); Rückerl et al., (2011) and WGII 11.9 on health impacts from air pollution attributable to coal; Solli et al., (2006), Dones et al., (2007) Dones et al., (2005), Simons and Bauer, (2012) on air pollution attributable to nuclear; see section 7.9.2 for comparison.[5]See section 7.9.3 and references cited therein: Epstein et al., (2010); Burgherr et al., (2012); Chen et al., (2012); Chan and Griffiths, (2010); Asfaw et al., (2013). [6]See section 7.9.3, in particular Cardis et al., (2006); Balonov et al., (2011); Moomaw et al., (2011a); WHO (2013). [7]Abdelouas, (2006); Al-Zoughool and Kewski, (2009) cited in Sathaye et al. (2011a); Smith et al., (2013); Schnelzer et al., (2010); Tirmarche (2012); Brugge and Buchner, (2011). [8]Visschers and Siegrist, (2012); Greenberg (2013a); Kim et al., (2013); Visschers and Siegrist, (2012); see Section 7.9.4 and references cited therein: Bickerstaff et al.,(2008); Sjoberg and Drottz-Sjoberg, (2009); Corner et al., (2011); Ahearne, (2011). [9]Simons and Bauer, (2012) for comparison of nuclear and coal. See section 7.9.2 and references cited therein for ecological impacts of coal: Galloway et al., (2008); Doney, (2010); Hertwich et al., (2010); Rockstrom et al., (2009); van Grinsven et al., (2013) for eutrophication and acidification, Emberson et al., (2012); van Geothem et al., (2013) for photooxidants; IEA, (2011a); Pacyna et al., (2007) for increased metal emissions and Nagajyoti et al, (2010); Sevcikova et al., (2011); Mahboob, (2013) for the ecosystem effects of those emissions. [10]Adibee et al., (2013); Cormier et al., (2013); Smith et al., (2013) and reference cited therein: Palmer et al., (2010). [11]Møller et al., (2012); Hiyama et al., (2013); Mousseau and Moller, (2013); Møller and Mousseau (2011); Møller et al. (2011)[12]von Hippel et al., (2011, 2012); Sagan, (2011); Yim and Li, (2013); Adamantiades and Kessides (2009); Rogner (2010). [13]Sathaye et al., (2011), McCollum et al., (2013); Jewell et al., (2013); Cherp et al., (2013) [14]van der Zwaan et al. (2013); Cai et al. (2011); Lehr et al. (2012); Ruiz-Romero et al. (2012); Böhringer et al. (2013); Sathaye et al., (2011) and references cited therein, e.g. Frondel et al. (2010) and Barbier (2009). [15]For multipurpose use of reservoirs and regulated rivers, see (Kumar et al., 2011; Schaeffer et al., 2012); Smith et al. (2013); WCD (2000) and Moore et al. (2010), cited in Sathaye et al. (2011a). [16]IEA, (2011d), Williams et al., (2012); Sims et al., (2011); Holttinen et al., (2011); Rasmussen et al. (2012). [17]Sathaye et al., (2011); Smith, GEA, (2012), Smith et al. (2013), Fig. 7.8, Annex II and references cited therein. [18]Section 7.9.3, especially Moomaw et al., (2011a); Chen et al., (2012); Burgherr et al., (2012). [19]Pachauri et al., (2012); Sathaye et al., (2011); Kanagawa and Nakata, (2008); Bazilian et al., (2012); Sokona et al., (2012); Byrne et al., (2007); D'Agostino et al., (2011); Pachauri et al., (2012); Díaz et al., (2013); van der Vleuten et al., (2013); Nguyen, (2007); Narula et al., (2012), Sudhakara-Reddy et al., (2009). [20]Lovich and Ennen (2013); Sathaye et al. (2011); Wiser et al., (2011). [21]Bao (2010); Scudder (2005); Kumar et al., (2011); Sathaye et al. (2011a) and references citere therein: Richter et al. (2010); Smith et al. (2013) and references citere therein: Hwang et al. (2011), McDonald-Wilmsen and Webber (2010), Finley-Brook and Thomas (2010). [22]See section 7.9.2 and references cited therein for ecological impacts of coal: Galloway et al., (2008); Doney, (2010); Hertwich et al., (2010); Rockstrom et al., (2009); van Grinsven, (2013) for eutrophication and acidification, Emberson et al., (2012) and van Geothem et al., (2013) for photooxidants. See Arversen and Hertwich, (2011, 2012) for wind, Fthenakis et al., (2008) and Laleman et al., (2011) for PV, Becerralopez and Golding, (2007) and Moomaw et al., (2011b) for CSP, and Moomaw et al., (2011a) for a general comparison. [23]See footnote 10 on ecosystem impact from coal mining. [24]Kumar et al., (2011); Alho, (2011); Kunz et al.,(2011); Smith et al. (2013); Ziv et al. (2012). [25]Wiser et al. (2011), Lovich and Ennen, (2013); Garvin et al., (2011); Grodsky et al., (2011); Dahl et al., (2012); de Lucas et al., (2012) Dahl et al., ((Dahl et al., 2012)); Jain et al., (2011)[26]Pachauri et al., (2012); Fthenakis and Kim, (2010); Sathaye et al., (2011); Moomaw et al., (2011a); Meldrum et al., (2013). [27]Pachauri et al., (2012); Fthenakis and Kim, (2010); Sathaye et al., (2011); Moomaw et al., (2011a); Meldrum et al., (2013); Berndes, (2008); Pfister et al., (2011); Fingerman et al., (2011); Mekonnen and Hoekstra, (2012); Bayer et al., (2013a). [28]Section 7.9.2, Kleijn and van der Voet, (2010); (33) Graedel, (2011); Zuser and Rechberger, (2011); Fthenakis and Anctil, (2013); Ravikumar and Malghan, (2013); Pihl et al., (2012); Hoenderdaal et al., (2013). [29]Vergragt et al., (2011); Markusson et al., (2012); IPCC (2005), Benson et al., (2005); Fankhauser et al. (2008); Shackley and Thompson (2012). [30]Atchley et al., (2013)– simarly applicable to animal health; Apps et al. (2010); Siirila et al., (2012); Wang and Jaffe (2004). [31]Koorneef et al., (2011); Singh et al., (2011), Hertwich et al., (2008); Veltman et al., (2010); Corsten et al., (2013). [32]Ashworth et al., (2012); Einsiedel et al., (2013); IPCC, (2005); Miller et al., (2007); de Best-Waldhober et al., (2009); Shackley et al., (2009); Wong-Parodi and Ray, (2009); Waööquist et al., (2009, 2010); Reiner and Nuttall, (2011). [33]Koorneef et al., (2011); Singh et al., (2011); Hertwich et al., (2008); Veltman et al., (2010); Corsten et al., (2013). [34]Zhai et al., (2011); Koorneef et al., (2011); Sathaye et al. (2011), Moomaw et al., (2011a). [35]Haszeldine et al. (2009); Sauer et al. (2013), Kudryavtsev et al. (2012); Held and Edenhofer (2009). [36]Wilkinson, (2011), Song and Liu, (2012). [37]Karacan et al., (2011); Deng et al., (2013); Wang et al, (2012); Zhang et al. (2013); Cheng et al (2011). [38]IEA, (2009); Jerrett et al., (2009); Shindell et al., (2012); Smith et al. (2013) and references cited therein: Kim et al. (2013); Ito et al., (2005); Ji et al. (2011). [39]Van Dingenen et al., (2009); Shindell et al., (2012); van Goethem et al., (2013) Co-benefits, adverse side effects, technical risks and uncertainties associated with alternative mitigation measures and their reliability (7.9.1-7.9.3) as well as public perception thereof (7.9.4) can affect investment decisions, individual behaviour as well as priority setting of policymakers. **Table 7.3** provides an overview of the potential co-benefits and adverse side-effects of the main mitigation measures that are assessed in this chapter. In accordance with the three sustainable development pillars described in chapter 4, the table presents effects on objectives that may be economic, social, environmental and health related.

7.9.1 Socio-economic effects

There is an increasing body of work showing that the implementation of energy mitigation options can lead to a range of socio-economic co-benefits for, e.g., employment, energy security, and better access to energy services in rural areas (Shrestha and Pradhan, 2010; IPCC, 2011a; UNEP, 2011).

Employment. Analysis by Cai et al. (2011) shows that as a result of the increased share of renewable energy in China, the power sector registered 472,000 net job gains in 2010. For the same amount of power generated, solar PV requires as many as 18 and 7 times more jobs than nuclear and wind, respectively. Using conservative assumptions on local content of manufacturing activities, van der Zwaan et al. (2013) show that renewable sources of power generation could account for about 155,000 direct and 115,000 indirect jobs in the Middle East by 2050. Examples of Germany and Spain are also noteworthy where 500 to 600 thousand people could be employed in the renewable energy supply sector in each country by 2030 (Lehr et al., 2012; Ruiz-Romero et al., 2012) while the net effect is less clear. Wei et al. (2010) also found that over 4 million full-time jobs could be created by 2030 from the combined effect of implementing aggressive energy efficiency measures coupled with meeting a 30% renewable energy target. An additional 500,000 jobs could be generated by while increasing the share of nuclear power to 25% and CCS to 10% of overall total generation capacity. In line with these trends, Kenley et al. (2009) show that adding 50,000 megawatts by 2020 of new nuclear generating capacity in the US would lead to 117,000 new jobs, 250,000 indirect jobs and an additional 242,000 non-nuclear induced jobs. Relating to CCS, although development in this sector could deliver additional employment (Yuan and Lyon, 2012; Bezdek and Wendling, 2013), safeguarding jobs in the fossil-based industry is expected to be the main employment co-benefit (Frankhauser et al., 2008). Whilst recognizing the growing contribution of mitigation options for employment, some sobering studies have highlighted that this potentially carries a high cost. In the PV sector in Germany for example, the cost per job created can be as high as $257,400 [€175,000 in 2008] (Frondel et al., 2010), underlining that continued employment and welfare gains will remain dependent on the level and availability of support and financing mechanisms (Alvarez et al., 2010; Furchtgott-Roth, 2012; Böhringer et al., 2013). Furthermore, given the higher cost of electricity generation from RE and CCS-based fossil fuels, at least in the short-term, jobs in energy intensive economic sectors are expected to be affected (Delina and Diesendorf, 2013). The structure of the economy and wage levels will nonetheless influence the extent of industry restructuring and its impact of labour redeployment.

Energy security. As discussed in Section 6.6.2.2, energy security can generally be understood as "low vulnerability of vital energy systems" (Cherp et al., 2012). Energy security concerns can be grouped as 1) the sufficiency of resources to meet national energy demand at competitive and stable prices and 2) the resilience of the energy supply.[19] Since vital energy systems and their vulnerabilities differ from one country to another, the concept of energy security also differs between countries (Chester, 2009; Cherp and Jewell, 2011; Winzer, 2012). Countries with a high share of energy imports in total imports (or export earnings) are relatively more vulnerable to price fluctuations and historically have

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[19] These dimensions are roughly in line with the treatment of energy security in the SRREN albeit with terminology based on recent literature– along the lines of the *sovereignty* and *robustness* perspectives on the one hand and *resilience* on the other described by Cherp and Jewell (2011). It is also very similar to the IEA's distinction between energy system *risks* and *resilience capacities* (IEA, 2011a; Jewell, 2011b).

focused on curtailing energy imports (GNESD, 2010; Jain, 2010; Sathaye et al., 2011), but more recently also building the resilience of energy supply (IEA, 2011a; Jewell, 2011b). For energy importers, climate policies can increase the sufficiency of national energy demand by decreasing imports and energy intensity while at the same time increasing the domestic resource buffer and the diversity of energy supply (Turton and Barreto, 2006; Costantini et al., 2007; Kruyt et al., 2009; Jewell et al., 2013; McCollum, Krey, et al., 2013). Energy exporting countries are similarly interested in stable and competitive global prices but they have the opposite interest of maintaining or increasing energy export revenues (Sathaye et al., 2011; Cherp and Jewell, 2011). There is uncertainty over how climate policies would impact energy export revenues and volumes as discussed in 6.3.6.6. One of the biggest energy security issues facing developing countries is the necessity to dramatically expand energy systems to support economic growth and development (Kuik et al., 2011; Cherp et al., 2012), which makes energy security in low and middle income countries closely related to the energy access challenge, discussed in the next paragraphs and in Section 6.6.2.3.

Rural development. In various developing countries such as India, Nepal, Brazil, and parts of Africa, especially in remote and rural areas, some renewables are already cost-competitive options for increasing energy access (Nguyen, 2007; Goldemberg et al., 2008; Cherian, 2009; Sudhakara Reddy et al., 2009; Walter et al., 2011; Narula et al., 2012). 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; Sokona, Y. et al., 2012; Pachauri et al., 2013) are some of the important co-benefits of some mitigation options. However, the co-benefits may not be evenly distributed within countries and local jurisdictions. While there is a regressive impact of higher energy prices in developed countries (Grainger and Kolstad, 2010), the empirical evidence is more mixed for developing countries (Jakob and Steckel, 2013). The impact depends on the type of fuel used by different income groups, the redistribution of the revenues through, e.g., a carbon tax, and in what way pro-poor measures are able to mitigate adverse effects (Casillas and Kammen, 2010). Hence, regulators need to pay attention that the distributive impacts of higher prices for low carbon electricity (fuel) do not become a burden on low income rural households (Rao, 2013). The success of energy access programmes will be measured against affordability and reliability criteria for the poor.

Other positive spill-over effects from implementation of renewable energy options include technology trade and knowledge transfer (see Chapter 13), reduction in the exposure of a regional economy to the volatility of the price of fossil fuels (Magnani and Vaona, 2013; see Chapter 14), and enhanced livelihoods conditions at the household level (Cooke et al., 2008; Oparoacha and Dutta, 2011).

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

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 lacked access to electricity in 2009, compared to 28% average in the developing countries (WHO and UNDP, 2009). About 71% of people in LDCs relied exclusively on biomass burning for cooking in 2009. 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). LDCs from sub-Saharan Africa and parts of Asia, with limited access to fossil-based electricity (and heat), would need to explore a variety of appropriate sustainable technologies to fuel their development goals (Guruswamy, 2011). In addition to deploying fossil-based and renewable technologies, improved biomass cooking from biogas and sustainably produced wood for charcoal will remain essential in LDCs (Guruswamy, 2011).

