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This chapter has been allocated 60 template pages (plus an additional 8 for the bioenergy annex). It currently counts 86 (plus an additional 9 bioenergy pages), so it is 27 pages over target (plus an additional 1 bioenergy page). Reviewers are kindly asked to indicate where the chapter could be shortened.]

Turquoise highlights are inserted comments from Authors or TSU i.e. [AUTHORS/TSU: ….]

Chapter 7: Energy Systems

Contents

Executive Summary

The energy sector is the largest contributor to global GHG emissions, but it provides only part (45%) of *energy-related* GHG emissions in form both fugitive methane emissions in fuel extraction and transportation and as result of fuel combustion in energy extraction, conversion, storage, transmission and distribution processes. Despite the recent swings witnessed in our economic and political systems, many of the trends in the energy sector observed in AR4 have continued unabated. Energy-related GHG emissions continue to grow; they have increased even faster in the last decade than the three decades previous to this period [7.3, high agreement; robust evidence]. Rapid economic development along with the failure to decarbonize the global fuel mix has driven most of the acceleration in emissions growth in the last decade. GHG emissions increased faster than the rate of energy consumption largely as a result of increased coal use in power generation [7.3, high agreement; robust evidence]. A wide array of GHG mitigation policies have been initiated in the energy supply sector, but these are not yet sufficient to achieve the substantive deviation from current trends by 2020 as required for most 450ppmv CO_2eq stabilization pathways [7.3, high agreement; medium evidence].

By 2050, growth in population, economic activity and energy access is expected to give rise to a 1.6 to 2.5 fold increase in energy use and energy related GHG emissions in business-as-usual scenarios [7.12, high agreement; medium evidence]. Fossil fuel resources are abundant and cost competitive with other energy forms. Since the industrial revolution, fossil fuel combustion released almost 400 Gt C into the atmosphere. Left hydrocarbon reserves alone contain two to four times that amount of carbon. Therefore, limits or constraints on fossil fuel availability cannot be relied upon to limit global GHG concentrations to levels consistent with the Copenhagen Accord [7.4, high agreement; robust evidence].

Numerous low carbon and GHG mitigating power and heat generation technologies are already available. When taken together, these technologies can facilitate deep reductions in energy-related GHG emissions [7.12, high agreement; robust evidence]. Anticipated technological advances and reduced production costs will continue to expand the possible options over time [7.5, high agreement; robust evidence]. Although there may be constraints at a regional level, and for individual technologies, at the global level, the combined technical potential of low carbon technologies in the energy supply sector is not the factor limiting their widespread deployment [7.4, medium agreement; robust evidence]. Significant and relatively inexpensive medium-term emissions reductions can be achieved by replacing coal fired power plants with modern, highly efficient gas fired ones [7.5, high agreement; robust evidence]. The regional technical potential of RE as a whole is at least 2.6 times as large as 2007 global primary energy supply [7.4, medium agreement; medium evidence], but only a small fraction of this potential has so far been tapped [7.4, high agreement; robust evidence]. A growing number of RE technologies have achieved a level of technical and economic maturity to be deployed at significant scale and, in 2011, RE accounted for almost half of all the new electricity generating capacity added globally [7.5, high agreement; robust evidence]. RE is likely to penetrate most rapidly in electricity generation, at least in the near to medium term, followed by RE for heating/cooling and transport [7.5, medium agreement; medium evidence]. Resolutions on many issues remain for the continued use and further expansion of nuclear energy worldwide as a response for mitigating climate change, including efforts to improve the safety, economics, resource sustainability, waste management, and proliferation concerns. Significant efforts are underway to develop new fuel cycles and reactor technologies that address the concerns of nuclear energy use. The capture and storage of CO_2 (CCS) provides a means by which fossil fuel emissions can be dramatically reduced. Applications include most large point sources of CO_2 emissions, e.g. fossil fuels production sites, power plants, refineries, chemical processing plants and cement kilns. Presently, all of the components of integrated CCS systems exists and are in use. Total practical geologic storage capacity is large and likely sufficient to meet demand for CO_2 storage over the course of this century, but geographically unevenly distributed. The prospect of moving CO_2 by ocean vessels in addition to pipelines opens the door to a potential "global CO_2 storage market." Use of bioenergy with CCS creates an opportunity for negative emissions and opens a door to an active reduction in atmospheric CO_2 concentrations [7.5, high agreement; robust evidence].

Mitigation technologies are at various stages of technical maturity, with differing energy costs, and have distinctly different regional potential. They are also subject to a diversity of societal preferences and context so that the resulting technology mix adopted can be expected to vary regionally and over time [7.10, 7.12, high agreement; robust evidence]. Factors such as sustainability concerns, public acceptance, systems integration and infrastructure constraints, and economic competitiveness may limit the deployment of individual low carbon options well before technical potential limits are reached [7.4, high agreement; robust evidence]. For least developed countries, their dissemination will imply a massive technology transfer coupled with financial support. In favourable settings, some of the low carbon energy supply technologies are already economically competitive: for example, larger-scale RE power supplies can be competitive with fossil fuel alternatives, while smaller-scale hydropower, solar photovoltaics, and modern bioenergy systems can sometimes be less expensive than other alternatives to increasing energy access in off-grid, remote and rural areas [7.8, medium agreement; medium evidence].

Power production is the largest single emitting sector (40% of *energy-related* GHG emissions) and it will play a major role in transformation scenarios with deep cuts of GHG emissions [7.12, high agreement; robust evidence]. The diverse characteristics of various forms of low-carbon energy supply suggest that combinations of options rather than a single dominant source will minimize the cost and technical integration challenges of achieving low GHG concentrations. Because of the unique characteristics of certain forms of low-carbon energy supply, however, some combinations of options may be less attractive than others [7.6 and 7.12, high agreement; medium evidence]. The unavailability of any one key low GHG energy supply option will necessitate systemic changes in the use of the remaining set of low GHG resources, technologies and demand measures, or emissions will rise, increasing both marginal and total cost of achieving a prescribed emissions limit [7.12, high agreement; medium evidence]. Infrastructure and integration issues vary by mitigation technology and region, and while they are not generally technically insurmountable, such issues must be carefully considered in energy supply planning and operations to ensure reliable and affordable energy supply and may require changes in patterns of energy use and consumer expectations, and result in higher energy costs [7.6, medium agreement; robust evidence]. These factors may also apply to deployment of fossil fuels [7.4, high agreement; robust evidence].

There are often co-benefits from the use of mitigation technologies in the energy supply sector, such as reduction of air pollution, employment opportunities, lower energy production related fatality rates, better energy security, improved energy access and reduced vulnerability to price volatility [7.9, high agreement; robust evidence]. At the same time, however, many low carbon technologies can have substantial negative ecological impacts, though those impacts can be mitigated to a degree through the appropriate selection, design and siting of the technology [7.9, high agreement; robust evidence]. Additionally, at high penetration, GHG emissions from low carbon technology can act to limit penetration if a low GHG stabilization target is desired [7.8, high agreement; robust evidence].

Considerable populations do not have access to modern energy resources and technologies, especially in Africa and Asia [7.3, high agreement; robust evidence]. Providing universal access to modern affordable energy services will require removing different cultural, institutional and legal barriers, but not necessarily lead to any significant changes in GHG emissions [7.9, high agreement; limited evidence].

To increase social acceptance of low-carbon technologies, a variety of procedures have been shown to be effective, such as: ensuring that accurate and unbiased information about the technology, its impacts and benefits, and its interplay with other technologies is widely distributed; aligning the expectations and interests of different stakeholders; adjusting to the local societal context; adopting benefit sharing mechanisms; obtaining explicit support at the local and national levels prior to development; building collaborative networks, and developing mechanisms for articulating conflict and engaging in negotiation [7.9, medium agreement; medium evidence]. Integrated analysis tools and modeling frameworks, accounting for the range of possible co-benefits and trade-offs of different policies that tackle access, security and/or environmental concerns, as well as institutional and human capacity for the use of such tools and frameworks, are required to better support integrated decision making [7.9, medium agreement; medium evidence].

Energy systems are highly path dependent: policy decisions and investments made in the near term will have a large impact on the attainability and costs of long term mitigation pathways [7.10, 7.12, high agreement; medium evidence]. Transition to low GHG concentrations will not be achieved by current energy investments nor simple evolution of business-as-usual of energy supply systems [high agreement; robust evidence]. Existing energy-related capital stock has already locked in 80% of the permissible 2035 CO_2 emissions under a 450ppm CO_2eq stabilization scenarios [7.12, high agreement; robust evidence]. Strong policy support of low-carbon energy supply options will be necessary to achieve this goal requiring energy related GHG emissions to peak already by 2020 [7.12, high agreement; robust evidence]. Energy policies consistent with ambitious long-term greenhouse gas concentration levels, such as are described in Chapter 6, are not observed in most of the world at present, though governments have pledged to reduce emissions in line with the Copenhagen Accord [7.3. and 7.12, high agreement; robust evidence].

7.1 Introduction

7.1.1 Goals and context (boundaries) of this chapter

After relatively stable development in 2000-2005 (the period covered by the WG3 IPCC AR4) the global economic and energy systems entered times of high turbulence and uncertainty. Deep global economic recession of 2008-2009; extremely volatile energy prices; Arab Spring of 2011 with concerns on stability of oil supply from the Middle East and North Africa; devastating earthquake and tsunami in Japan, which made the nuclear power future more uncertain; slow and uneven pace of global economy recovery impacted by the debt crisis in Europe and the USA, and finally failure to reach binding agreement of GHG emission control in Copenhagen, and at following UNFCCC COPs meetings - all those events significantly altered both recent trends in energy systems developments and energy related GHG emissions, as well as assumptions for the projections and visions of the near and long-term future.

The global energy related CO_2 emissions growth accelerated from 1,1% per year in 1990-2000 to 2,6% in 2001-2010, and 3% in 2011 (IEA, 2011a; Enerdata, 2012). This acceleration was mostly driven by emissions from non-Annex I countries, which in 2008 for the first time surpassed those of the Annex I countries, who managed to keep emissions since 2008 below 1990 levels (IEA, 2011a). The gap in per capita energy related CO_2 emissions between Annex I and non-Annex I countries is still large, but shrunk from 6:1 to 3.7:1 in 2000-2009. Annex I countries are not any more at the top of CO_2 emitting countries list. In 2007 China took the leading position in this list and in 2010 it emitted already 40% more than the second largest emitter – the USA. In 2009 it took over the USA the position of leading energy consuming nation, and in 2011 – position of the largest global electricity consumer (Enerdata, 2012). In 2010 India overcame the Russian Federation to become the third largest CO_2 emitter position (IEA, 2011a). With such acceleration the global community is approaching the no-return point for 450 ppmv like scenarios leaving little additional room for maneuver and scaling up the need to introduce zero- and low- carbon technologies (IEA, 2011a).

Chapter 7 is dealing with energy systems, which dominated global GHG emissions and includes activities on energy sourcing, conversion, storage, transmission and distribution to supply energy to downstream energy consumers. Technical complexity of energy systems is scaling up and involves more and more conversion and delivery stages. They are designed to produce primary energy, to convert it into secondary energy carriers, store them and deliver to final users to provide energy services in forms allowing improving both the quality of life and overall economic productivity.

This chapter assesses what a new and different in the literature on energy systems from earlier IPCC reports. Section 7.2 pre-sets static picture of global energy balance, presents status of global and regional energy markets and energy flows, scale and structure of energy related GHG emissions. A dynamic picture with accent on new developments in energy related emission trends, drivers and policies as well as on gaps with targets for GHG emission reduction is presented in section 7.3. The following section presents data on resources bases for different energy resources split by production costs and shows the evolution of primary energy resources base. Section 7.5 presents results on the evaluation of new technologies and practices for energy sourcing, conversion, transmission and distribution and potential for their penetration. Infrastructure and systemic perspectives, issues of system integration and intermittency, technological innovations allowing for a better integration of energy supply systems are covered in section 7.6. Section 7.7 allows understanding better how potential or already registered climate change impact or may impact energy demand and supply with more comprehensive material in this issue presented in AR5 WG2 report. Section 7.8 presents technical potentials of mitigation measures, current levelized cost of energy, historic cost changes and a discussion of economic potentials including an accounting of infrastructure costs. The next section is on issues of co-benefits, technological, environmental and other risks, and spill-over effects, and on public acceptability of energy technologies options. Barriers and opportunities including technological, physical, financial, institutional, cultural, legal ones as well as inertia issue are dealt with in section 7.10. Section 7.11 presents energy sector specific policies including RD&D, greenhouse gas pricing, and technology specific policies as well as associated enabling conditions. Sectoral implication of transformation pathways and sustainable development are covered in section 7.12. Two last sections address gaps in knowledge and data and frequently asked questions. The allocation of cross-cutting issues among other chapters allows understanding better the chapter 7 boundaries. Energy requirements for meeting basic needs, as well as the importance of energy for social and economic development are reviewed in Chapter 4 and lesser degree in section 7.10 of this chapter. Chapter 6 presented long-term transformation pathways and futures for energy systems. This chapter concentrates on medium-term projections (to 2030-2035). Comparisons with stabilization pathways allow understanding the gap and challenge, including sustainable development implications of rapid transformations and disruptive changes. Local fuel supply infrastructure is the subject of Chapter 8. Building integrated power and heat generation as well as biomass use for cooking are addressed in chapter 9. Responsive load issues are dealt with by chapters 8 and 9. Chapter 7 considers mitigation options in energy extraction industries (oil, gas, coal, uranium etc.) while other extractive industries are addressed in Chapter 10. This chapter addresses the transformation of wood into charcoal, but does not address natural forest management. This chapter also considers energy storage. Only energy sector related policies are considered in this chapter while broader and more detailed policy picture is presented in chapters 13-15.

7.1.2 Summary of AR4

4AR concluded that the world is not yet on a course to achieve a sustainable energy future. Mitigation has therefore become even more challenging. Decisions taken today that support the deployment of long lasting carbon-emitting technologies could have profound effects on GHG emissions for the next several decades. Without the near-term introduction of supportive and effective policies by governments, the global energy supply will continue to be dominated by fossil fuels for several decades and total greenhouse gas (GHG) emissions arising from the global energy supply sector continue to increase.

The wide range of energy sources and carriers that provide energy services need to offer energy access for all, long-term energy security, be affordable and have minimal impact on climate and the environment. To reduce the resultant GHG emissions will require a transition to zero and low-carbon technologies. This transition has begun and there is large mitigation potential available for increased deployment at costs below 20 US$/tCO2.

Conventional oil reserves will eventually peak, but it is uncertain exactly when and what will be the nature of the transition to alternative liquid fuels. Conventional natural gas reserves are larger by scale, but less evenly distributed across regions. Unconventional oil and gas resources are abundant, with uncertain future for the scale of their economic development (IEA, 2012). More reliance on coal will demand viable CCS technologies if GHG emissions from its use are to be limited. There are many barriers for nuclear energy to contribute more to GHG mitigation: long-term fuel resource constraints without recycling; economics; safety; waste management; security; proliferation, and adverse public opinion. Renewable energy sources provide currently small - contribution to global heat and electricity supply, but are the most rapidly increasing. Costs, as well as social and environmental barriers, are restricting this growth. Smaller-scale, distributed energy plants using local energy resources and low or zero-carbon emitting technologies, can give added reliability, be built more quickly and be efficient by utilizing both heat and power outputs locally.

No single policy instrument will ensure the desired transition to a future secure and decarbonized world. Policies will need to be regionally specific and both energy and non-energy co-benefits as well as social acceptance and technological risks should be taken into account based on sound science and economic analysis. Energy sector reform is critical to sustainable energy development and includes reviewing and reforming subsidies, establishing credible regulatory frameworks, developing policy environments through regulatory interventions, and creating market-based approaches such as emissions trading. For developing countries, particularly oil importing countries, lack of security and higher world-energy prices constrain endeavors to accelerate access to modern energy services that would help to decrease poverty, improve health, increase productivity, enhance competition and thus improve their economies.

7.2 Energy production, conversion, transmission and distribution

7.2.1 Global energy balance and energy flows

Not only energy future, but energy past is also uncertain. For 2009 different statistical sources report different total global energy consumption: 509 EJ (IEA, 2011b), 483 EJ (BP, 2011a), 523 EJ (US DOE, 2010), 469 EJ (UN, 2011).[1] Much of primary energy (over three quarters) is converted in energy supply sectors into other forms: electricity, heat, refined oil products, coke, enriched coal, and natural gas allowing for better energy services to final users.

Due to the technological progress - driven by high energy prices and climate mitigation policies among many other factors, there is a long standing trend of growing contributions from unconventional fuels and renewables contributing to the diversity of primary energy options. Of 171.5 EJ of “crude oil supply” in 2009 natural gas liquids contributed 14 EJ, extra heavy oil and bitumen 4.2 EJ, coal-to-liquids production is assessed at 0.4 EJ (IEA, 2010a), gas-to-liquids at 0.2 EJ, biofuels at 1.5 EJ (US DOE, 2010), with a small contribution from shale oil and light tight oil production (IEA, 2010a, 2011a). In the gas balance the share of non-conventional gas production (shale gas, tight gas, coal-bed methane and biogas) exploded to 14% in 2010 (IEA, 2012a). Nonetheless, conventional fossil fuels continue dominating total primary energy supply (TPES) and

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[1] The reasons for disagreements on the scale of the past global energy supply are rooted in different energy balance construction methodologies (for details see Appendix Methodology). More comprehensive coverage of energy resources, including non-commercial ones, allows for better understanding of energy transitions trends and laws (Bashmakov, 2007; Grubler, 2008, chapter 5). In contrast to IEA, the UNSD does not provide energy balances with consumption split by sectors grouped by regions, and aggregated to the global level.

moreover this dominance was enhanced in last decade (2001-2009) driven by growing coal use in power sector mostly in China (Figure 7.1).