Bioenergy production from unsustainable biomass harvesting, for direct combustion and charcoal production is commonly practiced in most LDCs. The net GHG emissions from these practices is significant (FAO, 2011), and rapid urbanization trends is likely to intensify harvesting for wood, contributing further to rises in GHG emissions, along with other localized environmental impacts. However, important initiatives from multilateral organizations and from the private sector with innovative business models are improving agricultural productivity for food and creating bioenergy development opportunities. One example produces liquid biofuels for stove cooking while creating, near cities, agroforestry zones with rows of fast-growing leguminous trees/shrubs and alleys planted with annual crop rotations, surrounded by a forestry shelterbelt zone that contains indigenous trees and oilseed trees and provides business opportunities across the value chain including for women (WWF-UK, 2011). The mixture of crops and trees, produces food with higher nutritive values, enable clean biofuels production for stove cooking, develops businesses and simultaneously avoids GHG emissions from deforestation to produce charcoal for cooking (Zvinavashe et al., 2011). A dearth of documented information and a lack of integration of outcomes of the many successful specific projects that show improved management practices of so called traditional forest biomass resource into sustainably managed forest propagate the impression that all traditional biomass is unsustainable. As more data emerge the record will be clarified. 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 with the potential to reduce future GHG emissions are currently being promoted (see Box 11.6). Other co-benefits associated with these programmes include reduced burden of fuel collection, employment, and improved health conditions of the end-users (Reddy et al., 2000; Lambrou and Piana, 2006; Hutton et al., 2007; Anenberg et al., 2013; Owen et al., 2013). The LDC contribution to climate stabilization requires minimizing future GHG emissions while meeting unmet (or suppressed) energy demand, which is likely to rise. For example, though emissions levels remain low, 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). Whilst growth in GHG emissions is expected as countries build their industrial base and consumption moved beyond meeting basic needs, minimizing this trend will involve exploring new opportunities for scaling up modern energy access where possible by embracing cleaner and more efficient energy options that are consistent with regional and global sustainability goals. One such opportunity is the avoidance of associated natural gas flaring in oil and gas producing developing countries where venting and flaring amounts to 69% of world total of 150 billion cubic metres – representing 1.2% of global CO_2 emissions (Farina, 2011; GGFR and World Bank, 2011). For a country such as Nigeria, which flares about 15 billion m^3 of gas – sufficient to meet its energy needs along with the current needs of many neighbouring countries (Dung et al., 2008), this represents an opportunity towards a low carbon pathway (Hassan and Kouhy, 2013). Collier and Venables (2012) argue that while abundant natural endowments in renewable and fossil resources in Africa and other LDCs should create opportunities for green energy development, energy sourcing, conversion, distribution and usage are economic activities that require the fulfilment of factors such as capital, governance capacity and skills (see Box 1.1).

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 7.3). Renewable energies are often seen as environmentally benign by nature. 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 environmental and health problems, assessments of mitigation technologies need to address a wide range of issues, such as land and water use, as well as air, water and soil pollution, which are often location specific. Whilst information is scarce and often difficult to generalise, trade-offs among the different types of impacts, affecting different species and at different times, become important in carrying out the assessments (Sathaye et al., 2011). Also, the analysis has to go beyond marginal changes (see section 3.6.3) in the existing system to address alternative futures. Environmental and health implications of different low carbon technologies as they are understood today are briefly discussed below.

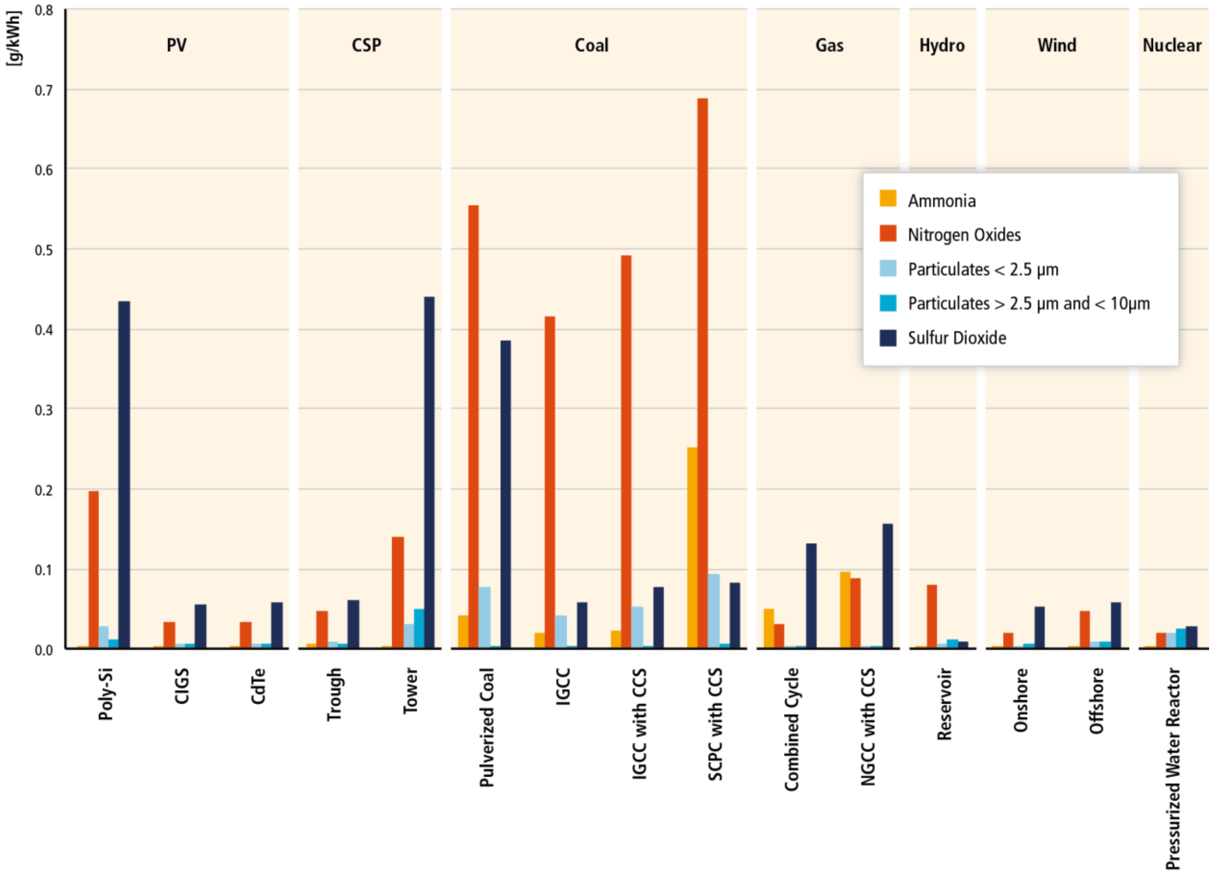

Figure 7.8. Life cycle inventory results of the production of 1 kWh of electricity for important air pollutants contributing to particulate matter (PM) exposure, the leading cause of health impact from air pollution. The technology modelling considers state-of-the-art pollution control equipment for fossil power plants. Data sources: Arvesen and Hertwich **(2011)**; Burkhardt et al., **(2011)**; Whitaker **(2013)**, Dones et al. **(2005)**; Singh et al. **(2011)**. Abbreviations: PV – photovoltaic, CSP – concentrating solar power, Poly-Si – polycrystalline silicon, CIGS – copper indium gallium selenide thin film, CdTe – cadmium telluride thin film, IGCC – integrated gasification combined cycle, CCS – CO_2 capture and storage, SCPC – supercritical pulverized coal, NGCC – Natural gas combined cycle.

Combustion-related emissions cause substantial human health and ecological impacts. Exposure to outdoor particulate matter emitted directly or formed from products of incomplete combustion, i.e. sulphur and nitrogen oxides and ammonia, lead to cardiovascular disease, chronic and acute respiratory illness, lung cancer and other health damages, causing in the order of 3.2 million premature deaths per year (Pope et al., 2009; Lim et al., 2012; Smith, Balakrishnan, et al., 2012). Despite air pollution policies, the exposure to ambient air pollution of 80% of the world’s population is estimated to exceed the WHO recommendation of 10 µg/m3 for PM2.5 (Brauer et al., 2012; Rao et al., 2013).[20] Sulphur and nitrogen oxides are involved in the acidification of fresh water and soils; and nitrogen oxides in the eutrophication of water bodies (Galloway et al., 2008; Doney, 2010), both

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[20] See WGII 11.9 (Smith et al., 2014) and Chapter 4 of the Global Energy Assessment “Energy and Health” (Smith et al., 2012) for a recent overview of human health effects associated with air pollution.

threatening biodiversity (Rockstrom et al., 2009; Hertwich et al., 2010; van Grinsven et al., 2013). Volatile organic compounds and nitrogen oxides cause the formation of photochemical oxidants (summer smog), which impact human health (Lim et al., 2012) and ecosystems (Emberson et al., 2012; van Goethem et al., 2013).[21] Coal is an important source of mercury (IEA, 2011a) and other toxic metals (Pacyna et al., 2007), harming ecosystems (Nagajyoti et al., 2010; Sevcikova et al., 2011; Mahboob, 2013) and potentially also human health (van der Voet et al., 2012; Tchounwou et al., 2012). Many of these pollutants can be significantly reduced through various types of pollution control equipment, but even with this equipment in place, some amount of pollution remains. In addition, surface mining of coal and tar sand causes substantial land use and mining waste (Yeh et al., 2010; Elliott Campbell et al., 2012; Jordaan, 2012).

Reducing fossil fuel combustion, especially coal combustion, can reduce many forms of pollution and may thus yield co-benefits for health and ecosystems. Figure 7.8 indicates that most renewable power projects offer a reduction of emissions contributing to particulate matter exposure even compared to modern fossil fuel fired power plants with state-of-the-art pollution control equipment.

Ecological and health impacts of renewable energy have been comprehensively assessed in the SRREN, which also provides a review of life cycle assessments of nuclear and fossil-based power generation (Sathaye et al., 2011). 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 that of fossil fuel based systems (Sathaye et al., 2011). For wind power plants, collisions with raptors and 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; de Lucas et al., 2012). For hydropower plants, dams present an obstacle to migratory species (Alho, 2011; Ziv et al., 2012). The large-scale modification of river flow regimes affects the amount and timing of water release, reduces seasonal flooding, and sediment and nutrient transport to flood plains (Kunz et al., 2011). These modifications result in a change of habitat of species adapted to seasonal flooding or living on flood plains (Young et al., 2011). Geothermal (Bayer et al., 2013b) and concentrating solar power (Damerau et al., 2011) can cause potential concerns about water use/pollution, depending on design and technological choices.

Wind, ocean and concentrating solar power need more iron and cement than fossil fuel fired power plants, while photovoltaic power relies on a range of scarce materials (Burkhardt et al., 2011; Graedel, 2011; Kleijn et al., 2011; Arvesen and Hertwich, 2011). Furthermore, mining and material processing is associated with environmental impacts (Norgate et al., 2007) which make a substantial contribution to the total life cycle impacts of renewable power systems. There has been a significant concern about the availability of critical metals and the environmental impacts associated with their production. Silver, tellurium, indium and gallium have been identified as metals potentially constraining the choice of PV technology, but not presenting a fundamental obstacle to PV deployment (Graedel, 2011; Zuser and Rechberger, 2011; Fthenakis and Anctil, 2013; Ravikumar and Malghan, 2013). Silver is also a concern for CSP (Pihl et al., 2012). The limited availability of rare earth elements used to construct powerful permanent magnets, especially dysprosium and neodymium, may limit the application of efficient direct drive wind turbines (Hoenderdaal et al., 2013). Recycling is necessary to ensure the long-term supply of critical metals and may also reduce environmental impacts compared to virgin materials (Anctil and Fthenakis, 2013; Binnemans et al., 2013). With improvements in the performance of renewable energy systems in recent years, their specific material demand and environmental impacts have also declined (Arvesen and Hertwich, 2011; Caduff et al., 2012).

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[21] See Chapter 3 of the Global Energy Assessment “Energy and Environment” (Emberson et al., 2012) for a recent overview of environmental effects associated with air pollution.

While reducing atmospheric GHG emissions from power 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. This is likely to increase the pressure 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 considered to be lower than the ecological and human health impacts avoided through reduced climate change (Singh et al., 2012). Uncertainties and risks associated with long-term storage also have to be considered (Chapter 7.5.5 and 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.

The handling of radioactive material[22] poses a continuous challenge to the operation of nuclear fuel chain and leads to releases of radionuclides. The most significant routine emissions of radionuclides occurs during fuel processing and mining (Simons and Bauer, 2012). The legacy of abandoned mines, sites, and waste storage causes some concerns (Marra and Palmer, 2011; Greenberg, 2013b; Schwenk-Ferrero, 2013b; Skipperud et al., 2013; Tyler, Dale, Copplestone, Bradley, Ewen, McGuire, and EM Scott, 2013). Epidemiological studies indicate an increase in childhood leukemia of populations living within 5 km of a nuclear power plant in a minority of sites studied (Kaatsch et al., 2008; Raaschou-Nielsen et al., 2008; Laurier et al., 2008; Heinävaara et al., 2010; Spycher et al., 2011; Koerblein and Fairlie, 2012; Sermage-Faure et al., 2012), so that the significance of a potential effect is not resolved (Fairlie and Körblein, 2010; Laurier et al., 2010).

Thermal power plants with high cooling loads and hydropower reservoirs lead to reduced surface water flows through increased evaporation (Bates et al., 2008; Dai, 2011), which can adversely affect the biodiversity of rivers (Hanafiah et al., 2011) and wetlands (Amores et al., 2013; Verones et al., 2013).

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, and well-designed low carbon electricity supply outperforms fossil-based systems on most indicators. In this context it should be noted that the environmental performance of fossil-based technologies are expected to decline with increasing use of unconventional resources with their associated adverse environmental impacts of extraction (Jordaan et al., 2009; Yeh et al., 2010).

7.9.3 Technical risks

Within the context of sustainable development, a comprehensive assessment of energy supply and GHG mitigation options has to take into account technical risks, especially those related to accidents risks. In the event of accidents, fatality and injury may occur among workers and residents. Evacuation and resettlements of residents may also take place. This section therefore updates the risk assessment presented in chapter 9 of the IPCC SRREN report (IPCC, 2011a). “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).” (IPCC, 2011a), p. 745. An analysis of the fatalities caused by large accidents (≥5 fatalities or ≥10 injured or ≥200 evacuated) recorded in the Energy-Related Severe Accident Database (ENSAD) (Burgherr et al., 2011), as presented in SRREN, allows for a comparison of the potential impacts. The analysis in SRREN included accidents in the fuel chain, such as coal mining and oil shipping, 1970-2008.

SRREN indicates high fatality rates (>20 fatalities per PWh[23]) associated with coal, oil and hydro power in non-OECD countries and low fatalities (<2 fatalities per PWh) associated with renewable

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[22] Accidents are addressed in 7.9.3.

[23] The global electricity production in 2008 was 17 PWh.

and nuclear power in OECD countries (Figure 9.12 in Sathaye et al., 2011). Coal and oil power in OECD countries and gas power everywhere were associated with impacts on the order of 10 fatalities per PWh.

Coal mining accidents in China were identified to have contributed to 25,000 of the historical total of 33,000 fatalities in severe accidents from 1970-2008 (Epstein et al., 2010; Burgherr et al., 2012). New analysis indicates that the accident rate in Chinese coal mining has been reduced substantially, from 5670 deaths in 2001 to 1400 in 2010, or from 5.1 to 0.76 fatalities per Mt coal produced (Chen et al., 2012). The majority of these fatalities is apparently associated with smaller accidents not covered in the ENSAD database. In China, accident rates in smaller coal mines are higher than those in larger mines (Chan and Griffiths, 2010), and in the United States, less profitable mines have higher rates than more profitable ones (Asfaw et al., 2013). A wide range of research into underlying causes of accidents and measures to prevent future accidents is currently under way.