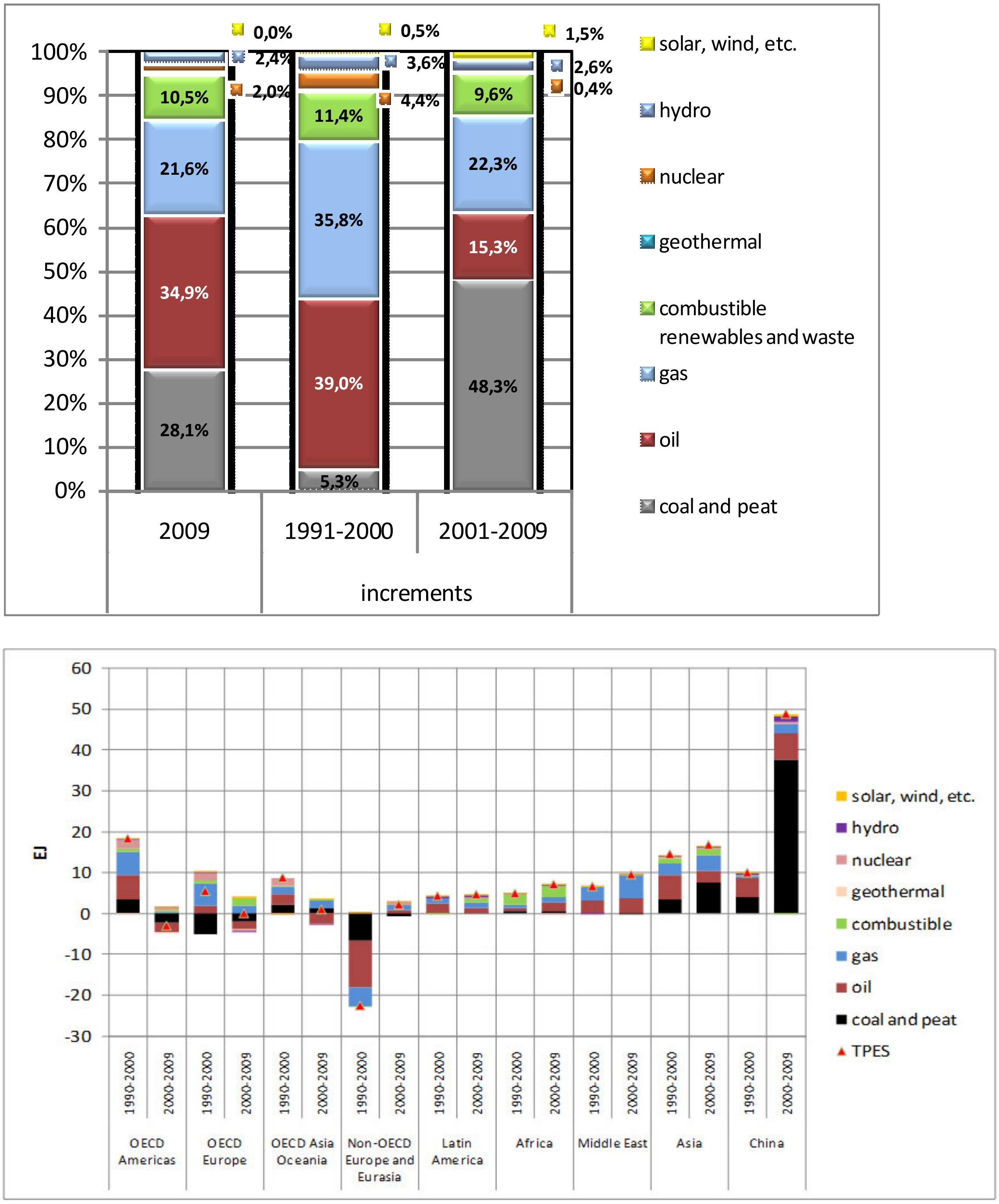

Figure 7.1. Shares of energy sources in global primary energy supply in 2009 (492.8 EJ) and in its global increments along with energy sources contribution to regional primary energy supply evolutions. Notes: Modern biomass contributes 40% of the total biomass share. Underlying data from IEA for this figure have been converted using the direct equivalent method of accounting for primary energy. [Author note: Figure will be updated upon new statistics release.]

As energy extraction, conversion, storage, transmission and distribution processes are becoming more diverse, the energy sector component of the global energy balance becomes more complex and more populated, with more processes providing solid, liquid, gaseous fuels, electricity and heat from the same primary energy source and often at the same site. The energy supply sector is itself the largest energy user. Energy losses assessed as the difference between the energy inputs to

(78.6% of the TPES) and outputs from this sector (50.7% of TPES) account for 27.9% of TPES (Table 7.1).

Table 7.1: 2009 World Energy Balance (EJ on a net calorific value basis)

Supply and consumption	Coal and peat	Crude oil	Oil products	Gas	Nuclear	Hydro	Geothermal. Solar.etc.	Combustible renewables and waste	Electricity	Heat	Total*	*Share in TPES*	*Conversion efficiency and losses*
Production	**144.42**	**167.24**	**0.00**	**105.78**	**9.73**	**11.71**	**2.13**	**51.79**	**0**	**0.04**	**492.84**	***101.20%***	
Imports	24.21	94.18	42.07	31.55				0.34	2.12	0.00	194.47	*39.94%*	
Exports	-25.72	-89.86	-46.57	-30.64				-0.33	-2.08	0.00	-195.20	*-40.09%*	
Stock Changes	-4.76	-0.09	-0.02	-0.33				0.02			-5.19	*-1.07%*	
TPES	**138.14**	**171.47**	**-4.53**	**106.35**	**9.73**	**11.71**	**2.13**	**51.82**	**0.04**	**0.04**	**486.91**	***100.00%***	
Share in TPES	*28.37%*	*35.22%*	*-0.93%*	*21.84%*	*2.00%*	*2.40%*	*0.44%*	*10.64%*	*0.01%*		*100.00%*		
Transfers	0.00	-5.74	6.11					0.02			0.39	*0.08%*	
Statistical Differences	-1.04	-0.52	0.00	-0.26			-0.01	0.00	0.28	0.00	-1.55	*-0.32%*	
Electricity Plants	-78.38	-1.27	-8.39	-26.60	-9.64	-11.71	-1.32	-2.27	65.37	-0.01	-74.23	*-15.24%*	*36.67%**
CHP Plants	-7.18		-0.98	-11.88	-0.10		-0.02	-1.29	6.85	5.86	-8.73	*-1.79%*	*27.87%**
Electricity generation (bln kWh)	*8119*	*16*	*1011*	*4301*	*2697*	*3252*	*370*	*288*		*1*	*20055*		
Share in electricity generation	*40.48%*	*0.08%*	*5.04%*	*21.45%*	*13.45%*	*16.21%*	*1.85%*	*1.44%*	*0.00%*	*0.01%*	*100.00%*		
Heat Plants	-4.04	-0.03	-0.51	-3.62				-0.36	-0.01	7.05	-1.53	*-0.31%*	*78.61%**
Gas Works	-0.28		-0.15	0.12							-0.31	*-0.06%*	*28.01%*
Oil Refineries		-162.47	160.93	-0.02							-1.56	*-0.32%*	*99.04%*
Coal Transformation	-8.07		-0.10	0.00				0.00			-8.18	*-1.68%*	
Liquefaction Plants	-0.79	0.46	0.00	-0.28							-0.61	*-0.13%*	*42.68%*
Other Transformation	0.00	0.01	-0.04	-0.09				-2.14		-0.01	-2.28		*0.30%*
Energy Industry Own Use	-3.46	-0.43	-8.67	-9.98			-0.01	-0.55	-6.10	-1.43	-30.62	*-6.29%*	*6.29%*
Losses	-0.07	-0.16	-0.03	-0.75			-0.01	-0.01	-6.08	-0.89	-7.99	*-1.64%*	*1.64%*
Total energy sector	**-102.27**	**-163.90**	**142.06**	**-53.09**	**-9.73**	**-11.71**	**-1.36**	**-6.62**	**60.02**	**10.56**	**-136.05**	***-27.94%***	
Share of energy sector	*74.03%*	*95.58%*	*11.72%*	*49.92%*	*100.00%*	*100.00%*	*63.71%*	*12.78%*	*8.17%*	*18.21%*	*32.50%*		
Total Final Consumption (TFC)	**34.83**	**1.32**	**143.64**	**53.00**			**0.76**	**45.22**	**60.35**	**10.60**	**349.71**	***71.82%***	*Share in FEC*
Share of energy carriers	9.96%	0.38%	41.07%	15.15%			0.22%	12.93%	17.26%	3.03%	100.00%		
Industry	26.97	0.46	12.97	18.48			0.02	7.79	24.26	4.61	95.55	*19.62%*	*27.32%*
Transport	0.14		89.41	2.94				2.16	0.97	0.00	95.63	*19.64%*	*27.35%*
Buildings	4.37		13.20	24.86			0.39	34.85	31.46	5.37	114.50	*23.51%*	*32.74%*
Agriculture/forestry/fishing	0.41		4.42	0.26			0.02	0.30	1.58	0.14	7.13	*1.46%*	*2.04%*
Non-Specified	1.38	0.01	0.50	0.75			0.34	0.12	2.07	0.49	5.66	*1.16%*	*1.62%*
Non-Energy Use	1.55	0.85	23.14	5.71							31.26	*6.42%*	*8.94%*

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

The share of energy sector in the global energy balance is a function of end users' demand for higher quality energy carriers (liquid fuels, electricity, district heat and gas), but also of relatively low average global efficiency of energy conversion, transmission and distribution processes: only 37% for fossil fuel power and just 79% for fossil fuel district heat generation; as well as of method applied to convert primary electricity and primary district heat into primary energy[2]. Those low efficiencies and large own energy use in energy sector result in a high potential indirect multiplication effects of energy savings from end users[3]

Much of the TPES (28.7%) are inputs to electricity plants and additional 4.4% – to CHP plants with generation losses from both equal to 16.7% of TPES. In 2009, 40.5% of all electricity was generated using coal, 5.1% – oil, 21.5% – gas, 13.5% – nuclear, 16.2% – hydro, 0.8% – geothermal, 0.06% – solar, 1% – wind, 1.4% – combustible renewables and waste, thus resulting in renewable energy contribution of 19.4% of global electricity supply (Table 7.1). Average efficiency of coal-fired plants is just 35% with variations between 15% and 50%. Gas-fired plants have global average efficiency of 43% (60% best practices), leaving a large room for efficiency improvement in power generation (IEA, 2011a; Rogner et al., 2011). The energy sector's own use is another 6% (Table 7.1). Losses in fossil fuels enrichment and conversion processes, as well as losses in delivering electricity, heat and natural gas through thousands kilometers long transmission and distribution networks linking energy conversion centres and consumers are 1.6% of TPES averaging globally to 8.2% for electricity and 6.9% for heat networks. These do not account for the energy used by the transportation sector to deliver fuels, which for the pipeline transport alone is 3 EJ (0.6% of TPES), and for water, rail and automobile transport may be just as large.

Ageing equipment, congested networks, and extreme peak-load demands contribute to system losses and low reliability, especially in developing countries, often requiring substantial upgrades. Existing infrastructure needs to be modernized to improve security, to add information and controls, and to reduce emissions (Rogner et al., 2011).

The energy supply sector provided energy to end-use sectors. Industry (including non-energy use)[4] consumes 82% of final use of coal and peat, 25% of petroleum products, 46% of natural gas, 40% of electricity, and 44% of heat. Transportation consumes 62% of liquid fuels final use. Building sector is responsible for 47% of natural gas consumption, 77% of combustible renewables and waste, 52% of electricity use, and 51% of heat (Table 7.1). Forces driving 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.

7.2.2 Global and regional energy markets

Geographical abundance together with physical characteristics of fossil fuels is shaping their supply chains and markets (MIT, 2011). Slightly less than 40% of primary energy is traded across country boundaries widening the scope of fuels to be used by different sectors, but at a price of threatening both energy security of energy importers and stability of energy exporters' revenues with the

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[2] The largest losses are attributable to the substitution method, while application of direct equivalent method generates the lowest losses [see Appendix Methodology].

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

[4] The UN Energy Balances and Electricity Profiles publications consider non-energy use as a part of energy sector (UN, 2011).

growing interdependence and vulnerability to unpredictable energy prices. Beside of global crude oil market, there are markets for other fuels which are more regionally segmented with the scale depending on the history, the source of energy and the region in focus.

The development of truly global oil market with a 54% share of crude oil cross-border trade in the global consumption and 27% for petroleum products is based on relatively low cost of oil and petroleum products transportation for any distance. Most prominent oil supply security concerns relate to over 3 bln. people living in 83 countries (including all of the world's low-income countries) importing more than 75% of the oil and petroleum products they consume (Rogner et al., 2011). Expansion of liquids use in 2000-2009 was originated in non-OECD countries (mostly non-OECD Asia and the Middle East, Figure 7.1**),** fueled by robust economic growth and escalating transportation use. To meet this demand resources of both conventional liquid supplies (crude oil and lease condensate, natural gas plant liquids, and refinery gain) and unconventional supplies (biofuels, oil sands, extra-heavy oil, coal-to-liquids, gas-to-liquids, and shale oil) are started to be mobilized (US DOE, 2011a). OPEC in 2011 provided 42.4% of the world's total oil supply keeping its share even above 1980 level with the 33% coming from the Middle East alone (BP, 2012). The most significant non-OPEC contributors to production growth since 2000 were Russia, Brazil, Canada, China and Kazakhstan (BP, 2011a; IEA, 2011a; Rogner et al., 2011; US DOE, 2011a). Increasing reliance on imports in the importing non-OECD regions, notably Asia, inevitably heighten concerns about the cost of imports and supply security (IEA, 2011a).

Natural gas penetrates many markets because it burns efficiently with low GHG emissions, and requires limited processing to prepare for end use. But it is disadvantaged in terms of transmission and storage, because of its low energy density, which makes transportation costs a large fraction of the total supply chain costs. This limits the development of gas markets to regional scales. The escalation of markets for LNG to 32% of international gas trade in 2011 (BP, 2012) is injecting more flexibility into gas markets, opens new markets and stimulates its transition to real global gas trade (MIT, 2011). The share of internationally traded gas continues to grow in scope and scale and has reached 32% with special concern for almost 650 mln. people living in 32 Eurasian countries each relying on import for over 75% of gas needs (Rogner et al., 2011). For Russia, some Middle East and African countries the export of natural gas provides an important share of the GDP. Increases in U.S. natural gas production (with the share of unconventional gas reached 59% in 2010) and decreasing prices in U.S. markets have resulted in the movement of LNG supplies to higher-priced markets in South America, Europe, and Asia (IEA, 2012a). Natural gas supply by pipelines still delivers the largest gas volumes in North America and in Europe and it is projected in coming decades to deliver large volumes of pipeline flows into China from both Russia and Central Asia (US DOE, 2011a).

Coal is more evenly geographically distributed, which together with high coal transportation costs limits internationally traded amounts to 19% of global coal use. Only 12 countries currently significantly depend on coal imports (Rogner et al., 2011). Coal international trade is dominated by two regional markets: Atlantic one, made up of countries in Western Europe, and the Pacific market consisting of developing and OECD Asian coal importers. Australia dominated the list of coal exporters (IEA, 2011a). China is responsible for nearly 90% of additional global coal use in 2000-2009 (Figure 7.1). India also plays an increasingly important role. Power generation remains the main driver of global coal demand (US DOE, 2011a).

About 433 nuclear reactors worldwide require annually 77,000 t of uranium oxide concentrate (U_3O_8). Uranium mines supply about 60,000 t of U_3O_8 with the rest supplemented by secondary supplies from ex-military materials and other inventories (World Nuclear Association, 2011). Trend for uranium production to expand by 52% observed in 2000-2010 is challenged recently by the Germany's decision to phase out its nuclear program by 2022 and the Fukushima major accident in

Japan. The number of uranium exporters is limited to a few countries - Kazakhstan, Uzbekistan, Namibia, Niger and to a lesser extent South Africa, as well as Australia and Canada ((World Nuclear Association, 2011). Markets for other energy carriers (combustible biomass, waste, electricity, and heat) are mostly domestic with very limited amounts of cross-border trade (Table 7.1).

7.2.3 Scale of global energy related GHG emissions

The energy sector is the largest contributor of GHG emissions, but it provides only part of *energy-related* GHG emissions in form both of fugitive methane emissions in fuel extraction and transportation and as a result of fuel combustion in energy extraction, conversion, storage, transmission and distribution processes. *Energy-related* GHG emissions are originated mainly in the form of CO_2 along with some release of other GHGs dominated by methane (of which 37% is attributed to mainly coal and gas production and transmission) and nitrous oxide (of which 10% comes from coal and fuel-wood combustion and from road transport) (IEA, 2011c, based on EDGAR 4.2 FT 2008 dataset). In 2009, 43% of CO2 emissions from fuel combustion were produced from coal, 37% from oil and 20% from gas (IEA, 2011c). Some of *energy-related* emissions are produced by other sectors. Energy sector as such accounts for about 45% of *energy-related* CO_2 with emissions originated in electricity and heat generation alone responsible for 40%. The energy sector is followed by transport (22%), industry (20%), with the rest allocated to buildings and other sectors (Figure 7.2).