For oil and gas, fatalities related to severe accidents at the transport and distribution stage are a major component of the accident related external costs. Over 22,000 fatalities in severe accidents for the oil chain were reported, 4000 for LPG, and 2,800 for the natural gas chain (Burgherr et al., 2011, 2012). Shipping and road transport of fuels are associated with the highest number of fatalities, and accident rates in non-OECD countries are higher than those in OECD countries (Eckle and Burgherr, 2013).

For hydropower, a single event, the 1975 Banqiao/Shimantan dam failure in China, accounted for 26,000 immediate fatalities. Remaining fatalities from large hydro power accidents amount to nearly 4000, but only 14 were recorded in OECD countries (Moomaw, Burgherr, et al., 2011a; Sathaye et al., 2011).

Severe nuclear accidents have occurred at Three Mile Island (1979), Chernobyl (1986), and Fukushima (2011). For Three Mile Island no fatality or injuries were reported. For Chernobyl, 31 immediate fatalities and injury to 370 persons occurred (Moomaw, Burgherr, et al., 2011a). Chernobyl resulted in high emissions of I131 which has caused measureable increases of thyroid cancer in the surrounding areas (Cardis et al., 2006). UNSCEAR identified 6000 thyroid cases in individuals who were below 18 at the time of the accident, 15 of which had resulted in mortalities (Balonov et al., 2011). A significant fraction of these are above the background rate. Epidemiological evidence for other cancer effects does not exist; published risk estimates often assume a linear no-threshold dose-response relationship, which is controversial (Tubiana et al., 2009). Between 14,000 and 130,000 cancer cases may potentially result (Cardis et al., 2006), and up to 9,000 potential fatalities in the Ukraine, Belarus and Russia in the 70 years after the accident (Hirschberg et al., 1998). The potential radiation-induced increase in cancer incidence in a population of 500 million would be too low to be detected by an epidemiological study and such estimates are neither endorsed nor disputed by UNSCEAR (Balonov et al., 2011). Adverse effects on other species have been reported within the 30km exclusion zone ller(Alexakhin et al., 2007; Møller et al., 2012; Geras'kin et al., 2013; Mousseau and Møller, 2013).

The Fukushima accident resulted in much lower radiation exposure. Some 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 Jacobson, 2012). The WHO does not estimate cancer incidence from low-dose population exposure, but identifies the highest lifetime attributable risk to be thyroid cancer in girls exposed during infancy in the Fukushima prefecture, with an increase of a maximum of 70% above relatively low background rates. In the highest exposed locations, leukemia in boys may increase by 5% above background, and breast cancer in girls by 4% (WHO, 2013).

Design improvements for nuclear reactors have resulted in so-called Generation III+ designs with simplified and standardized instrumentation, strengthened containments and “passive” safety designs seeking to provide emergency cooling even when power is lost for days. Nuclear power reactor designs incorporating a 'defence-in-depth' approach possess multiple safety systems including 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).

The fatality rates of non-hydro renewable energy technologies are lower than those of fossil chains, and are comparable to hydro and nuclear power in developed countries. Their decentralized nature limits their capacity to have catastrophic impacts.

As indicated by the IPCC SRREN report, accidents can result in the contamination of large land and water areas with radionucleids or hydrocarbons. The accidental releases of crude oil and its refined products into the maritime environment has been substantially reduced since the 1970s through to technical measures, international conventions, national legislations, and increased financial liabilities (see e.g. Kontovas et al., 2010; IPCC, 2011a; Sathaye et al., 2011). Still, oil spills are common and can affect both marine and freshwater resources (Jernelöv, 2010; Rogowska and Namiesnik, 2010). Furthermore, increased drilling in deep offshore waters (e.g., Gulf of Mexico, Brazil) and extreme environments (e.g., the Arctic) poses a risk of potentially high environmental and economic impacts (Peterson et al., 2012; Moreno et al., 2013; Paul et al., 2013). Leakage of chemicals used in hydraulic fracturing during shale gas and geothermal operations can potentially contaminate local water flows and reservoirs (Aksoy et al., 2009; Kargbo et al., 2010; Jackson et al., 2013). Further research is needed to investigate a range of yet poorly understood risks and risk factors, such as CCS storage (cf. section 7.5.5 and 7.9.4). Risks of CO_2 transport are discussed in 7.6.4.

7.9.4 Public perception[24]

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 (Sathaye et al., 2011). 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., Kumar et al., 2011). For wind energy, concerns primarily relate to visibility and landscape impacts 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), and 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, anxieties often focus on health and safety (e.g., accidents, disposal of wastes, decommissioning) and proliferation (e.g., terrorism, civil unrest). Further, perceptions are dependent on how the debate around 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; Visschers and Siegrist, 2012; Greenberg, 2013b; Kim et al., 2013).

Among CCS technologies, early[25] misgivings include the ecological impacts associated with different storage media, the potential for accidental release and related storage effectiveness of stored CO_2, and the perception that CCS technologies do not prevent all of the non-GHG social and environmental impacts of fossil energy sources (e.g., IPCC, 2005; Miller et al., 2007; de Best-

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[24] 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.

[25] Knowledge about the social acceptability of CCS is limited due to the early state of the technologies' deployment, though early research has deepened our understanding of the issues related to CCS significantly (de Best-Waldhober et al., 2009; Malone et al., 2010; Ter Mors et al., 2010; Corry and Reiner, 2011).

Waldhober et al., 2009; Shackley et al., 2009; Wong-Parodi and Ray, 2009; Wallquist et al., 2009, 2010; Reiner and Nuttall, 2011; Ashworth et al., 2012; Einsiedel et al., 2013). For natural gas, the recent increase in the use of unconventional extraction methods, such as hydraulic 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., Ashworth et al. 2010; Fleishman, De Bruin, and Morgan 2010; Mitchell et al. 2011; Terwel et al. 2010).

7.10 Barriers and opportunities

7.10.1 Technical aspects

From a global perspective, the large number of different technologies that are available to mitigate climate change (7.5.) facilitates the achievement of prescribed climate protection goals. Given that many different combinations of the mitigation technologies are often feasible, least-cost portfolios can be determined that select those options which interact in the best possible way (Chapter 6, 7.11). On a local scale and/or concerning specific technologies, however, technological barriers might constrain their mitigation potential. These limits are discussed in Section 7.4, 7.5, 7.6 and 7.9.

7.10.2 Financial and investment barriers and opportunities

The total global investment in the energy supply sector in 2010 is estimated to be USD 1,076 to 1,350 billion per year, of which 43 to 48% is invested in the power sector and 37 to 50% is invested in fossil extraction. In the power sector, 49 to 55% of the investments is used for power generation and 45 to 51% is used for transmission and distribution (see Chapter 16.2.2).

The total investment in renewables excluding hydropower in 2012 was $244 billion, which was six times the level in 2004. Out of this total, $140 billion was for solar and $80 billion for wind power. The total was down 12% from a record $279 billion in 2011 in part due to changes in support policies and also due to sharp reductions in renewable energy technology costs. Total investment in developed countries fell 29% in 2012 to $132 billion, while investment in developing countries rose 19% to 112 billion. The investment in renewables is smaller than gross investment on fossil-fuel plants (including replacement plant) at $262 billion, but much larger than net investment in fossil-fuel technologies, at $148 billion. The amount of installed capacity of renewables excluding hydropower was 85GW, up from 2011's 80GW (BNEF and Frankfurt School-UNEP Centre, 2013; REN21, 2013).

Additional investments required in the energy supply sector by 2050 are estimated to be USD 190 billion to USD 900 billion per year in order to limit the temperature increase below 2°C (about 0.30% to 1.4% of world GDP in 2010) (GEA, 2012; IEA, 2012h; Kainuma et al., 2013). The additional investment costs from both supply- and demand- sides are estimated to about USD 800 billion per year according to McCollum et al. (in press). With a greater anticipated increase in energy demands, developing countries are expected to require more investments than the developed countries (see also Chapter 6 and Chapter 16).

Investment needs in the 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 USD 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 as well as those due to energy efficiency improvements in the end-use sectors (IEA, 2012h).

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; RE quotas, and RE rendering/bidding schemes; carbon offset markets; removal of fossil fuel subsidies and private–public initiatives aimed at lowering barriers for investors – are currently being implemented (see Section 7.12, Chapter 13, 14 and 15.2), and still more measures may be needed to achieve low GHG stabilization scenarios. Uncertainty in policies is also a barrier to investment in low-GHG energy supply sources (United Nations, 2010; World Bank, 2011b; IEA, 2012h; IRENA, 2012a; BNEF and Frankfurt School-UNEP Centre, 2013).

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 (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 infrastructure investment, is also important (World Economic Forum, 2011; IRENA, 2012a; Sudo, 2013).

Rural areas in LDCs are often characterized by a very low population densities and income levels. Even with the significant decline in the price of PV systems, investment cost barriers are often substantial in these areas (IPCC, 2011b). Micro finance mechanisms (grants, concessional loans) adapted to the pattern of rural activities (for instance, instalments correlated with income from agriculture) may be necessary to lift rural populations out of the energy poverty trap and increase the deployment of low carbon energy technologies in these areas (Rao et al., 2009; Bazilian et al., 2012; IRENA, 2012c).

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 and improved energy efficiency will pose a series of challenges and opportunities particularly in the case of poor countries. Depending on the regions and the development, barriers and opportunities may differ dramatically.

Taking the example in the US, Sovacool (2009) points to significant social and cultural barriers facing renewable power systems as policymakers continue to frame electricity generation as a mere technical challenge. He argues that in the absence of a wider public discourse around energy systems and challenging entrenched values about perceived entitlements to cheap and abundant forms of electricity, renewable energy and energy efficiency programmes will continue to face public acceptability problems. 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 (Sathaye et al., 2011). Legal regulations and procedures are also impacting on the deployment of nuclear energy, CCS, shale gas, and renewable energy. However, the fundamental reasons (environment, health, and safety) may differ according to the different types of energy. The underlying risks are discussed in 7.5 and 7.9 and enabling policies to address them in 7.12.

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. In addition, in many slums there is a culture of non-payment of the bills (UN Habitat and GENUS, 2009). Orthodox electrification approaches appear to be inefficient in the context of urban slums. Adopting a holistic approach encompassing cultural, institutional and legal issues in the formulation 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 and theft. As a result prepayment was successfully implemented as it gives 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 energy-related CO_2 emissions reduction targets (IRENA, 2012d). Human capacity is critical in providing a sustainable enabling environment for technology transfer in both the host and recipient countries (Barker et al., 2007; Halsnæs et al., 2007). Human workforce development has thus been identified as an important near-term priority (IEA, 2010c).

There is increasing concern in the energy supply sector in many countries that the current educational system is not producing sufficient qualified workers to fill current and future jobs, which increasingly require science, technology, engineering, and mathematics (STEM) skills. This is true not only in the booming oil and gas and traditional power industries, but also in the rapidly expanding renewable energy supply sector (NAS, 2013b). Skilled workforce in the areas of renewable energy and decentralized energy systems, which form an important part of “green jobs” (Strietska-Ilina et al., 2011), requires different skill sets for different technologies and local context, and hence requires specific training (Moomaw, Yamba, 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 (UNEP, 2011), where shortages of teachers and trainers in subjects related to the fast-growing renewable energy supply sector have been reported (Strietska-Ilina et al., 2011) (ILO and EU, 2011). Well-qualified workers will also be required on other low-carbon energy technologies, particularly nuclear and CCS - should there be large-scale implementation (Creutzig and Kammen, 2011; NAS, 2013b).

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 (Mitchell et al., 2011; Jagger et al., 2013).

To avoid future skill shortages, countries will need to formulate short and long-term capacity 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). But producing a skilled workforce with the right skills at the right time requires additional or alternatives to conventional approaches. These include but are not limited to: increased industry-education-government partnership, particularly with industry organizations, in job demand forecasting, designing education and training curricula, topping-up available skills with specific skills, and adding energy supply sector experience in education and training (Strietska-Ilina et al., 2011; NAS, 2013b).

7.10.5 Inertia in energy systems physical capital stock turnover

The long life of capital stock in energy supply systems (discussed in detail in section 5.6.3) gives the possibility of path dependant carbon lock-in (Unruh, 2002). The largest contribution to GHG emissions from existing high carbon energy capital stock is in the global electricity sector which is also characterised by long-lived facilities – with historical plant lifetimes for coal, natural gas, and oil plant of 38.6, 35.8, and 33.8 years respectively (Davis et al., 2010). Of the 1549 GW investments (from 2000-2010) in the global electricity sector (EIA, 2011), 516 GW (33.3%) were coal and 482 GW (31.1%) were natural gas. Only 34 GW (2.2%) were nuclear investments, with combined renewable source power plants at 317 GW (20.5%). The investment share for renewable energy power plants accelerated towards the end of the decade. The transport, industrial, commercial and residential sectors generally have smaller technology sizes, shorter lifetimes and limited plant level data for directly emitting GHG facilities. However in combination contribute over half of the GHG emissions from existing primary energy capital stock (Davis et al., 2010).

Long-lived 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 generally expensive. Examples include low natural gas prices in the US due to shale gas production making existing coal plants uneconomic to run, or merit order consequences of new renewable plant which endanger the economic viability of dispatchable fossil fuel power plants in some European countries under current market conditions (IEA, 2013a). 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 extremely little 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 potentiale opportunities to develop a low carbon energy system, and hence reduce the effective carbon lock-in from broader energy infrastructures (e.g., oil refineries, industrial heat provision, transport networks) (Guivarch and Hallegatte, 2011), or the very long lived capital stock embodied in buildings and urban patterns (Jaccard and Rivers, 2007).

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 in order to achieve emissions reductions compatible with a range of long-term climate targets. Aggregated energy-related emissions, discussed in this section, comprise the full energy system, including energy sourcing, conversion, transmission, as well as the supply of energy carries to and their use in the end-use sectors.

Aggregated energy-related emissions are further split into emissions from electricity generation and the rest of the energy system.[26,27]

This section builds upon more than 1200 emissions scenarios, which were collated by Chapter 6 in the AR5 scenario database (Section 6.2.2). The scenarios were grouped into baseline and mitigation scenarios. As described in more detail in Section 6.3.2, the scenarios are further categorized into bins based on 2100 concentrations: between 430- 480 ppm CO2e, 480-530 ppm CO2e, 530-580 ppm CO2e, 580-650 ppm CO2e, 650-720 ppm CO2e, and >720 ppm CO2e by 2100. An assessment of geo-physical climate uncertainties consistent with the dynamics of Earth System Models assessed in WGI found that the most stringent of these scenarios – leading to 2100 concentrations between 430 and 480 ppmv CO2e – would lead to an end-of-century median temperature change between 1.6 to 1.8°C compared to pre-industrial times, although uncertainties in understanding of the climate system mean that the possible temperature range is much wider than this range. They were found to maintain temperature change below 2°C over the course of the century with a likely chance. Scenarios in the concentration category of 650-720 ppm CO2e correspond to comparatively modest mitigation efforts, and were found to lead to median temperature rise of approximately 2.6-2.9°C in 2100 (see Section 6.3.2 for details).

7.11.1 Energy-related greenhouse gas emissions

In absence of climate change mitigation policies,[28] energy-related CO_2 emissions are expected to continue to increase from current levels to about 55-70 $GtCO_2$ by 2050 (25th-75th percentile of the scenarios in the AR5 Scenario Database, see Figure 7.9).[29] This corresponds to an increase of between 80% and 130% compared to emissions of about 30 GtCO2 in the year 2010. By the end of the 21st century emissions could grow further, the 75th percentile of scenarios reaching about 90 $GtCO_2$.[30,31]

The stabilization of GHG concentrations requires fundamental change in the global energy system relative to a baseline scenario. 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 the majority of the scenarios compatible with a long-term concentration goal of below 480 ppm CO_2e, energy-related emissions peak between 2020 and 2030, and decline to about 10-15 $GtCO_2$ by 2050 (Figure 7.9). 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).

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[26] Note that the other sections in Chapter 7 are focusing on the *energy supply sector*, which comprises only energy **extraction, conversion, transmission, and distribution**. As noted in Section 7.3, CO_2 emissions from the energy supply sector are the most important source of climate forcing. Climate forcing associated with emissions from non-CO_2 greenhouse gases (e.g., CH4 and N2O) of the energy supply sector is smaller than for CO_2. For the most part non-CO_2 greenhouse gases are emitted by other non-energy sectors, though CH_4 is released in primary energy sourcing and supply as a bi-product of oil, gas, and coal production as well as in the transmission and distribution of methane to markets. While its share in total GHG emissions is relatively small, the energy supply sector is, however, a major source of sulphur and other aerosol emissions. (See also Section 6.6)

[27] The transformation scenarios in the AR5 Scenario Database do not provide information on energy-related emissions of non-CO_2 gases. The assessment in this section thus focuses on CO_2 emissions only.

[28] Beyond those already in effect.

[29] Note that the total energy-related emissions include in some scenarios also fossil fuel emissions from industrial processes, such as the use of fossil fuel feedstocks for lubricants, asphalt, or cement production. A split between energy and industrial process emissions is not available from the AR5 scenario database.

[30] The full uncertainty range of the AR5 Scenario Database includes high emissions scenarios approaching 80 $GtCO_2$ by 2050, and almost 120 $GtCO_2$ by 2100.

[31] If not otherwise mentioned, ranges refer to the 25-75 percentile of the AR5 Scenario Database.

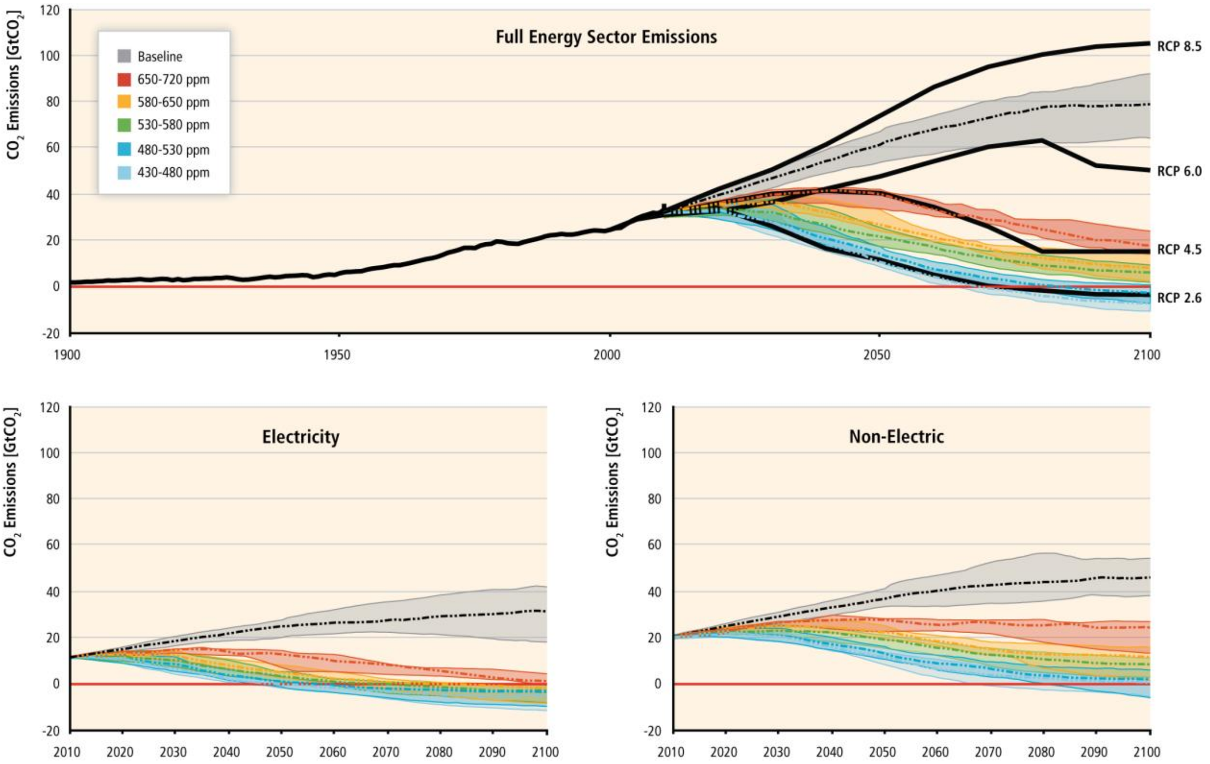

Figure 7.9. Global development of CO$_2$ emissions for the full energy system including energy supply, and end uses (upper panel) and the split between electricity and non-electric emissions (lower panels). The baseline emissions range (grey) is compared to the range of emissions from mitigation scenarios grouped according to their long-term CO$_2$-eq concentration level by 2100. Shaded areas correspond to the 25th-75th percentile and dashed lines to the median across the scenarios. "Non-electric" comprises emissions from the full chain of non-electric conversion processes as well as emissions from fossil fuels supplied to the end-use sectors. The upper panel includes in addition also the RCPs (black lines, see Chapter 6, Table 6.2). Source: AR5 Scenario Database (See Section 6.2.2 and Annex II.10). Note: Some scenarios report industrial process emissions (e.g. CO$_2$ released from cement manufacture beyond energy-related emissions) as part of the energy system.

7.11.2 Energy supply in low stabilization scenarios

While stabilizing CO2e concentrations requires fundamental changes to the global energy supply systems, a portfolio of measures is available that include the reduction of final energy demand through enhanced efficiency or behavioural changes as well as fuel switching (e.g. from coal to 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 7.10 shows three examples of alternative energy system transformation pathways that are consistent with limiting CO2e concentrations to about 480 ppm CO$_2$e by 2100. The scenarios from the three selected models are broadly representative of different strategies for how to transform the energy system. In absence of new 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 baseline scenarios increases from present levels to 900-1200 EJ/yr by 2050 (left-hand panels of Figure 7.10). Limiting concentrations to low levels requires the rapid and pervasive replacement of fossil fuel without CCS (see the negative numbers at the right-hand panels of Figure 7.10). 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 230-670 EJ lower than in non-climate-policy baseline scenarios.[32]

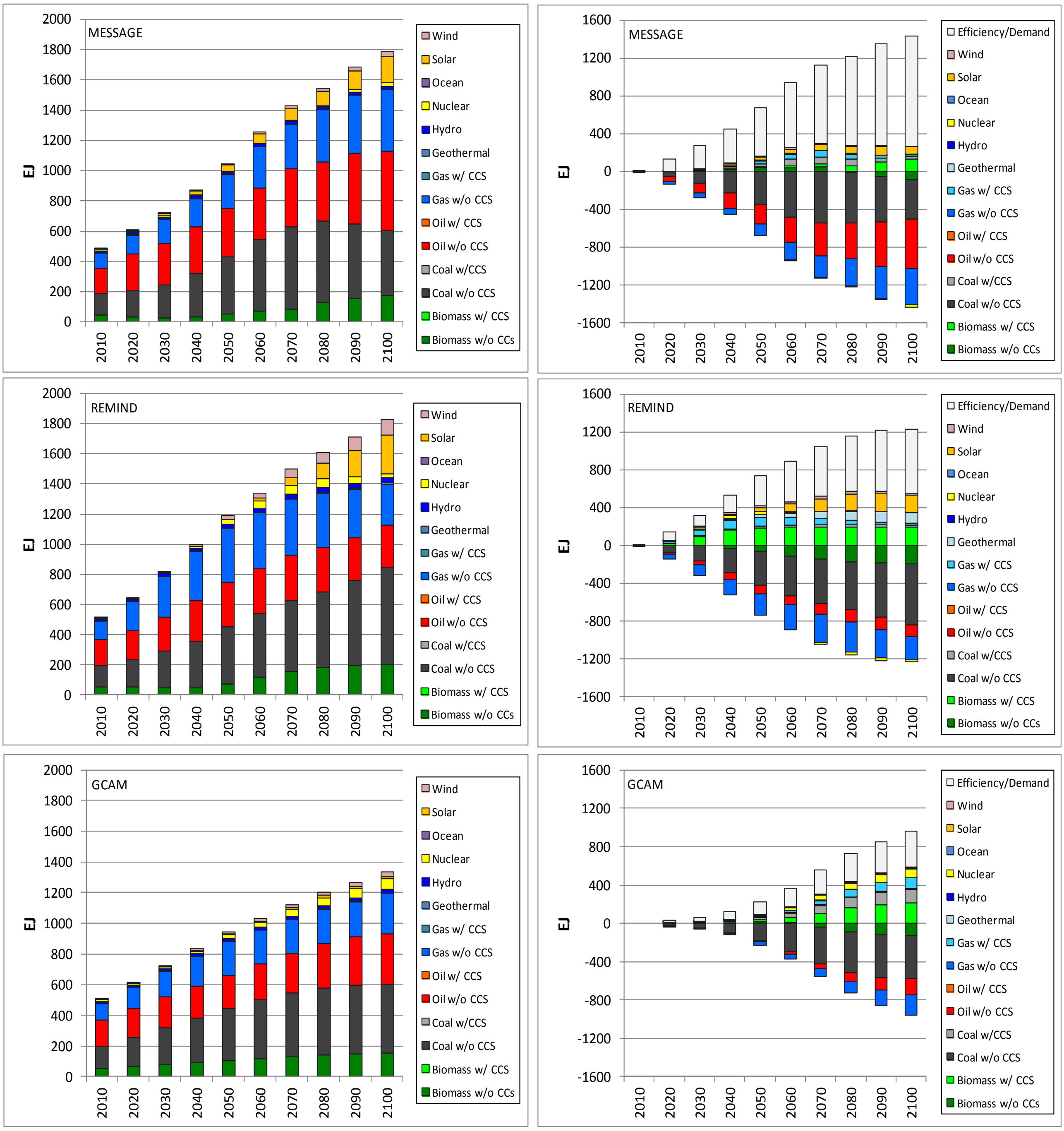

Figure 7.10. Development of primary energy (EJ) in three illustrative baseline scenarios (left-hand panel); and the change in primary energy compared to the baseline in order to meet a long-term concentration target between 430 and 530 ppm CO2eq. Source: ReMIND (Rose: Bauer et al, (2013), GCAM (AME: Calvin et al, (2012)); MESSAGE (GEA: Riahi et al, (2012)).[33]

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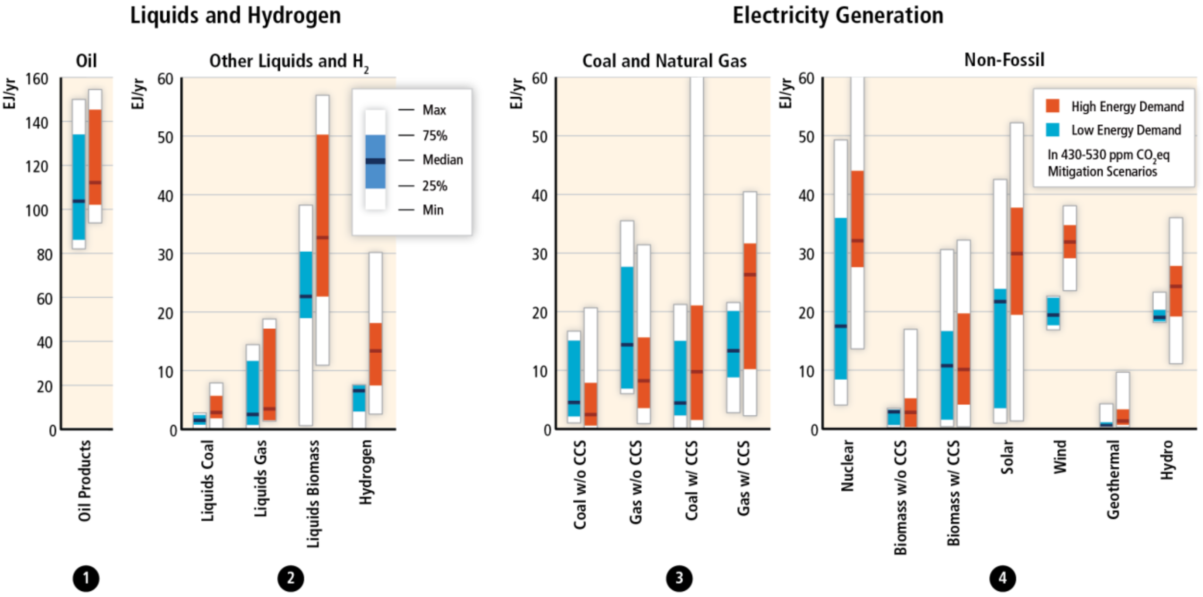
[32] The numbers refer to the replacement of freely emitting (unabated) fossil fuels without CCS. The contribution of fossil fuels with CCS is increasing in the mitigation scenarios.

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

The three scenarios achieve their concentration goals using different portfolios. These differences reflect the wide range in assumptions about technology availability and the policy environment[34]. 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 about 1200 EJ of fossil fuels are replaced through efficiency and demand-side improvements by 2100, compared to about 400 EJ in the GCAM scenario.



High energy demand scenarios show higher levels of oil supply.

In high energy demand scenarios, alternative liquid and hydrogen technologies are up-scaled more rapidly.

High energy demand scenarios show a more rapid up-scaling of CCS technologies but a more rapid phase-out of unabated fossil fuel conversion technologies.

In high energy demand scenarios non-fossil electricity generation technologies are up-scaled more rapidly.

Figure 7.11. Influence of energy demand on the deployment of energy supply technologies for stringent mitigation scenarios (430-530 ppm CO_2-eq) in 2050. Blue bars for "low energy demand" show the deployment range of scenarios with limited growth of final energy of <20% in 2050 compared to 2010. Red bars show the deployment range of technologies in case of "high energy demand" (>20% growth in 2050 compared to 2010). For each technology, the median, interquartile, and full deployment range is displayed. (Source: AR5 Scenario Database; see Annex II.10).