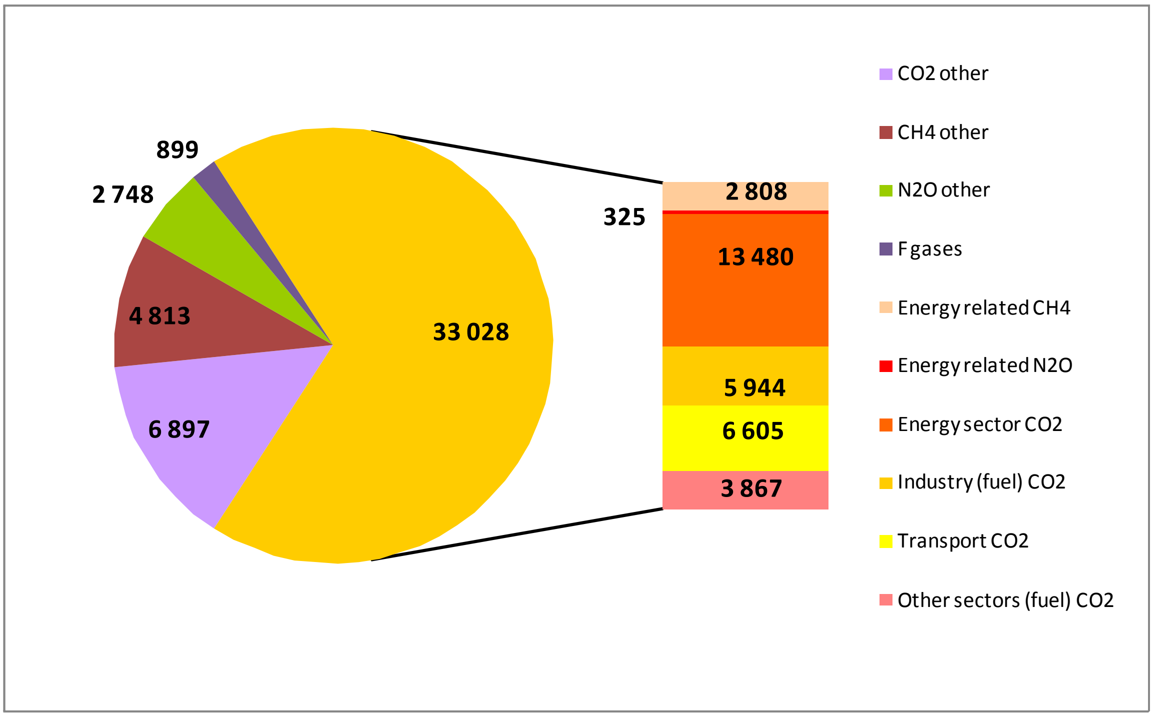

Figure 7.2. Scale and structure of the global anthropogenic greenhouse-gas emissions in 2008 (Gt CO2-eq) (IEA, 2011c). [Data will be updated upon new statistics is released]

As in the case with energy, there is some disagreement on the historical level of global *energy-related* CO_2 only emissions among different sources. Depending on fuel use data and emission evaluation methodologies it was reported for 2008 equal to 29.5-31.8Gt CO_2-eq. (BP, 2011a; IEA, 2011a; US DOE, 2011a). In 2008 *energy-related* GHG emissions exceeded 33 Gt CO_2-eq. providing over 68% of the total world anthropogenic GHG emissions (48.4Gt CO_2-eq, Figure 7.2).

There is a large variability in contributions of energy sector to total GHG emissions across countries, ranging 40-99% for developed countries and 1-99% for developing ones and economies in transition. For developing countries this is mainly due to least developed countries, where energy consumption is very low compared to global averages. However for large economies, either developed or emerging or in transition, the energy sector emissions contribute more than 60% to total national GHG emissions for the year 2009. Power generation dominates emissions in all 15 major emitting countries **(**Figure 7.3**).**

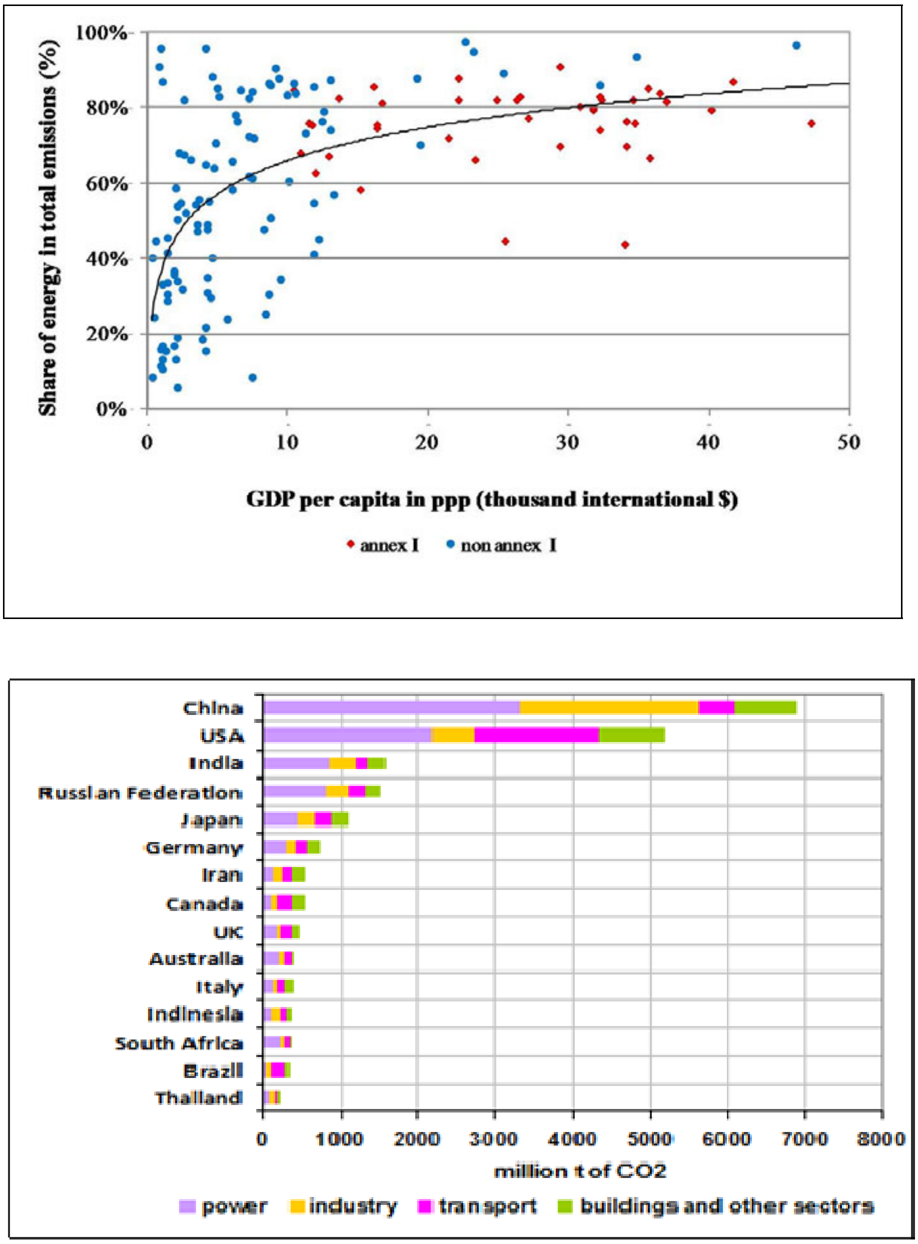

Figure 7.3. Share of energy related emissions in total GHG emissions (a); top 15 CO_2 emitting countries in 2009 (b). Sources: (UNFCCC, 2011; World Databank, 2011; IEA, 2011c)

7.3 New developments in emission trends and drivers

7.3.1 Global trends

7.3.1.1 Global primary energy supply and demand drivers

The major drivers for energy demand and supply growth include: natural resources availability, technology change; demographic factors; rates and structure of economic growth; energy prices, the structure of energy markets; government policies, including those to limit energy-related negative climate and environmental impacts and to provide energy security (Chapter 5; Rogner et al., 2011). Decomposition analysis allows for the identification of factors driving global energy demand, which can be presented as a function of population, GDP per capita, and energy intensity or a more diverse collection of factors. The interplay between the drivers in 2001-2010 was very different from that in the previous decades (Figure 7.4).Global total primary energy supply (TPES) expanded by 27%, or by 2.4% per annum (2% in 2011), which is much faster, than in 1980-2000, when energy prices were significantly lower.

Escalation of GDP per capita accelerated global GDP even with slower population growth. The rates of GDP energy intensity decline driven by new technologies penetration, as well as by structural changes in the economy (Ang et al., 2010; ODYSSEE, 2011) were slower and uneven: decline was interrupted three times in last 10 years (IEA, 2011a). Global GDP energy intensity evolution much dependent on the progress with energy efficiency improvements in non-OECD countries, particularly China, India and Russia (IEA, 2011a; Rogner et al., 2011; US DOE, 2011a).

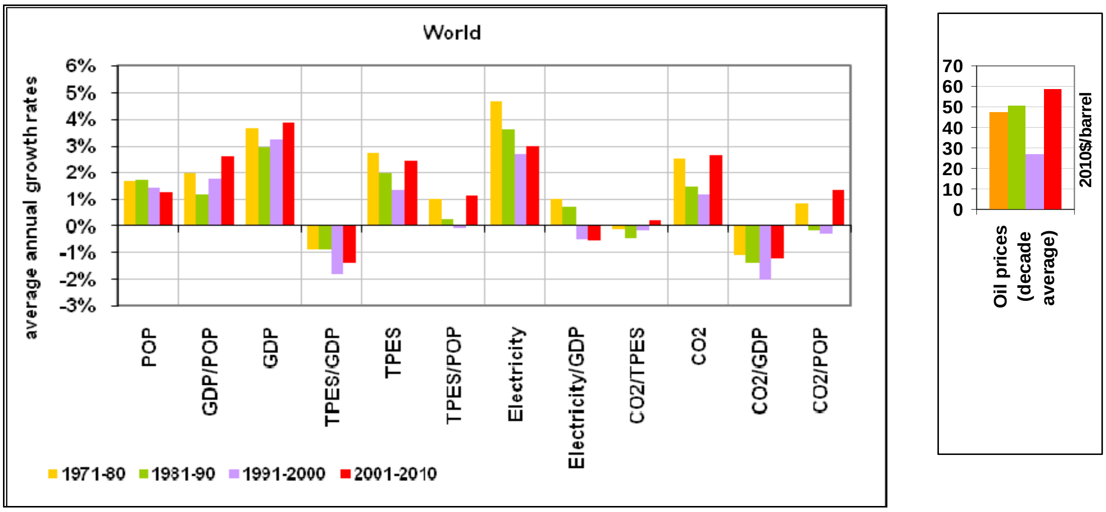

Figure 7.4. Composition of factors driving primary energy consumption and energy-related CO2 emissions, Sources: Developed based on data from IEA, (2010a); IEA, (2011c); IEA, (2011d); BP, (2011a). POP – population; GDP – GDP expressed in purchasing power parity; TPES – total primary energy supply; CO2 – energy related CO2 emissions. [Data will be updated upon new statistics is released]

Rates of global energy intensity decline were not sufficient to compensate for GDP growth, thus leaving room for energy demand to expand. The origin for energy demand growth is continuing to switch towards non-OECD countries (BP, 2011a; IEA, 2011a; US DOE, 2011a). Global energy consumption per capita after stabilization in 1991-2000 started growing as fast as it was back in 1971-1980.

The slow trend to diversification of energy sources away of fossil fuels was blocked in last decade (BP, 2011a; IEA, 2011a; US DOE, 2011a). Oil continues to suffer a long run decline in global energy market share. Nonetheless, despite energy security and climate concerns, oil demand was growing by 1% annually driven mostly by non-OECD transport with OECD demand likely peaked in 2005 and expected to decline (BP, 2011a; IEA, 2011a). Coal demand was growing by over 4% per annum and accounted for nearly half of the increase in global energy use in 2001-2010. The share of coal in the global energy mix after peaking around 28-30% in 2010-2011 is expected to decline. About all coal demand growth originated from non-OECD countries (Figure 7.1) with China pivotal in determining the future of global coal market (IEA, 2012a). With 2.7% per year consumption growth natural gas lost the status of the fastest growing fossil fuel to coal in the last decade. It is expected that its share will be back to the increase trajectory after flatting (IEA, 2012a).

In 2000-2010, nuclear power generation was growing slowly – by 0.6% per annum heavily loaded with public concerns related to safety, radioactive waste disposal, proliferation issues, high capital and maintenance costs (IEA, 2011a; US DOE, 2011a). Biomass and waste, including traditional and modern uses were growing by 2% per annum. The energy supply from renewables (including hydro) expanded by 3.6% per year in 2000-2010 and by 12-74% per year in most recent years for wind, solar and biofuel (see Figure 7.4). The rate at which modern renewables penetrate the global energy market is similar to the emergence of nuclear power in the 1970's and 1980's (BP, 2011a).

7.3.1.2 Evolution of global energy-related GHG emissions

According to the EDGAR 4.2 FT 2008 dataset, global total greenhouse-gas emissions increased by 27% during the 1990-2008 with CO_2 emissions from fuel combustion (+40%) drove much of this increase accompanied by CH_4 emissions from fossil fuel production (+43%) (EIA, 2011). CO_2 emissions trajectory partly mirrors the story of the global economic cycle and after decline in 2009 by about 2% regain over 5% in 2010 and by another 3% in 2011 reaching historical maximum of 31.4-33.2 Gt CO_2-eq. (BP, 2011a; Enerdata, 2012; IEA, 2012a).

In addition to the strong TPES growth, the last decade (2001-2010) was marked by the failure to decarbonize global fuel mix (**Figure 7.**5). The decade with the strongest ever carbon emission mitigation policies will be remembered as the one with the highest in last 40 years emission growth (2.6% per annum) driven mostly by additional coal use (by two thirds) and by growing power and heat generation (**Figure 7.**5).

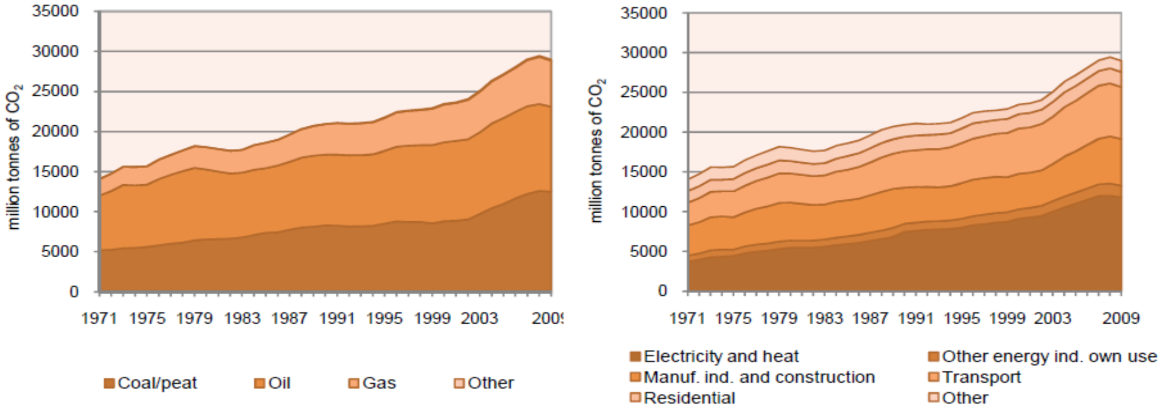

Figure 7.5. Dynamics and structure of energy-related CO2 emissions (IEA, 2011a). [Data will be updated upon new statistics is released]

7.3.2 Regional trends

7.3.2.1 Regional primary energy supply and demand drivers

In 2000-2009, TPES grew by 21% globally, 105% in China, 61% in the Middle East, 38% in Non-OECD Asia, 33% in Africa, 25% in Latin America, 5% in Non-OECD Europe and Eurasia, and 3% in OECD Asia Oceania. It was nearly stable for OECD Europe and 3% down for OECD Americas (IEA, 2011a). Studies do not support the leapfrogging hypothesis that developing countries would shift towards significantly less carbon-intensive energy use patterns while bridging income gaps with developed ones (Jakob et al., 2012).

The composition of energy demand drivers' impacts was different in the last decade for OECD and non-OECD countries. In the former, TPES in 2010 was slightly below the 2000 level, while in the latter, being much less impacted by the recent economic crisis and whose population and GDP growth accounted to 89% and 78% of global increments respectively, contributed all additional TPES in 2000-2010. Drivers' composition is even more diverse, when separate regions are in focus (Figure 7.6)**.** Population and income growth are the two most powerful (but not the only) driving forces behind the demand for energy and energy related CO_2 emissions. Demographic factor impact, a function of both population growth and per capita emissions, was low for OECD Asia and Oceania, and for Non-OECD Europe and Eurasia, while the largest contribution of this factor being in OECD Americas due to high per capita GDP and energy use.

Income evolution is the most influential determinant on the overall demand for energy. Global picture masks significant regional disparities. Two regions - non-OECD Asia and China - led world economic growth with 42% and 60% increase in global GDP in 1990-2000 and 2000-2009 respectively, driving their share in global TPES up from 18% in 1990 to 21% in 2000 and to 31% in 2009. Another region with large income-driven *energy-related* CO_2 emissions in 2000-2009 was Non-OECD Europe and Eurasia, but this driver there was about neutralized by improvements in energy intensity. This region was the only one that managed to decouple economic growth with energy use: its GDP in 2009 being 6% above the 1990 level while TPES declined by 32% over the same period.

Energy intensity in most regions (except Middle East) followed a downward convergence trend in 2000-2009, driven by the use of common technologies, and transition to similar consumption patterns. In particular it declined by 33% in Non-OECD Europe and Eurasia, 18% in Non-OECD Asia, between 10-15% in OECD Americas, China, OECD Europe, Africa, OECD Asia Oceania and Latin America, but grew by 8.2% in the Middle East (IEA, 2011d). The largest CO_2 mitigation effect of this factor by scale in 2000-2009 was observed in OECD Americas, Non-OECD Europe and Eurasia, followed by China and Non-OECD Asia. Besides technical improvements, falling energy intensities reveals structural changes away from industry toward less energy intensive activities – first in rich and then in newly industrialized economies.