Notes: Scenarios assuming technology restrictions and scenarios with final energy in the base-year outside ±5% of 2010 inventories are excluded. Ranges include results from many different integrated models. Multiple scenario results from the same model were averaged to avoid sampling biases. For further details see chapter 6.

Achieving concentrations at low levels (430-530 ppm CO_2e) requires significant up-scaling of low-carbon energy supply options. The upscaling of low-carbon options depends greatly on the development of energy demand, which determines the overall "size" of the system. Hence, scenarios with greater emphasis on efficiency and other measures to limit energy demand, generally show less pervasive and rapid up-scaling of supply side options (see right-side panels of Figure 7.11). Figure 7.11 compares stringent mitigation scenarios with low and comparatively high global energy demands by 2050. The higher energy demand scenarios are generally accompanied by higher deployment rates for low-carbon options and more rapid phase-out of freely emitting fossil fuels without CCS. Moreover, and as also shown by Figure 7.11, high energy demand leads to a further

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[34] For example, the MESSAGE scenario corresponds to the so-called "efficiency" case of the Global Energy Assessment, which depicts low energy demand in order to test the possibility of meeting the concentration goal even if nuclear power were phased out. GCAM on the other hand imposed no energy supply technology availability constraints and assumed advances across a broad suite of technologies.

"lock-in" into fossil-intensive oil-supply infrastructures, which puts additional pressure on the supply system of other sectors that need to decarbonise more rapidly in order to compensate for the increased emissions from oil products. The results confirm the importance of measures to limit energy demand (Wilson et al, 2012) in order to increase the flexibility of energy supply systems, thus reducing the risk that stringent mitigation stabilization scenarios might get out of reach (Riahi et al., 2013). Note also that even at very low concentration levels a significant fraction of energy supply in 2050 may be provided by freely emitting fossil energy (without CCS).

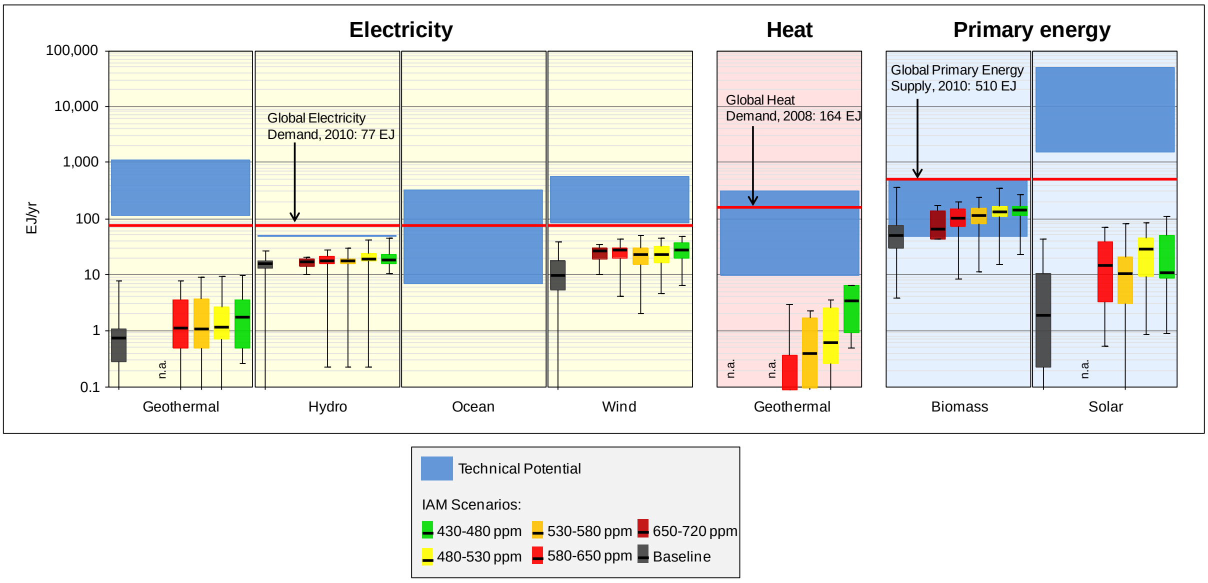


Figure 7.12. Comparison of global technical potentials of renewable energy sources (Moomaw, Yamba, et al., 2011) and deployment of renewable energy technologies in IAM scenarios in 2050 (AR5 Scenario Database, (See Annex II.10). Solar energy and biomass are displayed as primary energy as they can serve multiple uses. Note that the figure is presented in logarithmic scale due to the wide range of assessed data. IAM mitigation scenarios are presented for different ranges of CO2-equivalent concentration levels (see Chapter 6).

Notes: The reported technical potentials refer to the total worldwide annual RE supply. Any potential that is already in use is not deducted. RE power sources could also supply heating applications, whereas solar and biomass resources are represented in terms of primary energy because they could be used for multiple (e.g. power, heat and transport) services. The ranges were derived by using various methodologies and the given values refer to different years in the future., As a result, the displayed ranges cannot be strictly compared across different technologies. Additional information concerning data sources and additional notes that should be taken into account in interpreting the figure, see (Moomaw, Yamba, et al., 2011). Contribution of ocean energy in the IAM scenarios is less than 0.1 EJ and thus outside the logarithmic scale of the figure. Note that not all scenarios report deployment for all RE sources. The number of assessed scenarios differs thus across RE sources and scenario categories. "N.a." indicates lack of data for a specific concentration category and RE. Scenarios assuming technology restrictions are excluded.

The projected deployment of renewable energy technologies in the mitigation scenarios (Figure 7.12), with the exception of biomass, is well within the estimated global technical potentials assessed by the IPCC (2011a). As illustrated in Figure 7.12, global technical potentials of, for instance, wind, solar, geothermal, and ocean energy are often more than an order of magnitude larger than the projected deployment of these technologies by 2050. Also for hydropower the technical potentials are larger than the projected deployment, whereas for biomass, projected global deployment is within the wide range of global technical potential estimates. Considering the large upscaling in the mitigation scenarios, global technical potentials of biomass and hydropower seem to be more limiting than for other renewables (Figure 7.12). That said, considering not only global potentials, but also regional potentials, other renewable energy sources may also be limited by technical potentials under mitigation scenarios (cf., Fischedick et al., 2011). Additionally, reaching the global deployment levels as projected by the mitigation scenarios requires addressing potential environmental concerns, public acceptance, the infrastructure requirements to manage system integration and deliver renewable energy to load centres, and other barriers (see Section 7.4.2, 7.6, 7.8, 7.9, 7.10, IPCC, 2011a). Competition for land and other resources among different renewables may also impact aggregate technical potentials as well as deployment levels, as might concerns about the carbon footprint and sustainability of the resource (e.g., biomass) as well as materials demands (cf. Annex Bioenergy in Chapter 11; de Vries et al., 2007; Kleijn and van der Voet, 2010; Graedel, 2011). In many mitigation scenarios with low demand, nuclear energy supply is projected to increase in 2050 by about a factor of two compared to today, and even a factor of 3 or more in case of relatively high energy demand (Figure 7.11). Resource endowments will not be a major constraint for such an expansion, however, greater efforts will be necessary to improve the safety, uranium utilization, waste management, and proliferation concerns of nuclear energy use (see also Section 7.5.4, 7.4.3, 7.8, 7.9, 7.10).

Integrated assessment models (see 6.2) tend to agree that at about 100-150 $/tCO2 the electricity sector is largely decarbonized with a significant fraction being from CCS deployment (Krey and Riahi, 2009; Luckow et al., 2010; Wise et al., 2010). Many scenarios in the AR5 Scenario database achieve this decarbonization at a carbon tax of approximately 100$/tCO2. This price is sufficient, in most scenarios, to produce large-scale utilization of bioenergy with CCS (BECCS) (Krey and Riahi, 2009; Azar et al., 2010; Luckow et al., 2010; Edmonds et al., 2013). BECCS in turn allows net removal of CO_2 from the atmosphere while simultaneously producing electricity (7.5.5, 11.13). In terms of large scale deployment of CCS in the power sector, Herzog (2011), p. 597, and many others have noted that "Significant challenges remain in growing CCS from the megaton level where it is today to the gigaton level where it needs to be to help mitigate global climate change. These challenges, none of which are showstoppers, include lowering costs, developing needed infrastructure, reducing subsurface uncertainty, and addressing legal and regulatory issues." In addition, the upscaling of BECCS, which plays a prominent role in many of the stringent mitigation scenarios in the literature, will require overcoming potential technical barriers to increase the size of biomass plants. Potential adverse side-effects related to the biomass feedstock usage remain the same as for biomass technologies without CCS (7.5.5, 11.13, particularly 11.7, 11.13.6, 11.13.7).

Over the past decade, a standardized geologic CO_2 storage-capacity methodology for different types of deep geologic formations (Bachu et al., 2007; Bradshaw et al., 2007; Kopp et al., 2009; Orr, 2009; Goodman et al., 2011; De Silva et al., 2012) has been developed and applied in many regions of the world. The resulting literature has been surveyed by Dooley (2013), who reports that, depending on the quality of the underlying data used to calculate a region's geologic CO_2 storage capacity and on the type and stringency of various engineering and economic constraints, global theoretical CO_2 storage could be as much as 35,000 $GtCO_2$, global effective storage capacity is 13,500 $GtCO_2$, global practical storage capacity is 3,900 $GtCO_2$, and matched geologic CO_2 storage capacity for those regions of the globe where this has been computed is 300 $GtCO_2$. Dooley (2013) compared these estimates of geologic storage capacity to the potential demand for storage capacity in the 21st century by looking across more than 100 peer-reviewed scenarios of CCS deployment. He concludes that a lack of geologic storage space is unlikely to be the primary impediment to CCS deployment as the average demand for geologic CO_2 storage for scenarios that have end-of-century CO_2 concentrations of 400–500 ppm ranges from 448 $GtCO_2$ to 1,000 $GtCO_2$.

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 (Calvin et al., 2012; Bauer et al., 2013).

7.11.3 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 (two of the major sources of electricity generation today). Many mitigation scenario studies (Edmonds et al., 2006; as well as the AR5 database)(cf. Sections 6.3.4 and 6.8) have three generic components: 1. Decarbonize power generation, 2. Substitute electricity for direct use of fossil fuels in buildings and industry (see 9.3 and 10.4), and in part for transportation fuels (Chapter 8), and 3. Reduce aggregate energy demands through technology and other substitutions.

Most scenarios in the AR5 Scenario database report a continuation of the global electrification trend in the future (Figure 7.13). In the baseline scenarios (assuming no new climate policies) most of the demand for electricity continues to be in the residential, commercial and industry sectors (see Chapters 9 and 10), while transport sectors rely predominantly on liquid fuels (Chapter 8.9). Biofuels 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.

Electricity production is the largest single sector emitting fossil fuel CO_2 at present and in baseline 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 mitigation scenarios with deep cuts of GHG emissions. Many mitigation scenario studies report an acceleration of the electrification trend in mitigation scenarios (Figure 7.13).

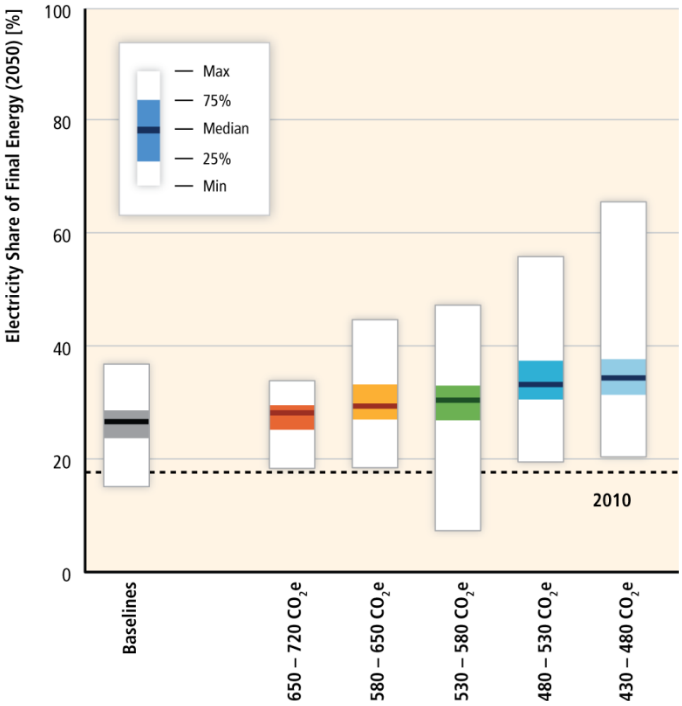


Figure 7.13 Share of electricity in total final energy for the year 2050 in baseline scenarios and five different levels of emissions mitigation stringency (long-term concentration levels in ppm CO2-eq by 2100). Bars show the interquartile range and error bands of the full range across the baseline and mitigation scenarios (See 6.3.2). Dashed horizontal line shows the electricity share for the year 2010. Source: AR5 Scenario Database. Scenarios assuming technology restrictions are excluded.

Mitigation scenario studies indicate that the decarbonisation of the electricity sector may be achieved at a much higher pace than in the rest of the energy system (Figure 7.14). In the majority of stringent mitigation scenarios (430-480 ppm & 480-530 ppm), 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.

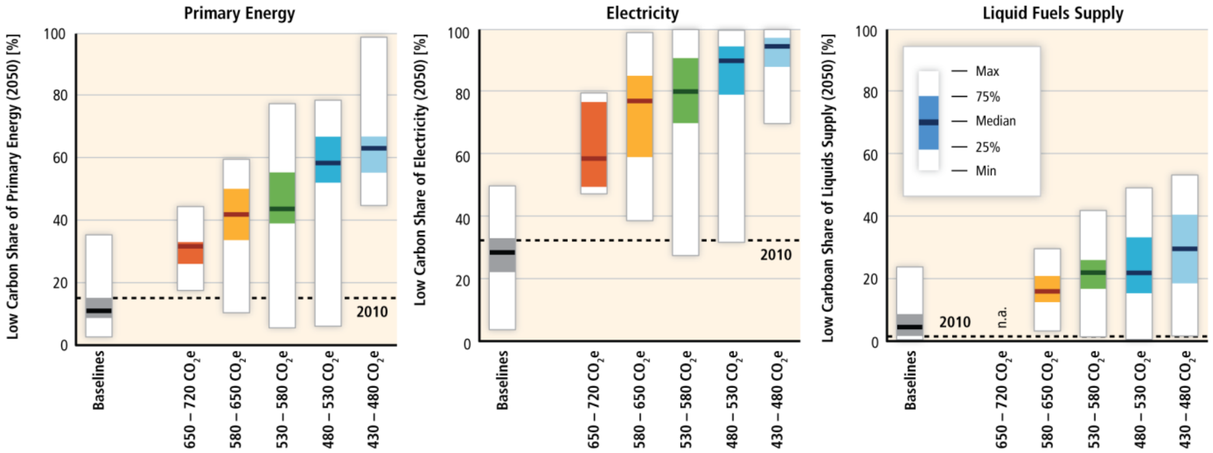


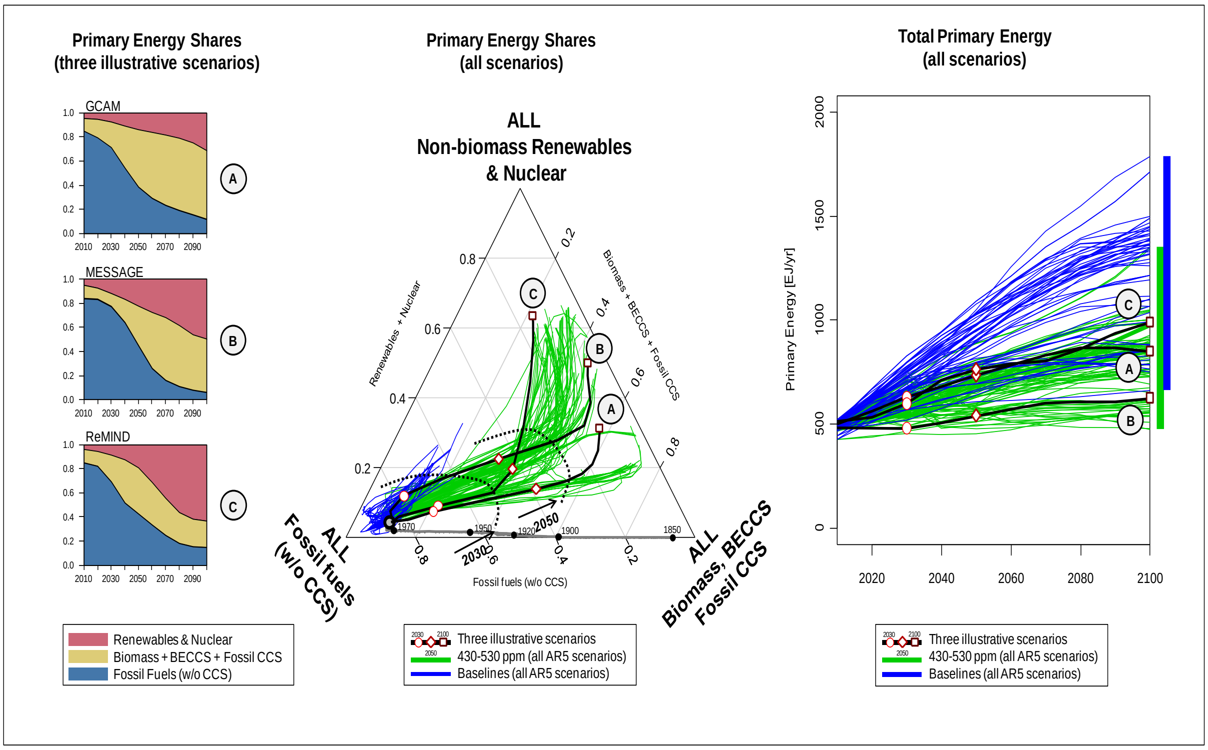
Figure 7.14. Share of low-carbon energy in total primary energy, electricity and liquid supply sectors for the year 2050. Bars show the interquartile range and error bands the full range across the baseline and mitigation scenarios for different CO2e ppm concentration levels in 2100 (Section 6.3.2). Dashed horizontal lines show the low-carbon share for the year 2010. Low-carbon energy includes nuclear, renewables, and fossil fuels with CCS. Source: AR5 Scenario Database. Scenarios assuming technology restrictions are excluded.

Figure 7.15 shows the evolution over time of transformation pathways for primary energy supply, electricity supply, and liquid fuels supply for reference scenarios and low concentration scenarios (430-530 ppm CO_2e). The development of the full scenario ensemble is further compared to the three illustrative mitigation scenarios by the ReMIND, MESSAGE, and GCAM models discussed in Section 7.11.2 (see Figure 7.10). The effect of climate policy plays out differently in each of the three supply domains. In aggregate, mitigation leads to a reduction in primary energy demands. However, two distinctly different mitigation portfolios emerge – one in which hydro-carbon fuels, including biomass, BECCS, and fossil CCS play 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 by 2100. Note that in the scenarios examined here, the major branch point occurs around the 2050 period, while the foundations are laid in the 2030 to 2050 period.

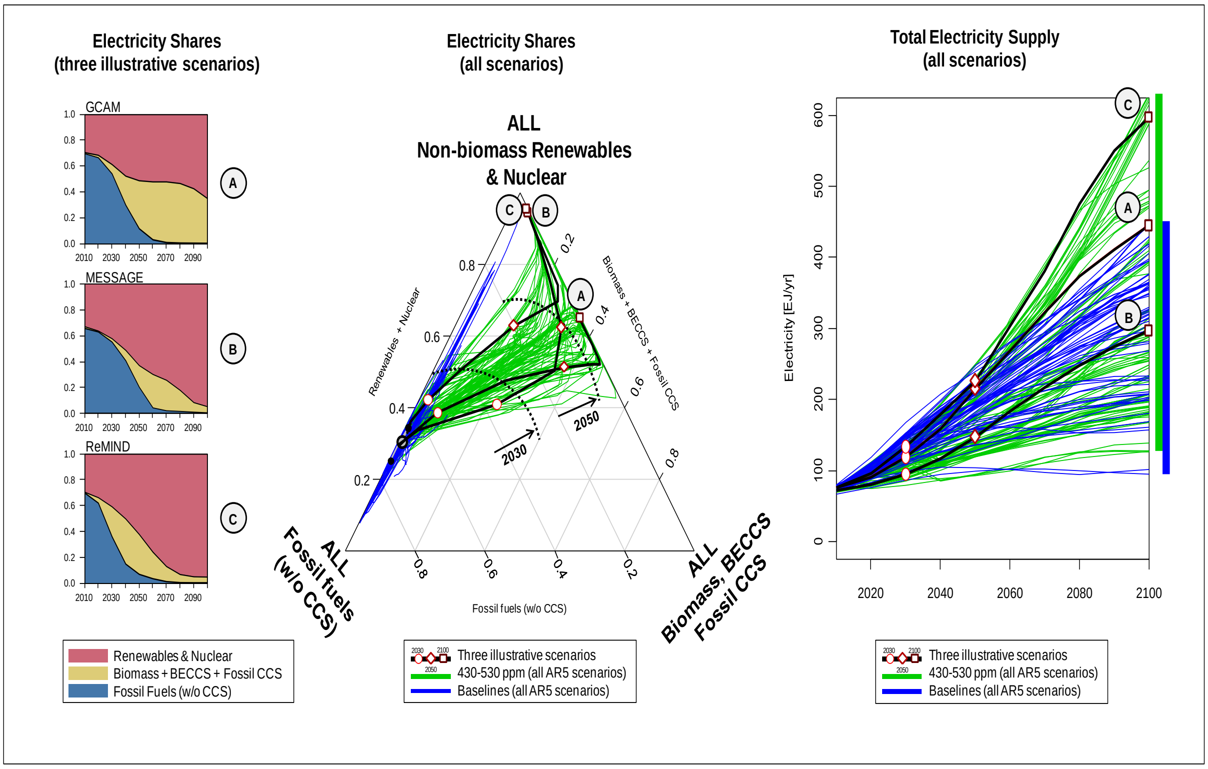
Electricity generation is a somewhat different story. While as previously noted, electricity generation decarbonizes rapidly and completely (in many scenarios emissions actually become negative), taken together, non-biomass renewables and nuclear power always play an important role. The role of CCS varies greatly, but even when CCS becomes extremely important to the overall mitigation strategy, it never exceeds half of power generation. By 2050 the contribution of fossil CCS technologies is in most scenarios larger than BECCS (see Figure 7.11). In contrast to the overall scale of primary energy supply, which falls in climate policy scenarios relative to baseline scenarios, the scale of power generation can be higher 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. With regards to the deployment of individual non-biomass renewables or different CCS technologies see also Figure 7.11 and Figure 7.12.

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. This transition is gradual, and becomes more pronounced in the second half of the century. Like aggregate primary energy supply the supply of liquid fuels is reduced in climate policy scenarios compared with baseline scenarios. In addition, the primary feedstock shifts from petroleum and other fossil fuels to bioenergy.

(i) Primary Energy



(ii) Electricity Generation



(iii) Liquid Fuels Supply

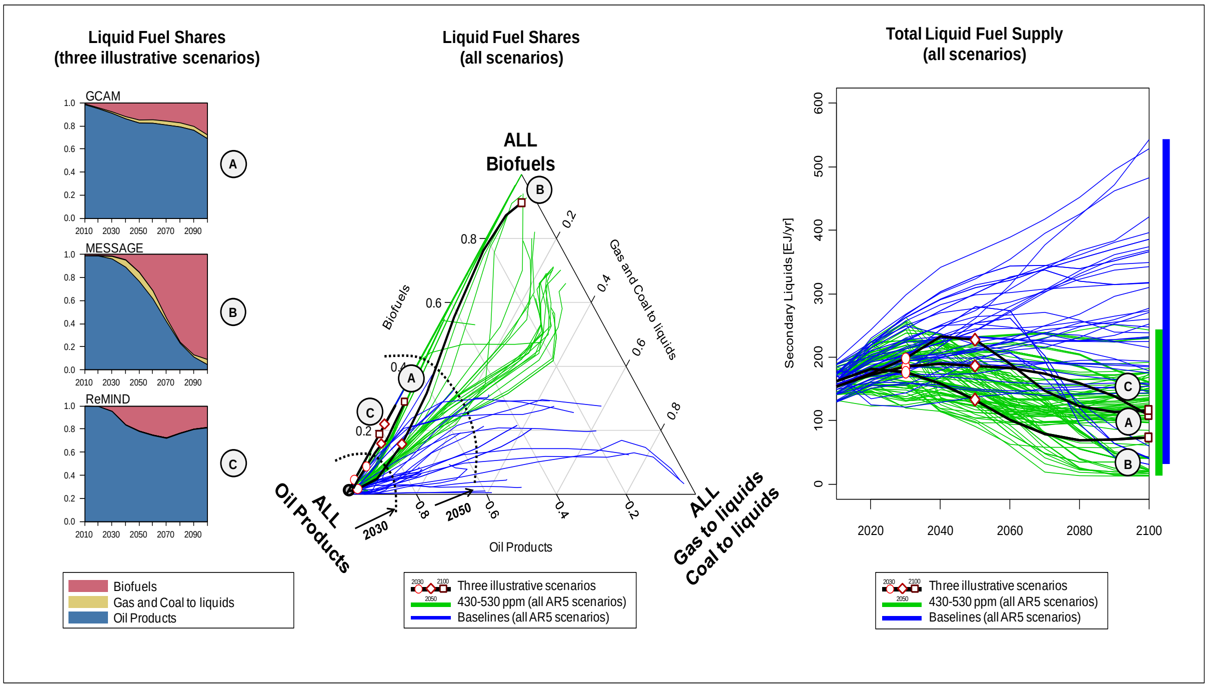


Figure 7.15. Transition Pathways for the Aggregate Energy Supply Transformation System (i), Electricity Supply (ii), and the Supply of Liquid Fuels (iii): 2010 to 2100 for baseline and stringent mitigation scenarios (430-530 ppm CO_2e). The pathways of three illustrative scenarios (cases A, B, and C) are highlighted for comparison. The illustrative pathways correspond to the same scenarios as shown in Figure 7.10. Dashed lines in the middle panels show the development to 2030 and 2050, and are indicative only for central trends across the majority of the scenarios. Source: AR5 Scenario Database (see Section 6.2.2 and Annex II.10) and three illustrative scenarios from ReMIND (Rose: Bauer et al., **(2013)**; GCAM (AME: Calvin et al., **(2012)**; and the MESSAGE model (GEA: Riahi et al., **(2012)**).

Note: Scenarios assuming technology restrictions and scenarios with significant deviations for the base-year (2010) are excluded

7.11.4 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 net emissions to decline to zero (Kheshgi et al., 2005).[35] Two important implications follow from this observation.

First, it is cumulative emissions over the entire century that to a first approximation 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 concentration goals see 6.3.2, and Meinshausen et al (2009)). For any stable concentration of CO_2 emissions must peak and then decline toward zero, and for low concentrations, some period of negative emissions may prove necessary.

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 Wan, 1996). The consequence of this latter feature is that emissions abatement and the deployment of mitigation technologies grows over time. When

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[35] The precise relationship is subject to uncertainty surrounding processes in both the oceans and on land that govern the carbon cycle. Processes to augment ocean uptake are constrained by international agreements.

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 (Section 7.5.5), 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 concentration 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) and Rogelj et al., (2013) assessed the relationship between emissions levels in 2020 and 2050 in order to meet a range of long-term targets (in 2100). They identified “emissions windows” through which global energy systems would need to pass in order to achieve various concentration goals.

Recent intermodel comparison projects AMPERE, LIMITS and ROSE (Bauer et al., 2013; Eom et al., 2013; Kriegler et al., 2013; Luderer et al., 2013; Riahi et al., 2013; Tavoni et al., 2014) have explored the implications of different near term emissions targets for the attainability and costs of reaching low concentrations levels of 430 to 530 ppm CO_2-eq. The studies illustrate that the pace of the energy transformation will strongly depend on the attainable level of emissions in the near term (Figure 7.16). Scenarios that achieve comparatively lower global emissions levels by 2030 (<50 Gt CO_2-eq) show a more gradual transformation to 2050 corresponding to about a doubling of the low-carbon energy share every 20 years. Scenarios with higher 2030 emissions levels (>55 Gt CO_2-eq) lead to a further “lock-in” into GHG-intensive energy infrastructures without any significant change in terms of the low-carbon energy share by 2030. This poses a significant challenge for the time period between 2030 and 2050, where the low carbon share in these scenarios would need to be rapidly scaled by nearly a factor of four (from about 15% to about 60% in 20 years).