Carbon intensity decline was fastest in OECD Europe followed closely by Non-OECD Europe and Eurasia in 1990-2000, and by Latin America and OECD Americas in 2000-2009 (IEA, 2010b; US DOE, 2011a). On the contrary most developing countries show little or no de-carbonization. Historical trends reveal that rising carbon intensity is a common feature of many developing nations in early industrialization stage in which heavy use of fossil fuels for power production plays a key role (Rogner et al., 2011).

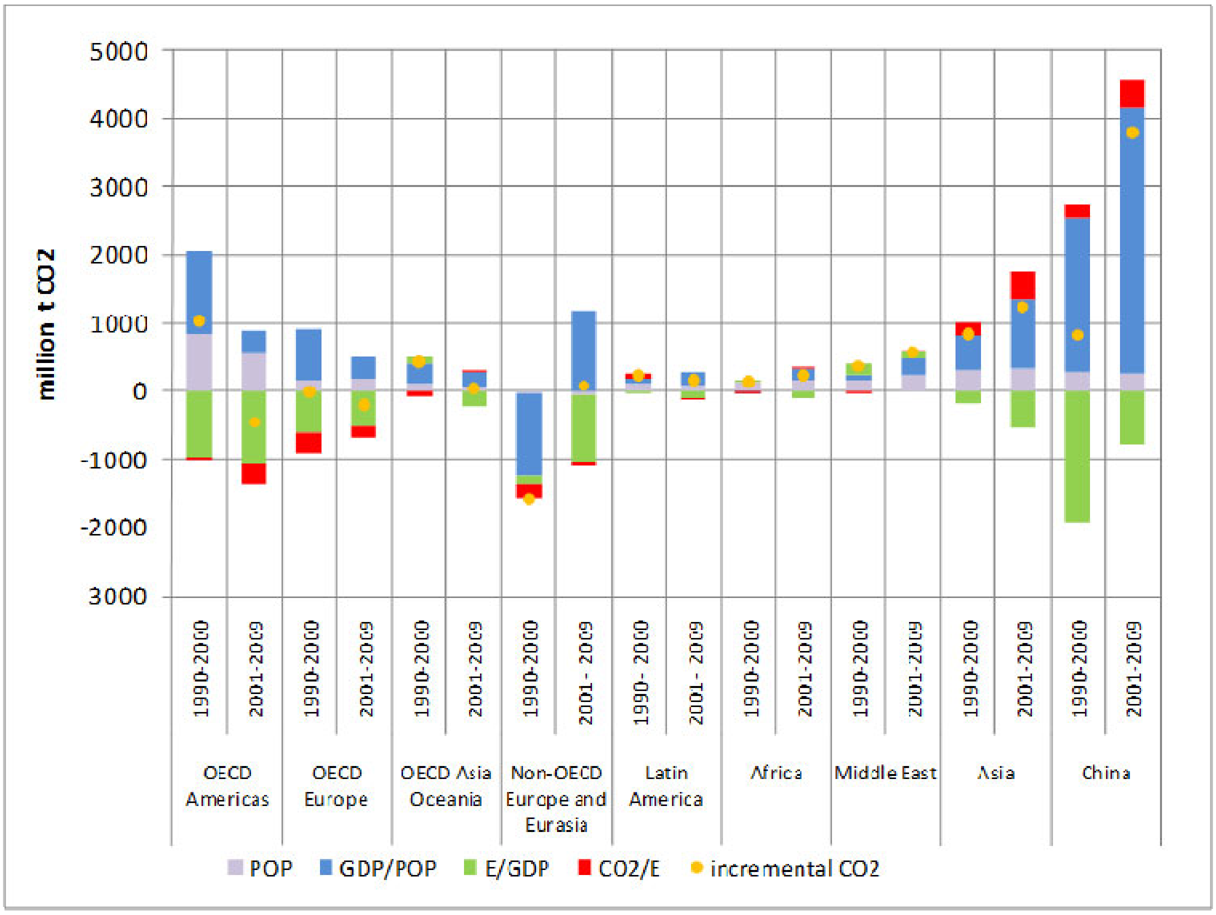

Figure 7.6. Decomposition of drivers for energy-related CO2 emissions in different world regions Note: Developed using data from IEA, (2011a). [Data will be updated upon new statistics is released]

7.3.2.2 Evolution of regional energy related GHG emissions

Energy de-carbonization progress in OECD countries (-0.3% per annum) was smaller than in three previous decades, but sufficient to compensate for their small TPES increment in 2001-2010 and keep 2010 emissions below the 2000 level. In non-OECD countries, average annual increase of energy-related CO2 emissions exploded from 1.1% in 1990-2000 to 4.7% in 2001-2010 due to the expansion of TPES accompanied by growing carbon intensity of energy of 0.6% per annum, driven to a large degree by coal demand in China and India (IEA, 2011a). As a result in 2010 non-OECD countries' energy-related CO2 emissions were 37% over that for OECD countries. Only Non-OECD Europe and Eurasia and, to a lesser extent OECD Europe, have reduced their CO2 emissions in absolute terms during the period 1990 to 2009 (Figure 7.6).

In 1990, OECD Americas was the world's highest emitter of energy-related CO2 at 26.5% of global total of 21Gt, followed by OECD Europe and Non-OECD Europe and Eurasia (19.3% each) and Non-OECD Asia (16.8%, China 10.7%), with the rest of the world emitting less than 20% (IEA, 2011a). By 2009, the distribution had changed remarkably. Non-OECD Asia became the major emitter with 34.6% of the global total of 29Gt; and China's emissions surpassed that of the US as well as India's emissions surpassed that of Russia. The shares of OECD North America, the OECD Europe, and Non-OECD Europe and Eurasia shrank to 21.3, 13.0 and 8.6% respectively (IEA, 2011a).

The rapid increase in emission in developing Asia was due to the region's dramatic economic growth and increased use of fossil fuels. However the per capita emission of Non-OECD Asia in 2009 was only 1.43 tCO2, against the world average of 4.29, OECD Americas' 13.27, OECD Asia and Oceania's 10.00, the Middle East's 7.76, Non-OECD Europe and Eurasia's 7.46. While India's per capita emission of 1.37 was close to the world's lowest emitting regions – Latin America (2.16) and Africa (0.92) (IEA, 2010a), the Chinese emission per capita, which was 5.14 in 2009, rapidly converge towards OECD countries levels, and exceeded France level in 2011 (Enerdata, 2012).

7.3.3 Current policies and commitments and GHG reduction challenge

As a beginning of the transition to a low GHG energy supply system, a wide array of climate change mitigation policy initiatives have been initiated – at the regional (e.g., EU), national and sub-national levels. As discussed in section 7.12, many of these policies are ad hoc and poorly coordinated across national boundaries. Collated policies can be found via centrally held databases (e.g., IEA5, REN216, MURE7), and illustrate the accelerating number of policy initiatives.

Recent major studies on projecting emissions (IEA, 2011a; US DOE, 2011a; BP, 2011b) include aggregated GHG emission reduction policies up to legislated measure as of mid-2011. Such policy mechanisms can be characterised as pricing, innovation and removal of barriers (NH Stern, 2007), but removal of fossil fuel subsidies (i.e., the G20 commitment made in 2009) and co-benefits from policies on energy security and local air pollution are also important for climate mitigation. The array of country specific policies is designed in part to meet the range of non-binding agreements on economy wide GHG emission reductions from the Copenhagen Accords[8].

Given the range of drivers and recent volatility seen in the energy supply system, it is an open question as to whether existing policies will deliver their desired quantitative reductions in energy use and/or emissions. Crucially, the impacts of existing initiatives or legislation represent a future cost, and existing policies may be revised or scrapped as iterative policy making occurs. The relatively few studies that undertook ex post verification of energy model baselines (e.g., Pilavachi et al., 2008; Strachan, 2011), or the US DOE's review of its energy forecasts (US DOE, 2011b), showed the evolution and inclusion of current policies was a key determinant of projected energy supply, demand, and prices. Recognising this difficulty in assessing the effectiveness of policy, the RCP scenarios (Chapter 6) have in-built Shared Climate Policy Assumptions (SPAs), that – although they vary by modelling team and target stringency – have a clear narrative, breakdown of key elements and quantitative policy metrics.

Global modelling studies (e.g., C Carraro and Massetti, 2011; M den Elzen et al., 2011) have analyzed the impact of current policies plus the emission reduction pledges under the Copenhagen Accords, finding that global GHG emissions in 2020 will be 2.6-7.7 GtCO_2eq too high to be generally consistent with a 450ppmv CO_2eq concentration target. Focusing on longer term CO_2-only emissions from the energy sector (energy supply plus end-uses), Figure 7.7 details the Current and New Policies scenarios, and a longer term stabilization pathway from IEA (2011a). Even if all "New Policies" are achieved, CO_2 emissions will continue to grow, which contrasts with the substantive deviation from current trends by 2020 as required for most 450ppmv CO_2eq pathways. Section 7.12 discusses the range of possible stabilization pathways including the timing of a radical break from current emission trends to achieve a Category II (450 ppmv CO_2eq) target and the potential long-term role of negative CO_2 emission technologies.

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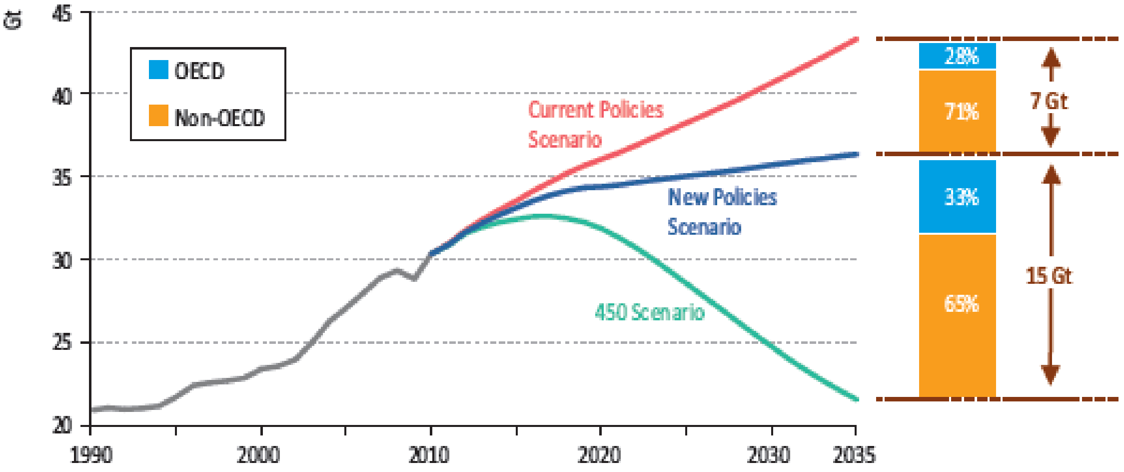
[5] See www.iea.org/textbase/pm/index.html

[6] See www.ren21.net/RenewablesPolicy/tabid/5023/Default.aspx

[7] See www.muredatabase.org/aboutmure.html

[8] See http://unfccc.int/meetings/copenhagen_dec_2009/items/5264.php



Note: There is also some abatement of inter-regional (bunker) emissions which, at less than 2% of the difference between scenarios, is not visible in the 2035 shares.

Figure 7.7. CO2 emissions forecasts illustrating the role of current policy. Source: (IEA, 2011a)

Finally it should be noted that the effectiveness of current policies may be further limited by "2nd best implementation" in terms of delayed timing, regional cooperation, technology innovation failures, and behavioural barriers (Edenhofer et al., 2010). This need for a radical break in current trends and the challenges of GHG reduction policy implementation illustrates the absolute scale of the GHG mitigation challenge.

7.4 Resources and resource availability

7.4.1 Fossil fuels

Oil, natural gas and coal are finite resources that cannot be reproduced in human time frames. Any extraction depletes the stock, and demand growth will rapidly lead to the exhaustion of remaining supplies. A finite stock plus rising demand equals depletion, increasing economic scarcity and peak production followed by inevitable decline, especially if production has persistently exceeded new discoveries.

Several tacit assumptions must be noted in this context. First, continuous production presupposes there is continuous demand for this finite resource. Second, the volume of the resource is known or defined a priori. Third, the geological occurrence and geophysical characteristics of the resource, e.g. concentration in a deposit or the technological mining conditions, are fully delineated. Fourth, technological changes in exploration and production technologies are not explicitly considered. Fifth, the costs of production have little or no impact on the marketability of the resource.

Resources, therefore, are not fixed things. What matters is the timely availability of a resource in the market place at competitive costs. Changing market prices for a mineral may expand or contract the economically recoverable quantities. If a resource becomes too expensive the market responds in two ways: consumers tend to shift to alternative resources (demand reduction); and producers seek additional supplies through enhanced exploration activities and innovative production methods, thus enabling production from previously inaccessible deposits. Moreover, technology change and improvements in knowledge push the frontier of exploitable resources towards deeper, more remote or lower concentration occurrences, making resources a dynamically evolving rather than a 'fixed' quantity.

The terms reserves, resources and occurrences are routinely used in the resource industry but there is no consensus on their exact meanings. Many countries and institutions have developed their own expressions and definitions with different meanings for the same terms. Reserves are generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions (BP, 2011a). 'Resources' are defined as 'concentrations of naturally occurring solid, liquid or gaseous material in or on the Earth's crust in such form that economic extraction is potentially feasible' (UNECE, 2010a). Occurrences then are the remaining fossil materials contained in the Earth's crust.

Reserve-to-production (R/P) ratios have been a popular but static indicator in the mineral industry signalling the years a reserve would last based on current production. R/P ratios ignore the dynamic development of demand, technological change, knowledge and prices. For oil, the R/P ratio has fluctuated around 40 years for more than a century, while production has steadily increased. The quasi-constant R/P ratio could only be the result of an equivalent increase in oil reserves.

The distinction between 'conventional' and 'unconventional' occurrences (e.g. extra heavy oils, oil shale, tar sands, coal-bed methane, shale gas, methane clathrates or uranium dissolved in sea water) is another area of misunderstanding when estimating future availabilities of exhaustible resources. Unconventional resources generally cannot be extracted with technology and processes used for, say, conventional oil, which is usually understood as crude oil capable of flowing under normal conditions.

Unconventional resources require different logistics and cost profiles, and pose different environmental challenges. Their future accessibility is, therefore, a question of technology development, i.e. the rate at which unconventional resources can be converted into marketable fuels at competitive costs.

Assessments and comparisons of global coal reserves and resources are subject to uncertainty and ambiguity, especially when reported in physical unit (tonnes) and without a clear distinction of their specific energy contents, which can vary between 5 GJ/t and 30 GJ/t. Additional quality criteria account for environmentally harmful substances, e.g., sulfur contents or heavy metals.

Geomining conditions (thickness and depth of coal seams, the angle of dip of seams, number of seams and degree of disturbance of coal seams, and faulting (Wagner, 1998) and the associated mining conditions determine the actual cost of production. Ground disturbances and faulting adversely affect the extent of mechanization in the coal mining operations, as well as mine safety, design, and layout. Highly mechanized and productive coal mining operations are presently confined to geologically relatively undisturbed coal deposits. Environmental constraints as well as economic, legal, and transportation constraints could limit coal mine capacity expansion. Coal occurrences are plentiful with reserves estimated at 13.3 to 21.0 ZJ (or 446 to 542 Gt C) and resources at 291 to 435 ZJ (or 7500 to 11,200 Gt C) globally.

Recent global **conventional oil reserve** estimates range between 117Gt (4.9 ZJ) and 182 Gt (7.6 ZJ) whereas the lower range has been argued on grounds that the reserve data reported by the governments of the Middle East are politically motivated and hence unrealistically high (EWG, 2008). When compared with cumulative past production of 162 Gt (6.8 ZJ), "peak oil" production is imminent or has already been passed. Including resources extends oil availability considerably - essentially doubling reserves (**Figure 7.**8). Even the higher range of reserves and resources would only postpone the peak by about two decades (depending on demand) before global conventional oil production starts its inevitable decline.

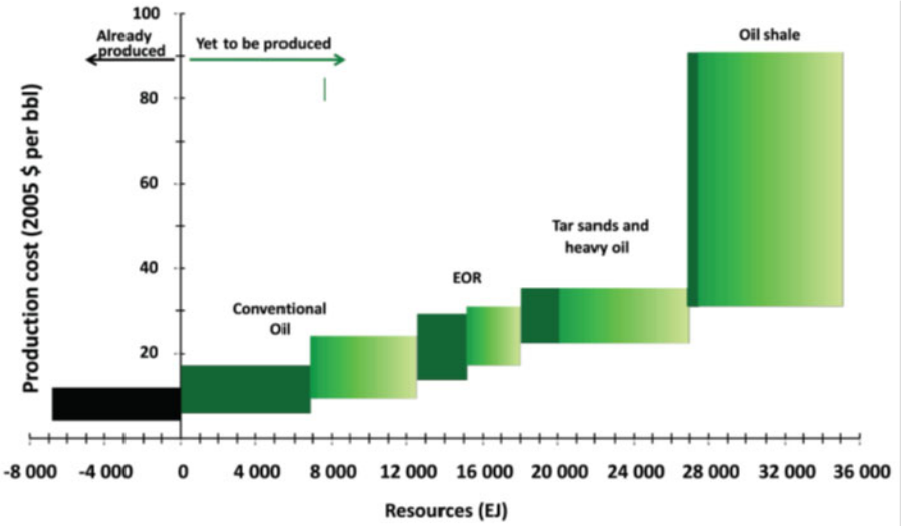


Figure 7.8. Liquid fuel supply potentials and production costs. The height of each bar indicates the estimated production cost range, and the width indicates the prospective resource availability. The shading reflects the state of current knowledge about the resource – the darker shading points to a higher geological assurance, while the lighter shading indicate the more speculative nature of their existence and producibility. Source: Adapted from Farrell (2008).