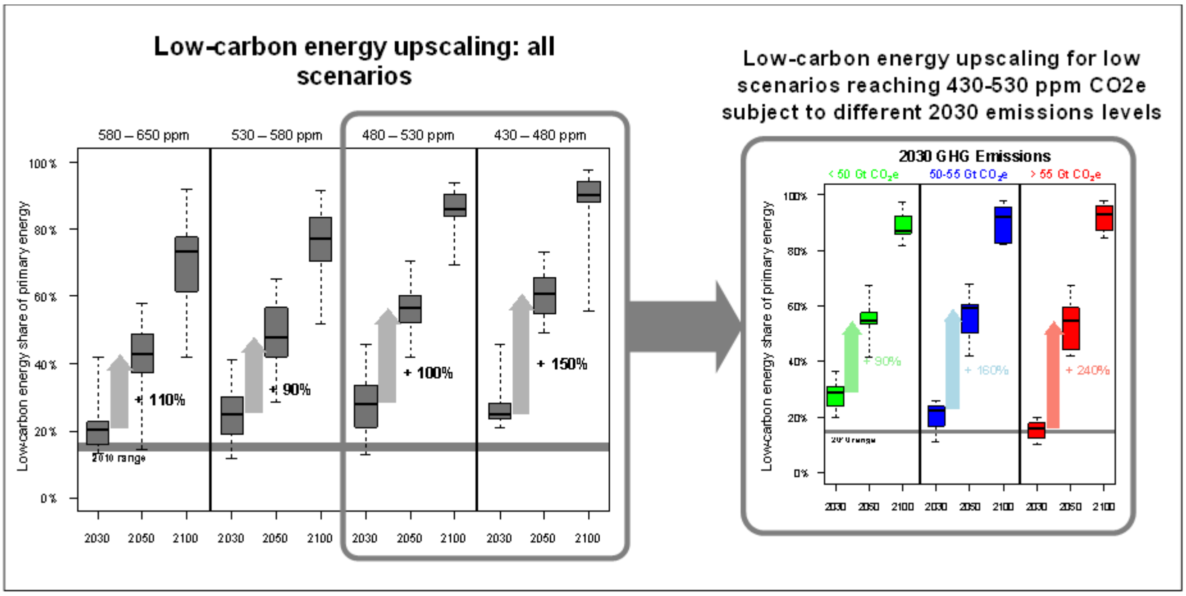

Figure 7.16. The up-scaling of low-carbon energy in scenarios meeting different 2100 CO2-equivalent concentration levels (left-hand panel). The right panel shows the rate of up-scaling for different levels of emissions in 2030. Bars show the interquartile range and error bands the full range across the baseline and mitigation scenarios (see Section 6.3.2 for more details). Low-carbon technologies include renewables, nuclear energy and fossil fuels with CCS. Sources: AR5 Scenario Database (left-hand panel) and scenarios from multimodel comparisons with explicit 2030 emissions targets (right-

hand panel: AMPERE: Riahi et al. **(2013)**, Eom et al. **(2013)**; LIMITS: Kriegler et al. **(2013)**, ROSE: Luderer et al. **(2013)**).

Note: Only scenarios with default technology assumptions are shown. In addition, scenarios with non-optimal timing of mitigation due to exogenous carbon price trajectories are excluded in the right-hand panel.

Eom et al. (2013) indicate that such rapid transformations due to delays in near-term emissions reductions would pose enormous challenges with respect to the upscaling of individual technologies. The study shows that depending on the assumptions about the technology portfolio a quadrupling of the low-carbon share over 20 years (2030-2050) would lead on average to the construction of 29 to 107 new nuclear plants per year. While the lower bound estimate corresponds to about the observed rate of nuclear power installations in the 1980s (Wilson et al., 2013), the high estimate is historically unprecedented. The study further indicates an enormous requirement for the future upscaling of renewable energy technologies. For instance, solar power is projected in the models to increase by 50-360 times of the year-2011 global solar capacity between 2030 and 2050. With respect to the attainability of such high deployment rates, the recent study by Wilson et al. (2013) indicates that the diffusion of successful technologies in the past has been generally more rapid than the projected technology diffusion by IAM models.

As shown in Figure 7.17, cost-effective pathways (without delay) show a remarkable near-term upscaling (between 2008 and 2030) of CCS technologies by about 3 orders of magnitude from the current CCS facilities that store a total of 5 $MtCO_2$ per year (see also, Sathre et al., 2012). The deployment of CCS in these scenarios is projected to accelerate even further reaching CO_2 storage rates of about half to double current global CO_2 emissions from fossil fuel and industry by 2100. The majority of the models indicate that in absence of this CCS potential, the transformation to low GHG concentrations (about 480 ppm CO_2-eq) might not be attainable if mitigation is delayed to 2030 (Riahi et al., 2013). Delays in mitigation thus reduce technology choices, and as a result some of the currently optional technologies might become “a must” in the future (Riahi et al., 2012, 2013; Rogelj et al., 2013). It should be noted that even at the level of CCS deployment as depicted by the cost-effective scenarios, CO_2 storage capacity is unlikely to be a major limiting factor for CCS (see above), however, various concerns related to potential ecological impacts, accidental release of CO_2, and related storage effectiveness of CCS technologies might pose barriers to deployment. (See 7.9)

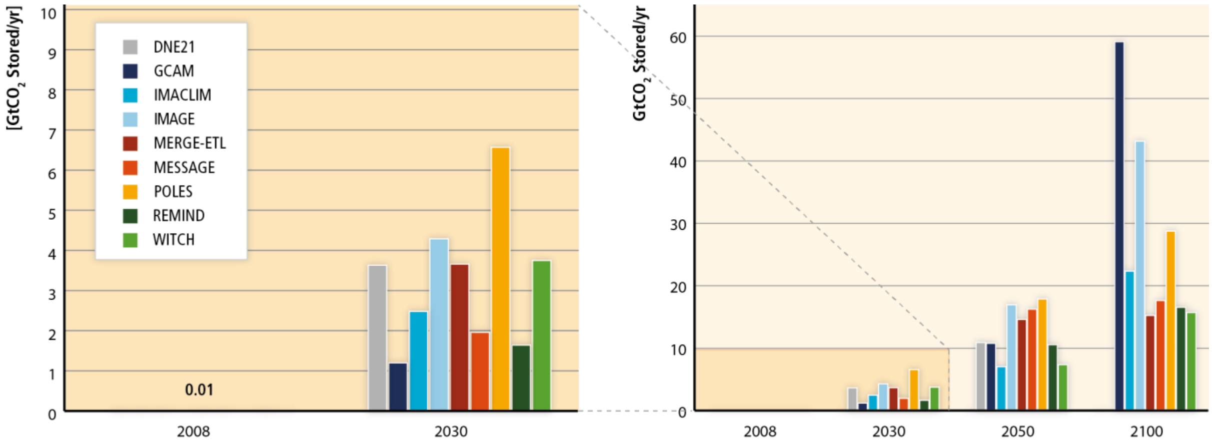

Figure 7.17. Annual Rate of Geological Carbon Sequestration in cost-effective mitigation scenarios reaching 430-530 ppm CO_2-eq. Source: AMPERE intermodeling comparison; Eom et al. (2013), Riahi et al. (2013).

Reprinted from *Technological Forecasting and Social Change*, Eom J. et al., "The impact of near-term climate policy choices on technology and emission transition pathways", 2013, with permission from Elsevier.

7.12 Sectoral policies

The stabilization of GHG concentrations at a level consistent with the Cancun agreement requires a fundamental transformation of the energy supply system, and the long-term substitution of freely emitting (i.e., unabated)[36] fossil fuel conversion technologies by low-carbon alternatives (Chapter 6, 7.11). Studies that have analysed current policies plus the emission reduction pledges under the Cancun agreement have found that global GHG emissions are expected to grow (den Elzen et al., 2011; IEA, 2011a; e.g., Carraro and Massetti, 2012). As a consequence, additional policies must be enacted and/or the coverage and stringency of the existing ones must be increased if the Cancun agreement is to be fulfilled.

Currently, most countries combine instruments from three domains: Economic instruments to guide investments of profit maximizing firms, information and regulation approaches to guide choices where economic instruments are politically not feasible or not fully reflected in satisficing behaviour of private actors, and innovation and infrastructure policies reflecting public investment in long-term transformation needs (Grubb et al., 2013). This section discusses the outcome of *existing climate policies* that address the energy supply sector in terms of their GHG emission reduction, their influence on the *operation* and (via changed investments) on the *structure* of the energy system, as well as the associated side-effects. The policy categories considered in the following are those introduced in section 3.8. The motivation behind the policies (e.g. their economic justification) and problems arising from enacting multiple policies simultaneously are discussed in 3.8.6, 3.8.7, 15.3, and 15.7. A general evaluation of the performance of the policies is carried out in section 15.5.

7.12.1 Economic Instruments

GHG pricing policies, such as GHG emission trading schemes (ETS) and GHG emission taxes, have been frequently proposed to address the market externalities associated with GHG emissions (see 3.8 and 15.5). In the power sector, GHG pricing has primarily been pursued through emission trading mechanisms and, to a lower extent, by carbon taxes (Sumner et al., 2009; IEA, 2010f; Lin and Li, 2011). Economic instruments associated with the provision of transport fuels and heat are discussed in Chapter 8, 9 and 10.

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[36] These are those not using carbon capture and storage technologies.

The existence of GHG (allowance or tax) prices increases the cost of electricity from fossil fuelled power plants and, as a consequence, average electricity prices. The short-term economic impacts of power price increases for industrial and private consumers have been widely discussed (Parry, 2004; Hourcade et al., 2007). In order to address the associated distributional impacts, various compensation schemes have been proposed (IEA, 2010f; Burtraw et al., 2012; EU Commission, 2012). The impact of an emission trading scheme on the profitability of power generation can vary. Allowances that are allocated for free lead to windfall gains (Keats and Neuhoff, 2005; IEA, 2010f, p. 8). With full auctioning, the impact on profitability can vary between different power stations (Keppler and Cruciani, 2010).

From an *operational* point of view, what counts is the *fuel and technology dependent* mark up in the marginal costs of fossil fuel power plants due to GHG prices. Power plants with low specific GHG emissions (e.g., combined cycle gas turbines) will see a smaller increase of their marginal costs compared to those with higher specific emissions (e.g., coal power plants). The resulting influence on the relative competiveness of different power plants and the associated effect on the generation mix depends, in part, on fuel prices (which help set the marginal cost reference levels) and the stringency of the GHG emission cap or tax (defining the GHG price) (IEA, 2010f).

Although GHG taxes are expected to have a high economic efficiency (see 15.5.2), explicit GHG taxes that must be obeyed by the power sector (e.g., as part of an economy wide system) have only been enacted in a couple of countries (WEC, 2008; Tanaka, 2011). In contrast, taxes on fuels are common (15.5.2). Concerning *operational decisions,* GHG taxes, taxes or charges on input fuels and emission permit schemes are equal as long as the resulting (explicit or implicit) GHG price is the same. Concerning *investment decisions (especially those made under uncertainty)*, there are differences that are discussed as part of the “prices versus quantities” debate (see Weitzman, 1974, 2007; OECD, 2009). Due to some weaknesses of existing emission trading schemes and associated uncertainties, there is a renewed interest in hybrid systems which combine the merits of both approaches by introducing price caps (serving as “safety valves”) and price floors into emission trading schemes in order to increase their flexibility in the context of uncertain costs (Pizer, 2002; Philibert, 2008). Concering the issue of potential intertemporal and spatial leakages as discussed in the Green Paradox literature (15.5.2.4), differences between tax and GHG emission trading schemes exist as well. Options to address these issues are discussed in 15.5.3.8 and Kalkuhl and Edenhofer, (2013).

The EU ETS[37] is perhaps the world’s most prominent example of a GHG trading scheme, and the GHG prices observed in that market, in combination with other policies that have been enacted simultaneously, have been effective in changing *operating and investment choices* in a way that has allowed the *short-term* fulfilment of the sector-specific GHG reduction goals (Ellerman et al., 2010; IEA, 2010f). The significant associated emission reductions compared to the baseline are discussed in 14.4.2.1. Shortcomings of emissions trading in general and the EU ETS in particular (e.g., the high GHG price volatility and the resulting lack of stable price signals) are addressed by (Grubb et al., 2006; Neuhoff et al., 2006; Åhman et al., 2007; Kettner et al., 2008; Ellerman et al., 2010; IEA, 2010f; Pahle et al., 2011). According to the IEA (2010f), these shortcomings can be mitigated by setting long-term emission caps that are consistent with given GHG concentration stabilization goals and by avoiding a free allocation of allowances to power producers. A general discussion of the performance of GHG trading schemes is given in 15.5.3, including programs outside Europe. The main factors that have contributed to the low EU ETS carbon prices currently observed include: caps that are modest in comparison to the Cancun agreement; relatively low electricity demand due to the economic crisis in the EU; increasing shares of RE; as well as an unexpected high inflow of certificates from CDM projects (IEA, 2013b).

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[37] For additional information on the history and general success of this policy see 14.4.2.1, 15.3.2 and 15.5.3.

In the longer term and provided that sufficiently stringent emissions caps are set, GHG pricing (potentially supplemented by technology support, see 15.6) can support low emitting technologies (e.g., RE, nuclear power and CCS) due to the fuel and technology dependent mark up in the marginal costs of fossil fuel power plants:

a) The economic performance of nuclear power plants, for instance, can be improved by the establishment of GHG pricing schemes (NEA, 2011b; Linares and Conchado, 2013).

b) CCS technologies applied in the power sector will only become competitive with their freely emitting (i.e. unabated) counterparts if the additional investment and operational costs associated with the CCS technology are compensated for by sufficiently high carbon prices or direct financial support (Herzog, 2011; IEA, 2013b). In terms of the price volatility seen in the ETS, Oda and Akimoto (2011) analysed the influence of carbon price volatility on CCS investments and concluded that carbon prices need to be higher in order to compensate for the associated uncertainty. The provision of capital grants, investment tax credits, credit guarantees and/or insurance are considered to be suitable means in order to support CCS technologies as long as they are in their early stages of development (IEA, 2013b, p. 79).

c) Many RE technologies still need direct (e.g., price-based or quantity-based deployment policies) or indirect (e.g., sufficiently high carbon prices and the internalization of other externalities) support if their market shares are to be increased (see 7.8.2, IPCC, 2011a; IRENA, 2012a). In order to achieve this goal, specific RE deployment policies have been enacted in a large number of countries (Halsnæs et al., 2012; Zhang et al., 2012; REN21, 2013). These policies are designed to facilitate the process of bringing RE technologies down the learning curve (IEA, 2011f; IRENA, 2012a). Taken together, RE policies have been successful in driving an escalated growth in the deployment of RE (IPCC, 2011a). Price-based mechanisms (such as feed-in-tariffs, FITs) and quantity-based systems (such as quotas or renewable portfolio standards, RPS, and tendering/bidding) are the most common RE deployment policies in the power sector (15.6, Halsnæs et al., 2012; REN21, 2013). With respect to their success and efficiency, the SRREN (IPCC, 2011a SPM, p. 25) notes “that some feed in tariffs have been effective and efficient at promoting RE electricity, mainly due to the combination of long-term fixed price or premium payments, network connections, and guaranteed purchase of all RE electricity generated. Quota policies can be effective and efficient if designed to reduce risk; for example, with long-term contracts.” Supported by Klessmann et al. (2013), a new study confirms: “Generally, it can be concluded that support schemes, which are technology specific, and those that avoid unnecessary risks in project revenues, are more effective and efficient than technology-neutral support schemes, or schemes with higher revenue risk” (Ragwitz and Steinhilber, 2013, p. 1).

Especially in systems with increasing and substantial shares of RE and “despite the historic success of FITs, there is a tendency to shift to tender-based systems because guaranteed tariffs without a limit on the total subsidy are difficult to handle in government budgets. Conversely a system with competitive bidding for a specified amount of electricity limits the total amount of subsidy required.” (Halsnæs et al., 2012, p. 6). A renewed tendency to shift to tender-based systems with public competitive bidding to deploy renewables is observed by REN21 (2013) as well. Assessing the economic efficiency of RE policies requires a clear distinction between whether a complete macroeconomic assessment is intended (i.e., one where competing mitigation options are taken into account as well) or whether prescribed and time dependent RE shares are to be achieved in a cost-effective manner. In addition, the planning horizon must be clearly stated. RE policies might be considered to be inefficient in a short-term (myopic) perspective, while they could be potentially justified in an intertemporal setting where a dynamic optimization over a couple of decades is carried out (see 15.6, IEA, 2011f; IPCC, 2011a SRREN, 11.1.1 and 11.5.7.3; Kalkuhl et al., 2012, 2013).