Unconventional oil resources are much more abundant than conventional oil reserves and resources. There are about 1380Gt (58 ZJ) of shale oil, heavy oil, bitumen, and extra-heavy oil) trapped in sedimentary rocks in several thousand basins around the world. Oil-shale resources are estimated at about 382-450 Gt (16-18.9 ZJ) (Dyni, 2006; WEC, 2007). These figures, particularly for oil shale, are somewhat conservative because of the lack of detailed exploration for these resources, particularly in countries with large conventional oil resources. Their production is technically, economically and environmentally more challenging than conventional oil. Oil prices in excess of $80 per barrel are probably needed to stimulate investment in unconventional oil development. Strict environmental protection and post mine closure remediation regulation may further raise market price requirements. **Figure 7.**8 plots a stylised long-term oil supply cost curve for conventional and unconventional oil reserves and resources. It also puts the potential future oil production (right of the vertical axis) in perspective with cumulative past production (left of the vertical axis) and stacks the different oil categories according to their estimated production costs. Oil resources (potentially yet to be produced) dwarf past cumulative production.

Conventional natural gas can be found as “associated gas” accumulated as a gas cap above an oil pool or, with high reservoir pressures, dissolved in the oil or as non-associated gas. Recovery of associated gas is generally a by-product of oil production. Depending on location, field size, geology, and gas in place, associated gas is either recovered for revenue generation, re-injected for field pressurization and prolonged oil recovery, or flared. Approximately 17% (~135 billion m^3 or 5 EJ) of total recovered associated gas is currently flared because of the lack of harvesting infrastructure, especially for remote or small fields that do not warrant a commercial gas collection and transportation system. Non-associated natural gas reservoirs are much more abundant than reservoirs with both oil and gas. When there are no significant liquid hydrocarbon components, a larger part of the in-place gas can be recovered by dropping reservoir pressures. In practice, approximately 60-80% of the in-place gas can be recovered (IEA, 2009a).Unlike oil, natural gas reserve additions have consistently outpaced production volumes and resource estimations have increased steadily since the 1970s (IEA, 2010a). The global natural gas resource base is vast and more widely dispersed geographically chan oil.

Unconventional natural gas reserves, i.e., coal bed methane (CBM), shale gas, deep formation and tight gas are now estimated to be larger than conventional reserves and resources combined. This does not include potential reserves from gas hydrates. In some parts of the world, unconventional gas already exceeds conventional supplies. In the Unites States unconventional gas now makes up about 60% of marketed production (IEA, 2011a).

Occurrences of hydrocarbons in the Earth's crust are plentiful. Yet despite numerous reviews, the range of resource estimates is large due to varying boundaries of what is included in the analysis of an exhaustible resource stock, e.g. conventional oil only or conventional oil plus unconventional occurrences. Mobilising resources might be hampered by inertia, long decision and investment cycles as well as market uncertainties stemming from both the supply and demand sides. Other potential constraints include production shifting to smaller and smaller deposits in harsher and harsher environments; rising exploration, production and marketing costs; excessive environmental burdens; diminishing energy ratios; and ever more stringent environmental policy and regulation.

For climate change, it is the carbon endowment potentially available for combustion that matters. Table 7.2 also presents the world's fossil resource endowment in terms of its carbon content. Since the industrial revolution, fossil fuel combustion released almost 400 Gt C into the atmosphere (Table 7.2). Fossil reserves alone contain two to four times that amount of carbon - a daunting outlook for climate stability.

Table 7.2: Fossil reserves, resources and occurrences and their carbon content Source: (Rogner et al., 2011)

	Historical production through 2010		Production 2010		Reserves		Resources		Additional occurrences	
	[EJ]	[Gt C]	[EJ]	[Gt C]	[EJ]	[Gt C]	[EJ]	[Gt C]	[EJ]	[Gt C]
Conventional oil	6 788	136	141.2	2.8	4 900 - 7 610	98 - 152	4 170 - 6 150	83 - 123		
Unconventional oil	629	13	22.7	0.5	3 750 - 5 600	75 - 112	11 280 - 14 800	226 - 296	>40 000	800
Conventional gas	3 572	55	105.5	1.6	5 000 - 7 100	76 - 108	7 200 - 8 900	110 - 136		
Unconventional gas	173	3	15.1	0.2	20 100 - 67 100	307 - 1026	40 200 - 121 900	614 - 1863	>1 000 000	>15,200
Coal	7 426	192	156.2	4.0	17 300 - 21 000	446 - 542	291 000 - 435 000	7510 - 11,230		

7.4.2 Nuclear energy

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

Uranium reserves are periodically estimated and are traditionally defined as those deposits that could be produced at less than 130 $/kg U. Stimulated by high spot prices of up to 350 $/kg in 2007, the 2010 edition of the Red Book (NEA, 2010) extended the cost ranges to 260 $/kg U.

Table 7.3 shows the identified uranium resources reported in the Red Book 2009 (NEA and IAEA, 2010). Altogether, there are 3700 EJ (or 6.3 MtU) of conventional uranium resources available at extraction costs of less than 260 $/kg U. Vast additional uranium occurrences can be mobilized at costs larger than 260 $/kg.

Most unconventional uranium resources reported to date are associated with uranium in phosphate rocks, but seawater and black shale are other potential sources. Uranium in seawater dwarfs any other exhaustible energy resource. However, it is estimated that processing of about 350,000 tonnes of water would be required to produce one kilogram of uranium. Research is effectively ongoing only in Japan and France. Recovery costs estimates vary between 260 $/kg U and 1700 $/kg U (Nobukawa et al., 1994; T Kato et al., 1999; Rogner et al., 2000; Bunn et al., 2003; Tamada, 2009).

Thorium is a naturally occurring, slightly radioactive metal. It is widely distributed in rocks and minerals and is found, to some extent, in virtually every continent of the world. The average content of thorium in the Earth's outer crust amounts to three to four times the average concentration of uranium (NEA, 2006).The present knowledge of the world's thorium resource base is poor and incomplete. The sparse data reported are often based on assumptions and surrogate data for mineral sands, not direct geological evidence. Identified thorium resource availability is estimated at more than 2.5 Mt at production costs of less than 80 $/kg Th. In addition, there are at least further 4 Mt of yet to be discovered thorium occurrences (NEA, 2008).

Lithium is a convenient source material for the deuterium-tritium fusion process. The availability of lithium could potentially supply the world's energy demand for thousands of years (Ongena and van Oost, 2004).Lithium is found joined (ionized) in various salts in nearly all igneous rocks (especially pegmatites), in sedimentary rocks, and hydrated in brines and in seawater. As in many resource estimations, lithium reserve and resource estimates vary wildly and lack consistency. Recent resource estimates vary between 22 Mt (Tahil, 2007) and 62 Mt (Yaksic and Tilton, 2009) of lithium globally, with the bulk located in Latin America (Bolivia and Chile account for more than 40% of global resources). The discrepancies typically result from varying assumptions, methodologies, use of terminology, and inclusion of deposits.

Table 7.3: Fissile and fertile reserves and resources[9]

	Historical production through 2010	Production 2010	Reserves	Resources	Additional occurrences
	[EJ]	[EJ]	[EJ]	[EJ]	[EJ]
Conventional uranium[a)]	1 484	31.6	2 400	7 400	
Unconventional uranium	34			7 100	> 2 600 000
Thorium			211 000	287 000	43 000

7.4.3 Renewable energy

Renewable energy (RE) can be defined as energy from solar, geophysical, or biological sources that, in principal, can be replenished by natural processes at a rate that at least equals its rate of use (IPCC, 2011a).[10] For the purpose of AR5, RE is defined to include bioenergy, direct solar energy, geothermal energy, hydropower, various forms of ocean energy, and wind energy.

The theoretical potential for RE, in total, greatly exceeds current and future energy demand (Moomaw et al., 2011). Because the theoretical potential does not take into account energy conversion losses or deployment barriers, the theoretical potential is of relatively little practical use. More relevant is technical potential, defined in Verbruggen et al. (2011) as: "the amount of

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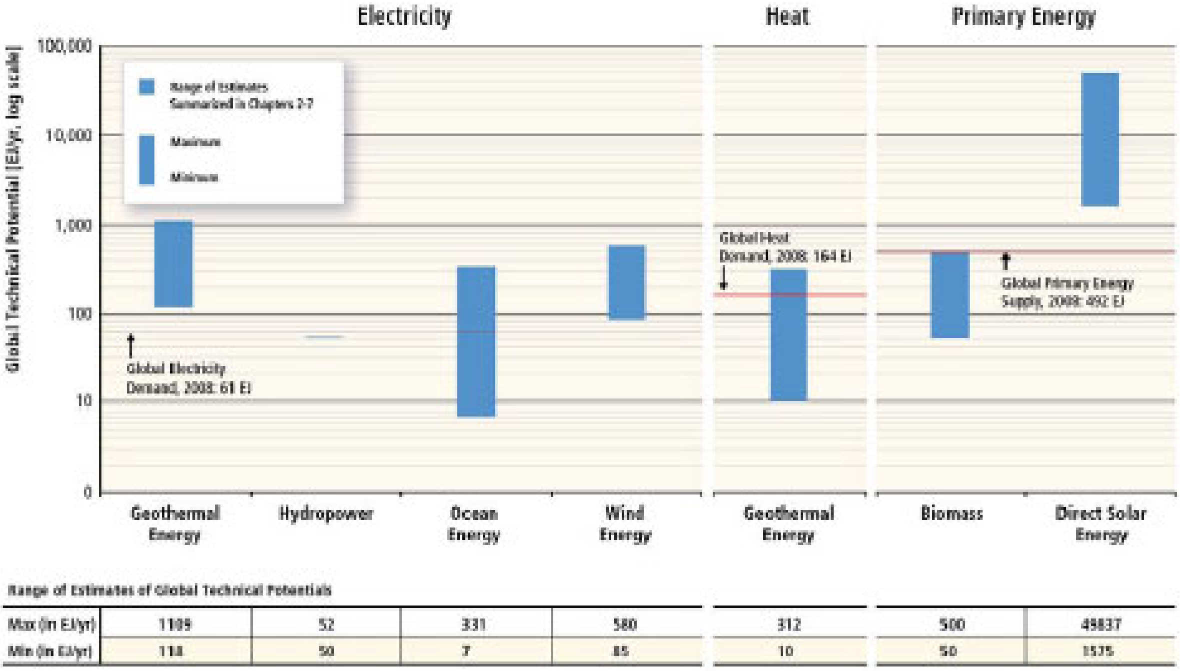
[9] Reserves and resources of uranium are based on a once-through fuel cycle operation. Closed fuel cycles and breeding technology would increase the uranium resource dimension 50–60 fold.

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

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. Definitions of technical potential therefore vary by study (e.g., Aviel 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).

Though comprehensive and consistent estimates for each individual RE source are therefore not available, the total global technical potential for RE as a whole is substantially higher than current global energy demands. **Figure 7.**9 summarizes the ranges of global technical potential for the different RE sources. The technical potential for solar is the largest by a large magnitude, but sizable potential exists for many forms of RE.



Range of Estimates of Global Technical Potentials

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

Figure 7.9. Ranges of global technical potentials of RE sources derived from studies presented in IPCC (2011a). Notes: Technical potentials represent total worldwide potentials for annual RE supply and do not deduct any potential that is already being utilized. The estimates are based on various methods and apply to different future years; consequently, they are not strictly comparable across technologies. For additional documentation, see (IPCC, 2011a).

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

As estimated by this literature, the global and regional technical potentials for RE as a whole are unlikely to limit deployment. Moreover, as noted in IPCC (2011b), "Even in regions with relatively low levels of technical potential for any individual renewable energy source, there are typically significant opportunities for increased deployment compared to current levels." Further, 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 (e.g., Wiser et al., 2011) (for wind energy), and Verbruggen et al. (2011) (more generally)).

Nonetheless, the long-term contribution of several individual RE sources to energy supply and climate change mitigation may be limited by the available technical potential, e.g., hydropower, bioenergy, and ocean energy, while even seemingly more-abundant RE sources (e.g., solar, wind) will be constrained in certain regions (e.g., Fischedick et al., 2011). Additionally, as RE deployment increases, progressively lower-quality resources are likely to remain for incremental use and energy conversion losses may increase, for example, if conversion to alternative carriers is required (Moriarty and Honnery, 2012). Competition for land and other resources among different RE sources may impact aggregate technical potentials, as might concerns about the carbon footprint and sustainability of the resource (e.g., biomass) (e.g., de Vries et al., 2007). In other cases, economic factors, environmental concerns, public acceptance, and/or system integration and infrastructure constraints might limit deployment well before absolute technical limits are reached (e.g., IPCC, 2011b).

7.5 Mitigation technology options, practices and behavioural aspects

7.5.1 Fossil fuel extraction, conversion and fuel switching

Fossil fuels are the major cause of anthropogenic climate forcing, primarily through CO_2 emissions arising from fuel combustion (13.7 $PgCO_2$ from energy sectors, 16.9 $PgCO_2$ from industry, transport and others) (IEA, 2011c), but also through fugitive and accidental releases of CO_2 and methane from coal beds, wells and pipelines (0.3$PgCO_2$, 1-2.8 $PgCO_2e$ CH_4) (Alsalam and Ragnauth, 2011; IEA, 2011c), and through the emissions of black carbon from incomplete combustion (WG1, Chx, Section 7.2.3).Fossil fuel combustion also causes negative forcing from sulphur and nitrogen oxides as well as partially combusted organic carbon, which counteract global warming (Shindell et al., 2012). This section focuses on the mitigation of emissions from the production and conversion of fossil fuels into energy carriers (electricity, solid, liquid or gaseous fuel) used by end uses. Climate forcing per unit energy delivered can be reduced though (1) switching to lower carbon-intensity fuels, (2) higher energy efficiency, and (3) reducing fugitive emissions along the supply chain and black carbon emissions from combustion.

Given the importance of heat and power production in the energy sector, large reductions in CO_2 emissions can be obtained by replacing existing coal fired power plants by highly efficient natural gas combined cycle (NGCC) power plants or combined heat and power (CHP) plants (IEA, 2011a). However, at present, there is a significant concern about fugitive methane emissions both for shale gas (Petron et al., 2012) and for conventional gas, which are both uncertain and potentially higher than assumed so far (Wigley, 2011; Alvarez et al., 2012; CL Weber and Clavin, 2012). Currently published life cycle assessments indicate a 60% reduction of greenhouse gas emissions when shifting from the current world-average coal fired power plant to a modern NGCC power plant (B Singh et al., 2011). This reduction is the result of the lower carbon content of natural gas (15.3 gC/MJ compared to 26.8 gC/MJ for anthracite) and the higher efficiency of combined cycle power plants (IEA, 2011c). More modest emissions reductions can be achieved when going to best available coal technology or less advanced gas power plants (**Figure 7.**10). Emissions associated with NGCC are still too high to meet long-term stabilization targets. Further emissions reductions are possible through CO_2 capture and storage (Section 7.5.3). It should be noted that, depending on specific circumstance of fuel production, liquefaction and transport, the range of life-cycle GHG emissions of electricity generated with LNG can be significantly closer to the emissions from current coal technology than the life-cycle emissions of natural gas produced domestically (Jaramillo et al., 2007).

Fossil fuel extraction and distribution currently contribute 5- 10% of total fossil-fuel related GHG emission, with a large uncertainty associated with fugitive emissions (Alsalam and Ragnauth, 2011; IEA, 2011c). Emissions may increase in the future due to the more energy-intensive production of oil and gas from mature fields, because of unconventional sources and the mining of coal from deeper mines, as well as through longer transportation distances (Gagnon, Luc et al., 2009; Leuchtenböhmer and Dienst, 2010). Emissions associated with fuel production and transport can be reduced through higher energy efficiency and the use of lower-carbon energy sources in mines, fields and transportation networks (IPIECA and API, 2007; Hasan et al., 2011), the capture and utilization (UNECE, 2010b) or treatment (US EPA, 2006; IEA, 2009b; Karacan et al., 2011; Karakurt et al., 2011; Su et al., 2011) of methane from coal mining, and the reduction of venting and flaring from oil and gas production (IPIECA and API, 2008; MR Johnson and Coderre, 2011).

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

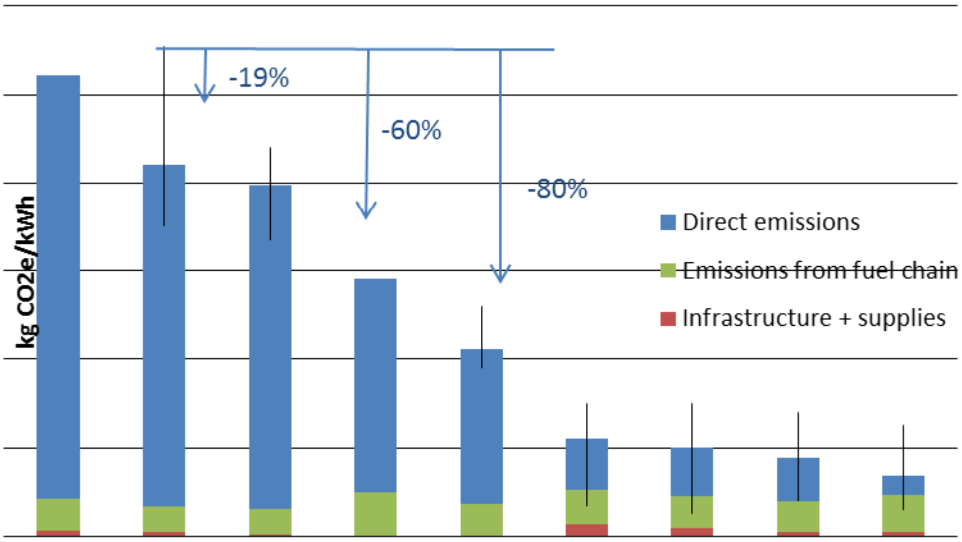


Figure 7.10. Greenhouse gas emissions from current world average coal and gas fired power plants and mitigation opportunities associated with going to best available technology (BAT) conventional plants and plants with CO2 capture and storage (CCS). Based on (B Singh et al., 2011) with the variation in reported emissions from (Ramírez et al., 2012)

7.5.2 Energy efficiency in transmission and distribution

Electrical losses associated with the transmission system are known as transmission losses, they are generally less than losses within the distribution system (distribution losses). These losses are due to a combination of cable or line losses and transformer losses. Losses as a fraction of energy delivered vary considerably between countries with developed countries tending to have lower losses. Combined transmission and distribution losses for the OECD countries taken together were 6.5% in 2000 (IEA, 2003a).

Approximately 25% of all losses in Europe are due to distribution transformers (and this will be similar in OECD countries) so use of improved transformer designs can make a significant impact. 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 takes place closer to loads than central generation, although if a significant amount of power, exceeding local loads, is exported back to the main power system then losses can increase again.

A number of other technology developments may also impact on transmission losses. These include new high temperature cable designs, dynamic loading, gas-insulated transmission lines, and high voltage DC transmission (HVDC). These are dealt with briefly below.

It is the cable sag of overhead lines that determines to a great extent the operational temperature limits. High-temperature low-sag (HTLS) conductors incorporate high tensile materials such as carbon or glass fibre alongside the conductors to take the load and limit the thermal expansion that results in sag (Mazón et al., 2004). HTLS conductors can operate at well over 100^{o}C, with new designs perhaps capable of temperatures up to 200 ^{o}C. Dynamic loading involves allowing higher loads when natural conductor cooling is high due to low ambient temperature and/or high winds. Both dynamic loading and HTLS are attractive because they allow better use of assets but they both will result in higher losses.

On the other hand, gas-insulated transmission lines (GILs) and HVDC have the potential to reduce losses. GILs are much more expensive than conventional lines and are likely to be used only for short buried sections of transmission (Benato et al., 2001). HVDC in contrast becomes cost effective for very long lines and in such applications will have overall lower losses (most HVDC losses result from the converters used).

The use of greater interconnection to ease the integration of time varying renewable into power systems would be expected to increase the bulk transfer of power over considerable distances. This has not so far been quantified in any detail but would be expected to increase transmission losses.

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

7.5.3 Carbon dioxide capture and storage (CCS)

All of the components of integrated carbon dioxide capture and storage (CCS) systems exists and are in use today by the hydrocarbon exploration, production and transport; petrochemical refining; and power engineering sectors. A complete end-to-end CCS system would mitigate CO_2 emissions by capturing CO_2 from large (e.g., typically larger than 0.1 $MtCO_2$/year) stationary point sources, compressing the captured CO_2, transporting and injecting the compressed CO_2 into a suitable deep (typically more than 800m below the surface) geologic structures, and then applying a suite of measurement, monitoring and verification technologies to ensure the safety, efficacy, and permanence of the captured CO_2's isolation from the atmosphere (IPCC, 2005; HJ Herzog, 2011). CCS is a technology suite that has the single purpose of capturing and storing CO_2 and therefore is not deployed without either limits on emissions or under very special circumstances in which the CO_2

has special value, such as is the case with tertiary recovery of hydrocarbons (IPCC, 2005). As of mind 2012, there are four large end-to-end commercial CCS facilities in operation around the world that collectively store 6-7 $MtCO_2$/year and which have stored more than 30$MtCO_2$ over their lifetimes (Eiken et al., 2011; Whittaker et al., 2011; Global CCS Institute, 2011b). There are dozens of other industrial-scale, field demonstration CCS projects across the world that are providing critical advances in our knowledge of CCS systems and their engineering, technical, economic and policy impacts (NETL, 2010; Global CCS Institute, 2011b). As of mid-2012, CCS has not been applied to a large, commercial fossil-fired electricity generation facility (Global CCS Institute, 2011b).

Research aimed at improving the performance and cost of CO_2 capture systems is significant and broad based across the three CO_2 capture technology groupings; pre-combustion (Edward S. Rubin et al., 2007; Figueroa et al., 2008), post-combustion (C-C Lin and Y-W Chen, 2011; Padurean et al., 2011; Versteeg and E.S. Rubin, 2011) and oxy-based capture (Scheffknecht et al., 2011; Wall et al., 2011). Xue et al. (2011), Stern et al. (2011), Brennecke and Gurkan (2010), Wappel et al., (2010), and Vaidhyanathan (2010) are exploring advanced CO_2 capture systems based upon novel approaches using amino acid and iocinc liquid-based capture materials which potentially represent the core of new CO_2 capture systems that would require dramatically less energy (typically heat) to regenerate the capture solvent.

The high capital costs and single purpose use for CO_2 capture equipment when mated to power plants drives these CCS-enabled power plants down the dispatch curve where they serve primarily to produce baseload power (TL Johnson and David W. Keith, 2004; MA Wise and J.J. Dooley, 2005). Chalmers and Gibbins (2007), Cohen et al., (2012), and Nord et al., (2009) have contributed initial explorations of how baseload CCS-enabled power plants could be modified to also serve peak electricity demand for brief periods. Vergrat et al., (2011), Bakker et al., (2010) as well as IPCC (2005) remind us that while in the long-term the largest market for CCS systems is most likely to be the electric power sector, that in the near-term early deployment of CCS in both developed and developing nations are likely to arise in the aspects of the industrial sector that produce high purity CO_2 waste streams that are typically vented to the atmosphere.

Integrated assessment models (see Chapter 6) tend to agree that at about \$100/tonCO_2 the electricity sector is largely decarbonized with a significant fraction being from CCS deployment (Krey and K. Riahi, 2009; MA Wise and JJ Dooley, 2009; Luckow et al., 2010). This is an important insight as it is at about this same price threshold that large-scale utilization of bioenergy with CCS (BECCS) is well underway (Krey and Riahi, 2009; Azar et al., 2010; Luckow et al., 2010), which would allow for net removal of CO_2 from the atmosphere while simultaneously producing electricity.

As noted by Bachu (2008), Krevor et al., (2012) and IPCC (2005) there are a number of key physical and chemical processes that work in concert to help ensure the efficacy of deep geologic CO_2 storage. There is also a growing body of literature that consolidates the significant knowledge base that exists on how to ensure the integrity of CO_2 injector and monitoring wells (J. William Carey et al., 2007; Jordan and Sally Benson, 2009; W. Crow et al., 2010; WJ Carey et al., 2010; Min Zhang and Stefan Bachu, 2011; Matteo and Scherer, 2012). Field experience and research from a number of groups around the world confirm this and taken together their work points to a declining long-term risk profile (i.e., a thin tail) for CO_2 stored in deep geologic reservoirs (Hovorka et al., 2006; Gilfillan et al., 2009; Jordan and Sally Benson, 2009). Issues related to storage risks are discussed in 7.9.3.

Over the past decade a much more robust and standardized CO_2 storage capacity methodology has been developed for different types of deep geologic formations (John Bradshaw et al., 2007; Stefan Bachu et al., 2007; Kopp et al., 2009; Orr, 2009; Goodman et al., 2011; PNK De Silva et al., 2012) and has been applied in many regions of the world. For example just since 2009, estimates of geologic

CO_2 storage have been published for regions as diverse as: 42 $GtCO_2$ for the Utsira formation in the North Sea (Strachan et al., 2011); 146 $GtCO_2$ in Japan and its nearby territorial waters (Ogawa et al., 2011); 360 $GtCO_2$ in Continental Europe (Vangkilde-Pedersen et al., 2009); 250-560 GtCO2 in depleted natural gas fields around the world (IEAGHG, 2009), 2,300 $GtCO_2$ in China (Dahowski et al., 2010, 2011); and 1,300 to 13,600 $GtCO_2$ in the continental USA. Utilizing the "Geologic CO_2 Storage Resource Pyramid" which has been promulgated by a number of key international research consortia (CSLF, 2008; IEAGHG, 2011) as a means of standardizing estimates of geologic CO_2 storage capacity computed with different levels of data and assuming various engineering and economic constraints, Dooley (2012) estimates global theoretical CO_2 storage at 35,000 $GtCO_2$, global effective storage capacity at 13,500 $GtCO_2$, global practical storage capacity at 3,900 $GtCO_2$, matched capacity for those regions of the globe where this has been computed at 300 $GtCO_2$, and lastly approximately 0.03 $GtCO_2$ of global geologic CO2 storage capacity has already been utilized.

Szulczewski et al., (2012) in one of the most sophisticated analyses done to date show that even when taking into account realistic limits on injection rates the geologic CO2 storage capacity of the USA should last at least a century. A survey of a number of published estimates the likely demand for CO_2 storage over the course of this century extends this core point the amount of geologic CO2 storage capacity is likely sufficient. To wit, the average demand for geologic CO_2 storage across a number of scenarios with end of century CO_2 concentrations of approximately 550 ppmv is on the order of 448 $GtCO_2$, while the average demand for CO_2 storage for scenarios that have end of century CO_2 concentrations of approximately 450 ppmv is approximately 640 $GtCO_2$, and the average demand for scenarios that have end of century CO_2 concentrations between 400-425 ppmv is 1000 $GtCO_2$ (US Climate Change Science Program, 2007; Bosetti et al., 2009; K Calvin et al., 2009; Krey and K. Riahi, 2009; Russ and van Ierland, 2009; J. J. Dooley and KV Calvin, 2011; Masui et al., 2011). Edmonds, et al., (2007) note that the value of having CCS in society's portfolio of responses to climate change is still on the order of trillions of dollars, "even if the realizable CO_2 storage potentials are an order of magnitude smaller than currently estimated. And even in these highly constrained cases, the relative cost of employing CCS as a means of addressing climate change could still be competitive with other large scale emissions mitigation measures."

7.5.4 Renewable energy

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

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

RE technologies have advanced substantially in recent decades, and since the IPCC's AR4. Notable recent advancements include: (1) improvements in manufacturing processes and photovoltaic (PV) cell efficiencies along with reductions in materials use, which have helped to substantially reduce the price of PV modules; (2) continued increases in the size and therefore energy capture of wind turbines deployed both on land and offshore; and (3) improvements in cropping systems, logistics, and multiple conversion technologies for bioenergy (e.g., D. J. Arent, Wise, and Gelman 2011; IPCC 2011a).

As a result of these and other advancements, a growing number of RE technologies have achieved a level of technical and economic maturity to be deployed at significant scale; others are less mature and not yet widely deployed (IPCC, 2011b). Hydropower technologies, for example, are mature. Bioenergy technologies, meanwhile, are diverse and span a wide range; examples of mature technologies include conventional biomass-powered electric boilers and heating systems, as well as ethanol production from sugar and starch, while lignocellulose-based transport fuels are at a pre-commercial stage. The technical maturity of solar energy ranges from R&D (e.g., fuels produced from solar energy), to relatively more mature (e.g., CSP), to mature (e.g., solar heating and wafer-based silicon PV). Geothermal power plants and thermal applications that rely on hydrothermal resources rely on mature technologies, whereas enhanced geothermal systems are in the demonstration phase while also undergoing R&D. With the exception of tidal barrages, ocean technologies are also at the demonstration phase and require additional R&D. Finally, though land-based wind technologies are already relatively mature, the use of wind energy in offshore locations is increasing but is less technically and commercially mature.

Because the cost of many 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 (Mitchell et al., 2011; IEA, 2011e; REN21, 2012). Additionally, because RE relies on natural energy flows, RE technologies must often be located at or near the energy resource, often collect energy from diffuse energy flows, and may produce energy output that is variable and—to some degree—unpredictable (IPCC, 2011b). The implications of these characteristics for infrastructure development and network integration are addressed in Section 7.6.

Though modern forms of RE (excluding traditional biomass) remain a relatively small fraction of global and regional energy supply (see Sections 7.2 and 7.3), deployment has been significant since the IPCC's AR4. In 2011, RE power capacity grew rapidly: REN21 (2012) reports that RE accounted for almost half of the 208 GW of new electricity generating capacity added globally in 2011. As shown in Table 7.4, the fastest growing sources of RE power capacity included wind power (40 GW added in 2011), solar PV (30 GW), and hydropower (25 GW).[11] Biofuels accounted for 3% of global road transport fuel demand in 2011 (REN21, 2012). By the end of 2011, the use of RE in hot water/heating markets included 290 GWth of modern biomass, 232 GWth of solar, and 58 GWth of geothermal heating (REN21, 2012).

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

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

In a review of the energy scenario literature, Fischedick et al. (2011) find that, while there is no obvious single dominant RE technology that is likely to be deployed at a global level, bioenergy, wind, and solar have been more commonly identified as the largest possible contributors by 2050.[12] The mix of RE technologies suitable in any specific location, however, will depend on local RE resource availability, with hydropower and geothermal also playing a significant role in certain countries. The scenarios literature has often found that, across all energy sectors, RE is likely to penetrate most rapidly in electricity generation, at least in the near to medium term, followed by RE for heating/cooling and transport (e.g., Fischedick et al. (2011). This is in part due to the fact that some forms of RE are primarily used to produce electricity (e.g., wind and hydropower) and only biofuels are used directly on a large scale in transportation applications (e.g., Armaroli and Balzani, 2011). As a result, the ultimate contribution of RE to overall energy supply may be dictated in part by the future electrification of transportation and heating/cooling or by using RE to produce other energy carriers, e.g., hydrogen (R Sims et al., 2011; MZ Jacobson and Mark A. Delucchi, 2011).

Table 7.4: Selected Indicators of Recent Growth in RE Deployment (REN21, 2012)

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

7.5.5 Nuclear energy

Nuclear power contributes significantly to the electricity needs of many nations around the world today. There are 433 commercial nuclear power reactors operating in 30 countries with a total installed capacity of 367 GWe as of October 2011 (IAEA, 2011). Nuclear electricity represented 14% of the world's electricity generation in 2010 with a total generation of 2630 TWh. The US, France, Japan, Russia, and South Korea with 101, 63, 44, 23, and 19 GWe of nuclear power, respectively, are the top five countries in installed nuclear capacity. Together they represent more than half, 68%, of the current total global nuclear capacity (IAEA, 2011; World Nuclear Association, 2012a).

The majority of the world's currently operating reactors are based on light-water technology of similar concept, design and fuel cycle. Of the 433 reactors worldwide, more than 80% or 353 of the reactors are light-water reactors (LWR), of which 268 are Pressurized Water Reactors (PWR) and 84 are Boiling Water Reactors (BWR) (IAEA, 2011). The remaining commercial reactor types consist mostly of heavy-water reactors (PHWR), and a few gas-cooled reactors (GCR) and graphite moderated reactors (RBMK/LWGR).

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[12] Due to its ability to be coupled with CCS and potentially deliver net-negative GHG emissions, analyses of global carbon mitigation scenarios have sometimes identified a sizable potential role for biomass CCS, especially in cases with particularly low GHG stabilization targets (e.g., see Chapter 6, Section 7.5.3, Section 7.12, and (D. P van Vuuren et al., 2010).

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

Other more revolutionary small modular reactors (SMR) with additional passive safety features are near commercial status (Kuznetsov, 2008; Rosner and Goldberg, 2011; World Nuclear Association, 2012b). The size of these reactors is typically less than 300 MWe and much smaller than the 1000 MWe size of current LWRs. Their lower power density, large heat capacity, and heat removal through natural means contribute to their improved safety. SMRs based on light-water designs rely on the substantial experience with current LWRs and utilize existing fuel cycle infrastructure. Light-water SMRs from Russia, South Korea, and US are near commercial status. Gas-cooled SMRs, in addition to their passive safety features, have higher operating temperatures for increased electricity generation efficiencies relative to LWRs and potential industrial applications as a source of high temperature process heat (EPRI, 2003; Ming Zhang et al., 2009). Gas-cooled SMRs are under development in China, France, South Africa, and US. In general, smaller reactors that can be constructed in a factory setting with modular construction techniques and flexibility for incremental additions to total power capacity could shorten the duration of construction periods and improve the quality and economics of new nuclear plants (Rosner and Goldberg, 2011).

The current nuclear fuel cycle has a direct impact on the issues of uranium resource sustainability, nuclear proliferation and waste management. Reliance on U-235, a relatively scarce uranium isotope, as the primary source of nuclear fission with the bulk of fissionable U-238 relegated to the waste stream means that the current nuclear fuel cycle does not utilize available uranium resources in an efficient manner. While the ultimate availability of natural uranium resources is uncertain (see 7.4.2), inefficient utilization of existing uranium resources implies quicker transition to ores grades of lower uranium concentration and higher uranium cost (E Schneider and Sailor, 2008).

Additionally, the necessity for uranium enrichment for LWRs and the presence of plutonium in the spent fuel are the primary proliferation concerns. There are differing national policies for the use or storage of fissile plutonium in the spent fuel, however, with some nations electing to recycle plutonium for use in new fuels and others electing to leave it intact within the spent fuel. The presence of plutonium and minor actinides in the spent fuel leads to greater waste disposal challenges as well. Heavy isotopes such as plutonium and minor actinides have very long half-lives, as high as tens to hundreds of thousands of years, which require final waste disposal strategies to address safety of waste disposal on such great timescales. Fission fragments, the inevitable byproduct of any fission reaction, have significantly shorter half-lives and waste disposal challenges for fission fragments are on the order of several hundreds of years. Thus, strategies to isolate and dispose of fission fragments only could have significant beneficial impact on waste disposal requirements (Wigland et al., 2006).

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, already contributes to improved uranium resource utilization and waste minimization efforts (OECD/NEA, 2007; World Nuclear Association, 2011). Ultimately, full recycling options based on either uranium or thorium fuel cycles that are combined with advanced reactor designs where only fission fragments are relegated as waste can significantly extend nuclear resources and reduce high-level wastes (GIF, 2002). Higher economic costs of advanced fuel cycles and reactor technologies are current drawbacks. Potential access to fissile materials from widespread application reprocessing technologies further raises proliferation concerns. Thus, the merits of alternative reprocessing technologies are being investigated.