Issues related to synergetic as well as adverse interactions of RE policies with GHG policies (Halsnæs et al., 2012) are discussed in detail in section 15.7 and IPCC, SRREN, 11.1.1 and 11.5.7.3. A new line of reasoning shows that delayed emission pricing policies can be partially compensated by near-term support of RE (Bauer et al., 2012). The macroeconomic burden associated with the promotion of RE is emphasized by Frondel et al. (2010). The relationship between RE policy support and larger power markets is also an area of focus. Due to the "merit order effect", RE can, in the short term, reduce wholesale electricity prices by displacing power plants with higher marginal costs (Bode, 2006; Sensfuß et al., 2008; Woo et al., 2011; Würzburg et al., 2013), though in the long-term the impact may be more on the temporal profile of wholesale prices and less on overall average prices. The promotion of low carbon technologies can have an impact on the economics of backup power plants needed for supply security. The associated challenges and options to address them are discussed in Lamont, (2008), Sáenz de Miera et al., (2008), Green and Vasilakos, (2011), Hood, (2011), Traber and Kemfert, (2011), IEA, (2012b, 2013a; b), and Hirth, (2013).

According to Michaelowa et al., (2006), Purohit and Michaelowa, (2007), Restuti and Michaelowa, (2007), Bodas Freitas et al., (2012), Hultman et al., (2012), Zhang et al., (2012), and Spalding-Fecher et al., (2012) the emissions credits generated by the Clean Development Mechanism (CDM) have been a significant incentive for the expansion of renewable energy in developing countries.

Zavodov (2012) however has questioned this view and argues that CDM in its current form is not a reliable policy tool for long-term RE development plans. In addition, CCS has been accepted as an eligible measure under the CDM by the UN (IEA, 2010g).

The phase-out of inefficient fossil fuel subsidies as discussed during the G20 meetings in 2009, 2010, 2011, and 2012 will have a visible influence on global energy-related carbon emissions (Bruvoll et al., 2011; IEA, 2011g, 2013b). Removing these subsidies could lead to a 13 percent decline in CO_2 emissions and generate positive spill-over effects by reducing global energy demand (IMF, 2013). In addition, inefficiently low pricing of externalities (e.g. environmental and social costs of electricity production) in the energy supply sector introduces a bias against the development of many forms of low carbon technologies (IRENA, 2012a).

A mitigation of GHG emissions in *absolute terms* is only possible through policies/measures that either reduce the amount of fossil fuel carbon oxidized and/or that capture and permanently remove GHGs from fossil fuel extraction, processing and use from the atmosphere [7.5, 7.11]. The deployment of renewable or nuclear energy or energy efficiency as such does not guarantee that fossil fuels will not be burned (in an unabated manner). The interplay between growth in energy demand, energy efficient improvements, the usage of low carbon energy, and fossil fuel is discussed in detail in IPCC, SRREN, Chapters 1 (Figure 1.14) and 10.

The question whether or not the deployment of low carbon technologies *substitutes fossil fuels that otherwise would have emitted GHG* have to take into account the complexity of economic systems and human behaviour (York, 2012). A central aspect in this context is the rebound effect which is extensively discussed in chapter 3.9.5 and 5.6.2. Spillover effects that are highly related to this issue are discussed in 6.3.6. In order to constrain the related adverse effects, carefully drafted packages combining GHG pricing schemes with technology policies in a way which avoids negative interactions have been proposed (see IPCC, 2011a, SRREN, Chapter 11).

7.12.2 Regulatory approaches

The formulation of low carbon technologies targets 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 138 countries have renewable targets in place. More than half of them are developing countries (REN21, 2013).

The success of energy policies heavily depends on the development of an underlying solid legal framework as well as a sufficient regulatory stability (Reiche et al., 2006; IPCC, 2011a). Property rights, contract enforcement, appropriate liability schemes, and emissions accounting are essential for a successful implementation of climate policies. For example, well-defined responsibilities for the long-term reliability of geologic storages are an important pre-requisite for successful CCS applications (IEA, 2013b), while non-discriminatory access to the grid is of similar importance for RE.

Concerning the promotion of RE, the specific challenges that are faced by developing countries and countries with regulated markets are addressed by IRENA (2012a), IRENA, (2012b), Kahrl (2011) and Zhang et al. (2012). Renewable portfolio standards (or quota obligations, see 15.5.4.1) are usually combined with the trading of green certificates and therefore have been discussed under the topic of economic instruments (see above). Efficiency and environmental performance standards are usual regulatory instruments applied to fossil fuel power plants.

In the field of nuclear energy, a stable policy environment comprising a regulatory and institutional framework that addresses operational safety and the appropriate management of nuclear waste as well as long-term commitments to the use of nuclear energy are requested for in order to minimise investment risks for new nuclear power plants (NEA, 2013).

In order to regain public acceptance after the Fukushima accident, comprehensive safety reviews have been carried in many countries. Some of them included “stress test” which investigated the capability of existing and projected reactors to cope with extreme natural and man-made events, especially those lying outside the reactor design assumptions. As a result of the accident and the subsequent investigations, a “radical revision of the worst-case assumptions for safety planning” is expected to occur (Rogner, 2013), p. 291.

7.12.3 Information Programmes

Though information programs play a minor role in the field of power plant related energy efficiency improvements and fossil fuel switching, awareness creation, capacity building and information dissemination to stakeholders outside of the traditional power plant sector plays an important role especially in the use of decentralized RE in LDCs (IRENA, 2012c). Other low carbon technologies like CCS and nuclear would require specifically trained personnel (see 7.10.4). Furthermore, enhanced transparency of information improves public and private decisions and can enhance public perception (see 7.9.4).

7.12.4 Government Provision of Public Goods or Services

Public energy-related R&D expenditures in the IEA countries peaked in 2009 as a result of economic stimulus packages, but soon after suffered a substantial decline. Although R&D spending is now again rising, energy-related expenditures still account for less than 5% of total government R&D – compared to 11% that was observed in 1980 (IEA, 2012j). Nuclear has received significant support in many countries and the share of RD&D for RE has increased, but public R&D for CSS is lower, and does not reflect its potential importance (see 7.11) for the achievement of negative emissions (von Stechow et al., 2011; Scott et al., 2013) (IEA, 2012j).

Although private R&D expenditures are seldom disclosed,[38] they are estimated to represent a large share of the overall spending for RD&D activities (IEA, 2012j). Private R&D investments are not only stimulated by R&D policies. Additional policies (e.g., deployment policies, see above and 15.6) addressing other parts of the innovation chain as well as broad GHG pricing policies might assist in triggering private investments in R&D (IPCC, 2011a, p. 851; Rogge et al., 2011; Battelle, 2012).

The integration of variable RE poses additional challenges, as discussed earlier in section 7.6, with a variety of possible technical and institutional responses possible. Many of these technical and institutional measures require an enabling regulatory framework facilitating their application. Infrastructure challenges, e.g. grid extension, are particularly acute for RE deployment in developing countries, sometimes preventing deployment (IRENA, 2012a). Governments can play a prominent role in providing the infrastructure (e.g., transmissions grids or the provision of district heating and

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[38] A rare exception is the annual forecast of Battelle (2012).

cooling systems) that is needed to allow for a transformation of energy systems towards lower GHG emissions (IEA, 2012b; Grubb et al., 2013).

7.12.5 Voluntary Actions

Voluntary agreements (see 15.5.7.4) have been frequently applied in various sectors around the globe, though they often have been replaced by mandatory schemes in the long-term (Halsnæs et al., 2012). According to chapter 15, their success is mixed. “Voluntary agreements had a positive effect on energy efficiency improvements, but results in terms of GHG emissions reductions have been modest, with the exception of Japan, where the status of these voluntary agreements has also been much more ‘binding’ than in other countries in line with Japanese cultural traditions” (Halsnæs et al., 2012, p. 13; IPCC, 2007; Yamaguchi, 2012).

7.13 Gaps in knowledge and data

Gaps in knowledge and data are addressed to identify those which can be closed through additional research and others which are inherent to the problems discussed and are therefore expected to persist. Chapter 7 is confronted by various gaps in knowledge, especially those related to methodological issues and availability of data:

- The diversity of energy statistic and GHG emission accounting methodologies as well as several years delay in the availability of energy statistics data limit reliable descriptions of current and historic energy use and emission data on a global scale. [7.2, 7.3]
- Although fundamental problems in identifying fossil fuel and nuclear resource deposits, the extent of potential carbon storage sites, and technical potentials of RE are acknowledged, the development of unified and consistent reporting schemes, the collection of additional field data and further geological modeling activities could reduce the currently existing uncertainties. [7.4]
- There is a gap in our knowledge concerning fugitive CH_4 emissions as well as adverse environmental side-effects associated with the increasing exploitation of unconventional fossil fuels. As novel technologies are applied in these fields, research could help reduce the gap. Operational and supply chain risks of nuclear power plants, the safety of CCS storage sites and adverse side-effects of some RE, especially biomass and hydro power, are often highly dependent on the selected technologies and the locational and regulatory context in which they are applied. The associated risks are therefore hard to quantify, although further research could, in part, reduce the associated knowledge gaps. [7.5]
- There is limited research on the integration issues associated with high levels of low carbon technology utilization. [7.6]
- 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]
- 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. Especially, there is a lack of consistent and comprehensive global surveys concerning the current cost of sourcing and using unconventional fossil fuels, RE, nuclear power and the expected ones for CCS and BECCS. In addition, there is a lack of globally comprehensive assessments of the external cost of energy supply and GHG related mitigation options. [7.8, 7.9, 7.10]
- Integrated decision making requires further development of energy market models as well as integrated assessment modeling frameworks, accounting for the range of possible co-

benefits and trade-offs between different policies in the energy sector that tackle energy access, energy security and/or environmental concerns [7.11].

- Research on the effectiveness and cost-efficiency of climate-related energy policies and especially concerning their interaction with other policies in the energy sector is limited. [7.12]

7.14 Frequently Asked Questions

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

The energy supply sector 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 supply sector was responsible for 46% of all energy-related GHG emissions (IEA, 2012b) and 35% of anthropogenic GHG emissions, up from 22% in 1970. [7.3]

In the last ten years, the growth of GHG emisisons from the energy supply sector has outpaced the growth of all anthropogenic GHG emissions by nearly 1% per year. Most of the primary energy delivered to the sector is transformed into a diverse range of final energy products including electricity, heat, refined oil products, coke, enriched coal, and natural gas. A significant amount of energy is used for transformation, making the sector the largest consumer of energy. Energy use in the sector results from end user demand for higher quality energy carriers such as electricity, but also the relatively low average global efficiency of energy conversion and delivery processes. [7.2, 7.3]

Increasing demand for high quality energy carriers by end users in many developing countries has resulted in significant growth in the sector's GHG emission, particularly as much of this growth has been fueled by the increased use of coal in Asia, mitigated to some extent by increased use of gas in other regions and the continued uptake of low carbon technologies. While total output from low carbon technologies, such as hydro, wind, solar, biomass, geothermal and nuclear power, has continued to grow, their share of global primary energy supply has remained relatively constant; fossil fuels have maintained their dominance and carbon capture and storage (CCS) has yet to be applied to electricity production at scale. [7.2, 7.5]

Biomass and hydro power dominate renewable energy, 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. Renewable energy accounts for one fifth of global electricity production, with hydroelectricity taking the largest share. Importantly, the last ten years has seen significant growth in both wind and solar which combine to deliver around one tenth of all renewable electricity. Nuclear energy's share of electricity production declined from maximum peak of 17% in 1993 to 11% in 2012. [7.2, 7.5]

FAQ 7.2 What are the main mitigation options in the energy supply sector?

The main GHG mitigation options in the energy supply sector are: energy efficiency improvements; the reduction of fugitive non-CO_2 GHG emissions; switching from (unabated) fossil fuels with high specific GHG emissions (e.g. coal) to those with lower ones (e.g. natural gas); use of renewable energy; use of nuclear energy; and carbon capture and storage (CCS). [7.5]

No single mitigation option in the energy supply sector will be sufficient to hold the increase in global average temperature change below 2°C above pre-industrial levels. A combination of some, but not necessarily all, of the options is needed. Significant emission reductions can be achieved by energy efficiency improvements and fossil fuel switching, but they are not sufficient by themselves to provide the deep cuts needed. Achieving deep cuts will require more intensive use of low GHG technologies such as renewable energy, nuclear energy, and CCS. Using electricity to substitute for other fuels in end-use sectors plays an important role in deep emission cuts, since the cost of decarbonizing power generation is expected to be lower than that in other parts of the energy supply sector. [Chapter 6, 7.11]

While the combined global technical potential of low carbon technologies is sufficient to enable deep cuts in emissions, there are local and regional constraints on individual technologies [7.4, 7.11]. The contribution of mitigation technologies depends on site and context specific factors such as resource availability, mitigation and integration costs, co-benefits/ adverse side-effects and public perception [7.8, 7.9, 7.10]. Infrastructure and integration challenges vary by mitigation technology and region. While these challenges are not in general technically insurmountable, they must be carefully considered in energy supply planning and operations to ensure reliable and affordable energy supply [7.6].

FAQ 7.3 What barriers need to be overcome in the energy supply sector to enable a transformation to low GHG emissions?

The principal barriers to transforming the energy supply sector are: mobilizing capital investment; lock-in to long-lived high-carbon systems; cultural, institutional and legal aspects; human capital; and lack of perceived clarity about climate policy. [7.10]

Though only a fraction of available private-sector capital investment would be needed to cover the costs of future low-GHG energy supply, a range of mechanisms – including climate investment funds, carbon pricing, removal of fossil fuel subsidies and private–public initiatives aimed at lowering barriers for investors – need to be utilized to direct investment towards energy supply. [7.10.2]

Long-lived fossil energy system investments represent an effective (high carbon) lock-in. The relative lack of existing energy capital in many developing countries therefore provides opportunities to develop a low-carbon energy system. [7.10.5]

A holistic approach encompassing cultural, institutional and legal issues in the formulation and implementation of energy supply strategies is essential, especially in areas of urban- and rural-poverty where conventional market approaches are insufficient. Human capital capacity building - encompassing technological, project planning, institutional and public engagement elements – is required to develop a skilled workforce and to facilitate widespread adoption of renewable, nuclear, CCS and other low GHG energy supply options. [7.10.3, 7.10.4]

Elements of an effective policy aimed at achieving deep cuts in CO2 emissions would include a global carbon pricing scheme supplemented by technology support, regulation and institutional development tailored to the needs to individual countries (notably less developed countries). [7.12, Chapter 13 – 15]

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