There is not a commonly accepted single worldwide approach to dealing with the long-term storage and permanent disposal of high-level waste. Regional differences in the availability of uranium ore and land resources, technical infrastructure and capability, nuclear fuel cost, and societal acceptance of waste disposal have resulted in alternative approaches to waste storage and disposal. Regardless of these differences and the fuel cycle ultimately chosen, some form of long-term storage and permanent disposal, whether surface or geologic (subsurface), is required. Finland and Sweden are the furthest along in selecting a site for the direct disposal of their high-level waste (Posiva Oy, 2011; SKB, 2011). Other countries, particularly in Europe and Japan, have chosen to recycle used fuels as part of their waste disposal strategy (OECD / NEA, 2007). Yet others, such as South Korea, are pursuing a synergistic application of light and heavy water reactors to reduce the total waste by extracting more energy from used fuels (Myung et al., 2006). In the US, waste disposal options are currently under review with the termination of the Yucca Mountain nuclear waste repository in Nevada. The Yucca Mountain facility, originally approved in 2002 as a geologic repository for spent nuclear fuel and other high-level waste, was cancelled in 2009 (CRS, 2012). Indefinite dry casks storage of high-level waste at reactor sites and interim storage facilities is to be pursued until decisions on waste disposal are resolved.

In March of 2011, an unprecedented earthquake of 9.0 magnitude and ensuing tsunami off the east coast of Japan caused a severe nuclear accident in Fukushima, Japan (Prime Minister of Japan and His Cabinet, 2011). The significant release of radioactive materials from the Fukushima accident rate it a Level 7, the maximum level of the International Nuclear and Radiological Event Scale (INES) for nuclear accidents, and on par with the 1986 Chernobyl nuclear accident in Ukraine (IAEA, 2008). The severity of the nuclear accident in Japan has brought about a reinvestigation of nuclear energy policy and deployment activities for many nations around the world, most notably in Japan and Germany. The response to the accident has been otherwise mixed and its full impact may not be realized for many years to come (see 7.9.3).

For those nations with significant on-going and planned nuclear deployment activities, nuclear power is strongly motivated by the rapid growth in the demand for electricity and the desire for increased diversification of power supplies. There are 65 nuclear reactors, representing 63 GWe of capacity, currently under construction in 14 countries (IAEA, 2011). 49 of the reactors under construction are located in only four countries, China, Russia, India, and South Korea. China has the most active nuclear reactor deployment program of any nation with 27 reactors under construction. The demand growth for electricity has exceeded 10% per annum for many years in China and South Korea, and more recently, the demand for electricity has been high in India, Russia, Ukraine, and others with active nuclear programs (IEA, 2010b). Beyond those reactors under construction, there are future plans or proposals for the deployment of nearly 500 additional reactors worldwide (World Nuclear Association, 2012a). The majority of these are in emerging nations and outside of the OECD and traditional nuclear powers.

Nuclear power has been around for five decades or more, but unresolved issues remain for the continued use and further expansion of nuclear energy worldwide particularly as a response for mitigating climate change. Efforts to improve the safety, economics, resource sustainability, waste management, and proliferation concerns of nuclear power use continue. Research and development of the next generation nuclear energy system, beyond the evolutionary LWRs and SMRs, is being undertaken through national and international efforts (Generation IV International Forum, 2009). The limits to harnessing energy from nuclear fission have not been fully explored, and significant efforts are underway to develop new fuel cycles and reactor technologies that address the concerns of nuclear energy use.

7.6 Infrastructure and systemic perspectives

7.6.1 Electrical power systems

There are many different ways to reduce greenhouse gas emissions associated with electricity generation. The choices made will affect the operation of the power system as a whole and may require significant additional infrastructure. GHG reductions achieved will depend both on the specific mitigation technologies and on their interaction with the rest of the electricity system.

To achieve reliable operation, an electric power system must maintain a balance between supply and demand at all times. This requires the planning, installation and operation (through scheduling and dispatch) of adequate generation plant and it also requires adequate network infrastructure to transfer power from generation to end-users. To achieve a high reliability the system as a whole must be robust to the failure of individual components, and in particular must be designed to withstand a major transient loss or temporary unavailability of generation plant or transmission lines. Any emissions mitigation measures will need to be undertaken in a manner that preserves these fundamental requirements.

In general, available literature and actual experience suggests that integrating higher shares of low-carbon energy supplies into the electricity system is technologically feasible, but may require wide ranging changes to the power system itself and how it is operated. The nature of those challenges and the costs are technology and system specific, and depend on the penetration of certain low-carbon energy supplies. The challenges are usefully described as: system balancing; resource adequacy; and transmission and distribution.

Substantial mitigation using variable renewable energy supplies will likely require the most significant changes in terms of increased flexibility, greater capacity of generation resources to meet reliability targets, and increased transmission infrastructure. As noted in the IPCC's SSREN, "in spite of the complexities, there are few, if any, fundamental technological limits to integrating a portfolio of RE technologies to meet a majority share of total energy demand in locations where suitable RE resources exist or can be supplied" (IPCC, 2011a). Even without fundamental technological limits, however, engineering complexities and costs may constrain deployment. Additionally, changes to accommodate large shares of low-carbon energy supplies must address numerous institutional barriers (Olmos et al., 2011; Perez-Arriaga and Batlle, 2012).

7.6.1.1 System balancing - flexible generation and loads

Electricity demand is variable, reflecting the temporal changes in the needs of users. Generating plant must be scheduled and dispatched in balancing areas (or control areas) either automatically or by a central electricity system operator to match these variations. The mix of generation plant on the system at any time must have sufficient flexibility, in concert with any available storage or demand flexibility, to follow variations in demand and also to respond very quickly to contingencies such as the loss of a large generator or transmission line. This requires a combination of part loaded plant that can adjust output rapidly (known as spinning reserve) and other reserve plant that can be brought on line with limited delay.

No major flexibility and balancing issues are expected for GHG mitigation via improved plant conversion efficiency or fuel switching (7.5.1). An exception may be the addition of CHP, where electrical operation may be constrained by the underlying heating needs, with little resultant operational flexibility. However, flexibility of CHP plants can be improved through boiler changes or the addition of thermal storage (e.g., Lund and Andersen, 2005; Blarke, 2012).

Nuclear and CCS are capital-intensive technologies with, in the case of nuclear at least, relatively low variable costs, leaving little inherent motivation to design these plants to operate in a flexible mode. Specifically, the high capital cost implies that an economic decision to build nuclear or CCS would likely be based on the expectation that the plants would operate at full capacity (i.e. baseload) for most of the year. Low variable costs relative to other forms of electricity generation imply that it will then often be most economical to operate nuclear (and, to a lesser extent, CCS) plants at full output rather than in a mid-merit or load following mode (Knapp, 1969; Johnson and Keith, 2004; Chalmers et al., 2009; Pouret et al., 2009; Cohen et al., 2011). Furthermore, in many countries flexible operation of nuclear plants is restricted based on regulatory constraints rather than feasibility or economic reasons (Perez-Arriaga and Batlle, 2012). Because demand is variable and generation must remain in balance with demand, system flexibility in systems with high proportions of nuclear or CCS may require modifying plant design to make nuclear and CCS capable of providing additional flexibility (Paul Denholm et al., 2012), or alternatively, flexibility will need to come from other resources such as the balance of the remaining conventional generation, storage, or responsive loads (Knapp, 1969; Wilson et al., 2010). Characterizing CCS flexibility is an area of active research (e.g. Hannah Chalmers and Jon Gibbins, 2007; Nord et al., 2009).

Renewable resources such as reservoir hydropower, bioenergy, geothermal, and CSP with storage can to some extent be dispatched and thus can provide flexibility, though capital intensity and low variable costs may, as argued above, encourage base load operation for technologies such as geothermal. Wind, solar photovoltaics and wave energy are highly variable in output across a wide range of time-scales important to electric power systems. These technologies also introduce additional uncertainty into the system because output cannot be perfectly forecast. Literature and actual operating experience shows that the integration of these sources is technically feasible, but significant use of variable renewable sources will increase the demand for system balancing services (see Chapter 8 of the SRREN for more details, i.e., Sims (2011).

Key strategies that have been, or could be used, to deal with these integration challenges include the use of forecasting in system operations; access to flexible thermal plants (either new or existing); more interconnection to create in effect larger area power systems; load control where demand is made to follow the availability of supply; and energy storage where available and cost effective (R Sims et al., 2011).

Most power system flexibility is currently provided by fossil plants and reservoir hydropower (Troy et al., 2010). The amount of variable renewable electricity that can be accommodated using existing balancing resources has been estimated to exceed 20% of total annual electricity supply in many regions and is even above 40% in some regions, **Figure 7.**11 (IEA, 2011f). If additional flexibility is required to facilitate higher penetration levels, it can be obtained from a number of sources including investment in new flexible generation and improvements in the flexibility of existing power plants (R Sims et al., 2011). Obtaining flexibility from fossil generation has a cost (see 7.8.2.1) and will also modestly affect the overall carbon emissions reduction potential of variable renewables (Martin Pehnt et al., 2008; Fripp, 2011; Wiser et al., 2011; Perez-Arriaga and Batlle, 2012). Larger interconnected power systems allow a wider diversity of renewable (and non-renewable) sources and studies have shown that combining different variable renewable sources will be beneficial in smoothing the variability of aggregate supply (Fusco et al., 2010; I Wilson et al., 2010; Wiser et al., 2011). Load control or demand response exploits the ability of loads to vary in response to supply conditions and/or price signals (e.g., Stadler, 2008). Water desalination loads, aluminium smelting, ice production, production line inventory and so on can offer such flexibility, as can many commercial and residential loads (Kirby, 2007; Milligan and Kirby, 2010; Keane et al., 2011). Variable retail prices can be used to make demand responsive to the availability of supply (Borenstein, 2005; Centolella, 2010). Energy storage can provide additional flexibility in a power system. To date, pumped hydropower storage is the only power storage technology deployed at a large scale, with 300 plants amounting to 95 GW worldwide (Deane et al., 2010) , but other technologies including compressed air energy storage and batteries may possibly be deployed on a large scale in the future (BP Roberts and Sandberg, 2011). Though the cost-effectiveness of storage will be system specific, large-scale energy storage is currently hampered by generally high capital costs and the inherent inefficiency of storage operation, even in regions with substantial wind power (e.g., Holttinen et al., 2011; Tuohy and O'Malley, 2011). Finally, if surplus renewable supply exists despite the best efforts of system operators, renewable energy generation can be curtailed by switching off unwanted plant or through regulation of the power output. Indeed curtailment of wind power is common practice where and when transmission constraints prevent full utilization of available wind.

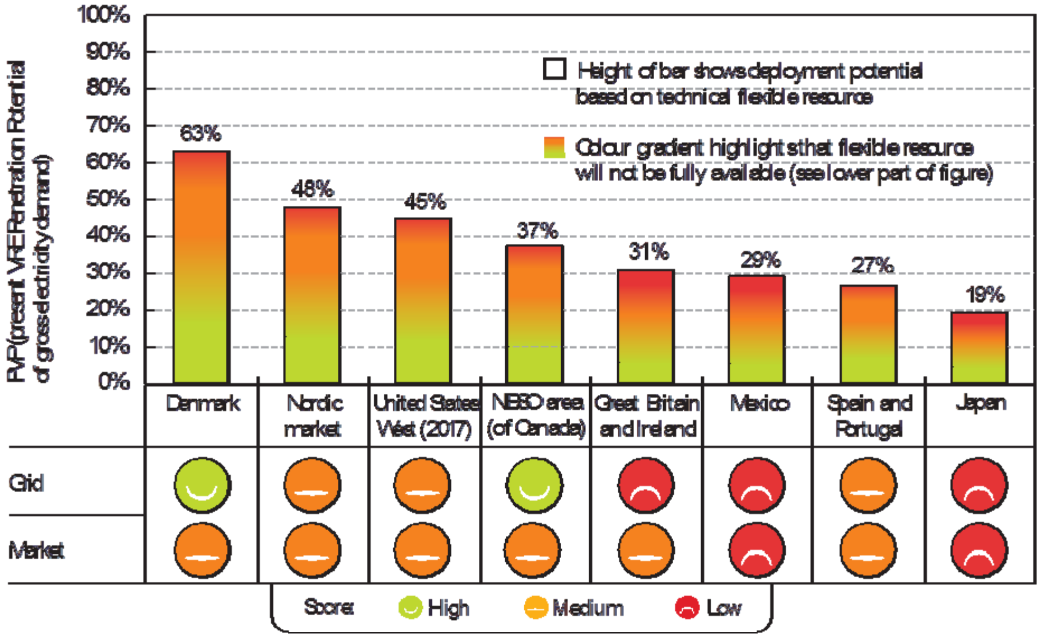

Figure 7.11. Technical capability for regions to balance large shares of variable renewables is constrained by a range of system attributes (VRE = variable renewable energy). Source: (IEA, 2011f)

The need for and relative contribution of these different possible solutions for system balancing will be context dependent, but will tend to increase with the penetration of variable renewable energy supply. Base-load operation of CCS and nuclear plant, on the other hand, is of little concern from a system balancing perspective up to the point where the capacity of nuclear and CCS approaches the minimum net load of the system. When supply of baseload nuclear or CCS exceeds minimum net load, however, the value of flexible operation of nuclear and CCS increases and/or the need for flexibility from other resources increases. As a result, certain combinations of GHG mitigation options may present challenges: high penetrations of variable renewable generation, for example, may not be ideally complemented with high penetrations of nuclear, CCS, and CHP plant (without heat storage) if those plants must be operated in an inflexible manner. In one example, over 60% of the annual electricity could be met by baseload resources in the ERCOT grid in Texas without variable generation, but if more than 30% of the annual electricity came from variable renewables none of the annual electricity could be met by resources operated in a pure baseload mode (Paul Denholm et al., 2012). Finally, if substantial GHG emissions reductions are required, some of the most cost effective current solutions for system balancing (e.g., relying upon flexible but GHG-emitting fossil plant) may no longer be acceptable, requiring the application of currently more costly options. These conclusions suggest that thoughtful, long-term consideration of overall mitigation transformation pathways, and related system balancing needs, is important for power system planning and operation.

7.6.1.2 Resource adequacy

Adequate resources need to be available to maintain a balance between supply and demand, including times of peak demand. Power systems are generally planned to operate with a reserve margin to deal with unplanned failures or scheduled maintenance of conventional generation. The resulting system reliability can be quantified in terms of various reliability metrics including the loss of load expectation (LOLE) (Allan and Billinton, 1988). The ability of different plant to contribute to meeting peak demands or to maintain the same level of reliability even with increased demand is reflected in the value of its capacity credit, also known as capacity value (Keane et al., 2011). Highly reliable generation with assured fuel supplies has a high capacity credit (i.e., greater than 90% of plant nameplate capacity), but plant that depend on a time variable resource like wind will generally have a lower capacity credit, in the range of 5% to 40% of the nameplate capacity in the case of wind power (Holttinen et al., 2011). The addition of significant plant with low capacity credit can lead to the need for a higher planning reserve margin (including the contribution of the low capacity credit plants, and leading to higher levels of aggregate capacity) to ensure the same degree of system reliability.

Nuclear plants with high availability are generally assigned high capacity credits due to their predominately base load operation. Due to parasitic loads from CCS plant operation, the net generation capacity of plant with CCS may be decreased relative to a coal plant without CCS, thus decreasing its capacity credit (Hannah Chalmers and Jon Gibbins, 2007). Research shows that options are potentially available to temporarily decrease these parasitic losses during peak loads so as to provide full capacity credit from such plant (Chalmers et al., 2009). The capacity credit of variable renewable resources generally depends on the coincidence of generation and periods of high demand. Ranges of capacity credits for renewable resources are summarized in Sims et al. (2011). Energy storage can also be used to contribute to system adequacy, but often at substantial cost. If specifically tied to renewable generation it can be seen as increasing the capacity credit of that source so that for example the capacity credit of CSP with thermal storage is greater than without thermal storage (Madaeni et al., 2011).

7.6.1.3 Transmission and distribution

Bulk generation of electricity is often located remote from demand centres requiring electricity to be transported over considerable distances (R Sims et al., 2007, 2011). Transmission upgrades are often justified by benefits including access to low cost generation resources, increased electricity reliability, decreased congestion, and facilitation of increased competition among electricity generators. Accessing new renewable sources will often require the installation of additional transmission capacity to connect these new sources (which are locationally constrained) to the existing transmission system, and may also require the strengthening of the existing system if greater power flows are required (R Sims et al., 2011). Similar considerations may apply to CCS plants depending on the trade-off between the cost of network infrastructure and the cost of pipeline transport of CO_2 to depositories suitable for sequestration (Svensson et al., 2004; H. Herzog et al., 2005; S. Benson et al., 2005; Spiecker et al., 2011), and may also apply to nuclear plant, since these tend to be located at some distance from load centres for reasons of health, safety and public acceptability. Increased interconnection and strengthened transmission systems, as planned in the EU for example, provide power system operators the capability to move surplus generation in one region to meet otherwise unmet demand in another, exploiting the geographical diversity of loads and also generation (R Sims et al., 2011). Overall, it is expected that the need for transmission will be greater with deployment of GHG reduction technologies relative to business-as-usual. However, the installation of new transmission infrastructure often faces institutional challenges since it is subject to planning consent and can be unpopular in the affected areas. Furthermore, in most cases the new network infrastructure needs to be in place before new generation can be connected, creating challenges associated with timing and cost allocation.

Though many GHG reduction technologies have locational constraints that may require network expansion, an exception is distributed generation (DG) where small generating units are connected directly to the electricity distribution system and thus can be located nearby to loads. 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).

7.6.2 Heating and cooling networks

Globally, 13.8 EJ were used in 2009 (2.6% of global TPES) to produce nearly 13 EJ[13] of district heat at CHPs (46%) and heat only boilers (54%). Those numbers include only heat produced for sale and do not account for heat generated for own use. After a long decline in the 90’s district heat returned to the growing trajectory in the last decade escalating by about 10% above the 2000 level (IEA, 2011d). Natural gas dominates in the fuel balance of heat generation (48%), followed by coal (38%), oil (6%), biofuels and waste (5%), geothermal and other renewables (2.5%) and a small contribution from nuclear. This market is dominated by the Russian Federation with a 44% share in the global heat generation, followed by Ukraine, USA, Germany, Kazakhstan, and Poland.

There is a substantial room for heat supply efficiency improvements. Statistically reported average global efficiency of heat generation by boilers is only 82%, while it is possible to improve it to 95%. About 6.9% of globally generated heat is lost in heating networks (IEA, 2011d). In the Russian Federation, which alone operated 172 thousand km of heating networks in 2010, of which 34 thousand km need urgent replacement, this share was 10.6% in 2010. In many West European countries with well-developed heat supply systems distribution losses do not exceed 5% (or 10% for small scale systems) (Sirola, 2004). In some Russian and Ukrainian municipal heating systems, however, heat distribution losses amount to 20-25% and more. A large part of losses is the result of improper district heating design (excessive centralization of many district heating systems) and of worn and poorly maintained heat supply systems (Bashmakov, 2009).

District heating and cooling systems could be physically more energy efficient when heat load density is high, triple generation is developed, the community or industrial cite can utilize the heat from waste incineration, heat (cooling) and power load show similar pattern with well managed heat loss control system. The promotion of district heating and cooling system should also consider the potential future technology development (high efficiency single housing boilers, fuel cells with characteristics of CHP, etc.), which may allow switching to more efficient systems. Pricing policy for heat and power affects the economics of district heating and cooling systems.

7.6.3 Fuel supply systems

As noted in 7.5.1, fossil fuel extraction, processing and distribution contributes around 5-10% of total fossil fuel related GHG emissions. It has also been noted that future GHG mitigation from this sector will be limited by the increased energy requirements of production of oil and gas from mature fields and unconventional sources, and the mining of coal from deeper mines. The flexibility, long operational life and distributed nature of the supply system infrastructure do however provide an

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

opportunity to reduce GHG emissions through the delivery of low carbon fuels. Opportunities for the petroleum system are likely limited to supply of such fuels as biodiesel and ethanol at the distribution end of the network; these are discussed in Section 8.3.3., while for gas, supply of low carbon fuels could occur within both the transport and distribution components of the network.

More than 100 countries around the globe transport high pressure natural gas through pipeline networks estimated to have a combined length of over 1.2million km. Although the networks in the USA and Russia account for almost 60% of this total, more than half of these countries have network lengths greater than 1000km (Central Intelligence Agency, 2011). Connected to these are the low 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. Low CO_2 emitting natural gas substitutes can be produced from renewable sources such as biomass and waste, or via coal when combined with CCS; CCS can also be added to production from renewable sources to further enhance CO_2 mitigation potential (Carbo et al., 2011). Provided the substitute natural gas meets the relevant gas quality standard (European Commission, 2001; IEA Bioenergy, 2006, 2009) there are no technical barriers to the injection of gas substitutes into the existing gas networks (European Commission, 2001). Substitutes are already being injected into natural gas networks. Examples of biomethane gas injection plants based on anaerobic production processes can be found in Canada, Finland, Norway, Sweden, and The Netherlands; Germany has over 50 operational plants injecting biomethane produced from animal waste and agricultural residues (IEA Bioenergy, 2011). In the USA a substitute-natural gas injection plant based on coal gasification and syngas methanation has been operating for more than 20 years (US DOE, 2006).

Although limited, the natural gas network also has the potential to transport and distribute hydrogen produced from biomass and fossil fuel sources, or produced to carry surplus energy generated from variable renewable sources such as wind or solar (IEA, 2006; Moriarty and Honnery, 2007; Honnery and Moriarty, 2009). Unless the amounts are small, combining hydrogen with natural gas is likely to mean gas quality standards will not be met (European Commission, 2004; Tabkhi et al., 2008). Large scale injection would require changes to gas appliances so remains a longer term option (Haeseldonckx and D'haeseleer, 2007). Additional factors limiting hydrogen injection relate to the integrity of steel pipelines and end user safety (European Commission 2004). For a hydrogen only distribution network, the distance to the point of demand and demand size are important determinants in delivery mode cost, with hydrogen pipeline delivery optimal for large scale systems (C Yang and Joan Ogden, 2007). The combined length of hydrogen pipelines is currently estimated to be less than 3000km (BCC van der Zwaan et al., 2011).

7.6.4 CO_2 transport

Options for CCS and CO_2 storage are presented in 7.5.5, the focus here is the infrastructure required for CO_2 transport. The recent CO_2 transport literature addresses the scale of the required CO_2 pipeline network and potential ways to optimize these (largely) yet-to-be-built pipeline networks. Dooley et al.,(2009) report that even under a stringent 450 ppm stabilization scenario, a "network" of dedicated source-to-sink pipelines (which the authors acknowledge should result in an overestimate of required pipeline length) for the U.S. would likely constitute less than 37,000 km of dedicated CO_2 pipelines by 2050. Moreover in this same 450 ppm analysis in the period up to 2030, perhaps as little 9,600 km of new CO_2 pipelines would be required, which should be manageable given that 6,300 km of CO_2 pipeline already exists in the U.S. The work of Johnson and Ogden (2011) suggests that in the early decades of CCS deployment, dedicated source to sink pipelines might be more economically appealing in many regions of the world, but that 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 regions like the United Kingdom and parts of Northern Europe where the vast majority of deep geologic CO_2 storage capacity lies offshore in the North Sea, it might be more economical to implement from the outset a more integrated CO_2 pipeline system. A system that gathers CO_2 from a number of onshore point sources and conveys it to large offshore injection fields via common trunk lines is likely the economically optimal choice (Strachan et al., 2011; ZEP, 2011a).

Although much can be learnt from existing CO_2 pipe line 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; IS Cole et al., 2011) with particular importance given to limiting the amount of water in the gas stream at its source to avoid corrosion.

While pipelines are likely to be the transport mode of choice for onshore and most offshore storage projects, in certain parts of the world, transport of CO_2 by large ocean going vessels might not only be feasible but could reflect the lowest-cost transport option (Aspelund et al., 2006; Decarre et al., 2010; Ozaki and Ohsumi, 2011; Yoo et al., 2011). The prospect of moving CO_2 by ocean vessel opens the door to a potential “global CO_2 storage market.” Regions with storage would be able to sell storage services to facilities that capture CO_2 in another region. International institutions and would be needed to facilitate such transactions within the context of emissions mitigation regimes.

7.7 Climate change feedback and interaction with adaptation

7.7.1 Climate change impacts on energy demand

Climate change affects energy demand for heating and cooling (See also 9.5). Effect of climate change on overall energy demand will vary geographically (Ruth and Lin, 2006; Franco and Sanstad, 2008; Zmeureanu and Renaud, 2008; Giannakopoulos et al., 2009; Hekkenberg et al., 2009; Hamlet and Lee, 2010; Mideksa and Kallbekken, 2010; Pilli-Sihvola et al., 2010; Wan et al., 2011). Many studies indicate the increase of electricity demand by climate change as cooling demand is mainly supplied by electricity and heating demand could also be supplied by other energy sources than electricity. It also has an impact on CHPs. (Isaac and D van Vuuren, 2009; Akpinar-Ferrand and A Singh, 2010; IPCC AR5 WGII ZOD, 2011).

Peak electricity demand could be increased because of climate change, especially with extreme events. The studies that examine effects on peak electricity demand emphasize that increases in peak demand would cause the grid more inflexible and disproportionate increases in energy infrastructure investment (IPCC AR5 WGII ZOD, 2011; USEPA, 2008). The Russian experience shows that extreme whether does not allow it to reduce peak heat demand, while heat demand is declining (IEPort.RU, 2012).

There is a need to balance electricity supply and demand to keep the grip stable. With the absence of any climate policy and significant negative anthropogenic climatic changes, demand for peak electricity should increase and the grid would seemingly be more inflexible (MA Wise and J.J. Dooley, 2005).

Although impacts on energy demands in sectors other than heating and cooling are less clear, possible effects could include increases in energy used to supply resources for climate-sensitive processes, such as pumping water for irrigated agriculture and municipal uses (USEPA, 2008).

7.7.2 Climate change impacts on energy supply

In addition to influencing the amount and nature of energy demand that must be met, climate change will have varied impacts on energy supply. This section focuses on impacts that relate to the potential future role of GHG mitigation technologies in the energy supply sector. Further details on these impacts, as well as a summary of how conventional higher-carbon energy supplies might be impacted, are offered in the WGII AR5 report, especially but not limited to Chapter 10 (D Arent and Tol, Forthcoming). Chapter 8, meanwhile, discusses the impact of climate change on shipping and transport, while Chapter 11 discusses in more depth feedbacks related to biomass and bioenergy.

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

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

The limited lifetime and portability of some RE technologies, such as wind turbines, solar panels, or bioenergy facilities, may mean that these technologies are more adaptable to such changes; a decline in resource potential in one area could lead to a shifting in the location of projects using these technologies over time to areas where the resource potential has not degraded. The non-portability and longer lifetimes of dams used for hydropower may mean that these facilities are less adaptable to such changes (Roberto Schaeffer et al., 2012).

Climate change may also impact the design and operation of energy production and delivery facilities. Offshore infrastructure, including gas and oil wells but also certain RE facilities such as offshore wind power plants, are vulnerable to an increase in the frequency and magnitude of extreme weather events (D Arent and Tol, Forthcoming; Karl et al., 2009; Wiser et al., 2011; World Bank, 2011). Production losses from thermal power plants (whether low- or high-carbon facilities) increase when temperatures exceed standard design criteria (Erdem and Sevilgen, 2006; Roberto Schaeffer et al., 2012). Power generation facilities and energy delivery infrastructures may also experience performance losses and other impacts related to changes in the access to and temperature of cooling water, as well as sea level rise and extreme weather events (D Arent and Tol, Forthcoming; Durmayaz and Sogut, 2006; Kopytko and Perkins, 2011; Roberto Schaeffer et al., 2012). The implications of extreme weather events for nuclear facilities may be especially severe given the nature of the risks associated with the technology (D Arent and Tol, Forthcoming). Adaptation strategies to these varied impacts include, but are not limited to, infrastructure relocation and reinforcement, cooling facility retrofit, and proactive water resource management (D Arent and Tol, Forthcoming; Rübbelke and Vögele, 2011).

Finally, inter-dependencies between the energy sector and other sectors of the economy are important to consider (de Lucena et al., 2009). For example, if climate change detrimentally impacts crop yields, bioenergy potential may decline and costs may rise because more land is demanded to maintain food crop production (Porter and Xie, Forthcoming); see also Chapter 11). Climate change may also exacerbate water and energy conflicts across sectors and regions, impacting hydropower development (Cisneros and Oki, Forthcoming; D Arent and Tol, Forthcoming; Kumar et al., 2011).

7.8 Costs and potentials

7.8.1 Potential emission reduction from mitigation measures

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

A comprehensive review of life-cycle assessments of energy technologies was conducted for SRREN (J. Sathaye et al., 2011), and further review papers have been published since. The largest GHG emissions are associated with the combustion of coal, with an interquartile range of 880 to 1130 gCO_2e per kWh electricity from coal identified by Sathaye et al. (2011) and a global average of 1040 g/kWh (B Singh et al., 2011). Oil fired steam power plants are only slightly better. Modern natural gas combined cycle plants bring significant reductions in CO_2 emissions (by 60% compared to coal), but concerns have recently emerged about high emissions of methane from both unconventional and conventional gas production (CL Weber and Clavin, 2012; Petron et al., 2012). If methane leakage can be controlled to less than 2%, the increased use of natural gas instead of coal can hence result in significantly reduced CO_2 emissions. Combined heat, cooling and power can also result in life-cycle emissions reductions compared to separate fossil fuel based heat, cooling and power provision (M. Pehnt, 2008). However, average emissions from power generation need to be reduced to below 100 gCO_2e per kWh by 2050 to meet the 2°C mitigation goal (IEA, 2010c) and eventually need to go to zero, so that the employment of technologies with even lower emissions is called for.

CO_2 capture plants are often evaluated based on a design of a capture rate of 90% of the CO_2 in the flue gas. When considering emissions of non-CO_2 greenhouse gases and those connected to fuel production, capture plant and CO_2 transport and storage, the emission reductions obtain from entire system are on the order of 64-78%. Emissions are 180-200 gCO_2e/kWh for coal power and 120-160 gCO_2e/kWh for gas power assuming 1% leakage (Koorneef et al., 2008; B Singh et al., 2011; Ramírez et al., 2012). The most substantial source for remaining emissions is the fuel production chain, where both fugitive and energy-related emissions are relevant. Measures to increase energy efficiency and reduce fugitive emissions in fuel production and distribution can give further emission reductions, but these gains may be offset by the need to tap lower-quality resources which result in higher fuel-chain emissions (Section 7.5.1).

Renewable heat and power production and nuclear energy can bring more significant and certain reductions in GHG emissions. The interquartile ranges of life-cycle greenhouse gas emissions reported in the literature are 15-50 gCO_2e/kWh for PV (Kim et al. 2012; Hsu et al. 2012), 20-34 for CSP (John J. Burkhardt et al., 2012), and 9-24 for wind power (Arvesen and EG Hertwich, in review). The reported range for nuclear energy is 8-45 gCO_2e/kWh (Warner and Garvin A. Heath, 2012). For all of these technologies, at least 5 studies are reviewed. The empirical basis for estimating the emissions associated with geothermal and ocean energy is much weaker, but ranges of 20-57 gCO_2e/kWh for geothermal power and 6-9 gCO_2e/kWh for ocean energy have been identified (J. Sathaye et al., 2011). Most of these emissions are associated with the manufacturing and installation of the power plants, but for nuclear plant the enrichment is significant. For all technologies, local resource conditions and other site-specific factors can have a substantial influence on the results, and studies generally assume good conditions. The life cycle climate effects of bioenergy are discussed in a cross-cutting bioenergy annex to this chapter.

Two qualifications of the present literature are required. First, according to some reviews, a large fraction of the available case studies exclude cumulatively significant parts of the life-cycle. More complete studies show typically twice as high emissions. The higher end of the estimates provides hence a more realistic picture (Arvesen and EG Hertwich, in review; Warner and Garvin A. Heath, 2012). Further, assessments are based on current technologies. Most of the GHG emissions occur either in the production of electricity used in manufacturing processes or as process emissions during material production. In a mitigation scenario, electricity mixes will become cleaner, and as these emissions are reduced, the life cycle emissions of clean energy technologies will go down. Emissions from material production can also be reduced through various mitigation measures (Ch. 10). Few studies explicitly address such effect, mostly in the form of scenario analysis. In a dynamic assessment of PV, improvements in steel, aluminium and electricity production would reduce life-cycle emissions by 15% between 2010 and 2030. Improvements in efficiency and design could lead to further improvements by 30% (Martin Pehnt, 2006). In an assessment of CSP, technology improvements and changes in the background energy mix would reduce emissions from 31 to 18 g/kWh between 2010 and 2050 (Viebahn et al., 2011).For wind energy, reduced emissions in the background energy mix and improved technology may lead to a reduction of life cycle emissions by 45% between 2010 and 2050 (Arvesen and EG Hertwich, 2011).

The climate effect of hydropower is very project specific. An important issue is the emissions of biogenic CO_2 and CH_4, primarily from hydropower reservoirs and not run-of-the-river plants. Dams interfere with the natural carbon cycle, stopping the flow of biomass to the oceans, leading to the accumulation of organic carbon in the reservoirs and the slow aerobic or anaerobic digestion of this biomass in the reservoir or after decommissioning. At the same time, power stations also affect the exchange of gases between the surface water and the atmosphere. A concise presentation of these issues can be found in SRREN (Kumar et al., 2011). Few studies quantify the net flux of GHG. In boreal and temperature regions, reservoirs can act both a sink and significant source of GHGs. In tropical regions, degradation of organic matter from the inundated vegetation and soils or added through tributaries leads to significant anoxic conditions, where anaerobic digestion produces methane. Without organic matter inputs, GHG uptake is reported for an older reservoirs (Kumar et al., 2011). Reported GHG emission from reservoirs range from 0 to 150 gCO_2e/kWh in SRREN and 4-400 gCO_2e/kWh in (Dones et al., 2007). The highest values in SRREN result from the decomposition from silt after decommissioning, a process omitted from most studies. Barros et al. (2011) estimate total emissions from hydroelectric dams to be equal to 48 Tg CO_2 and 3 Tg CH4, which would correspond to a world average 41gCO_2e/kWh. Reported life-cycle emissions of fossil GHGs from producing and operating hydropower stations vary between 0-40 g/kWh for the studies reviewed in SRREN and 3-7 g/kWh in (Dones et al., 2007).

Technologies can affect the climate also through other physical mechanisms not involving greenhouse gases. For fossil fuels, there is a sort-term cooling from sulphate and organic carbon aerosols, but a warming through black carbon emissions (Section 7.5.1). Nemet (2009), Georgescu et al. (2011) and Millstein and Menon (2011) discuss albedo feedback effects associated with PV panels and bioenergy crops. Wind power plants have the potential to alter local climates due to reduced wind speeds and increasing vertical mixing (e.g., Wiser et al., 2011; C Wang and Prinn, 2011), and there is some evidence that local climate and precipitation can be altered by large reservoirs (e.g., Degu et al., 2011).

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 run-of-the-river hydro power. Further improvements in these technologies will be attained as a feedback to a cleaner energy supply in the production of the technologies and through performance improvements.

7.8.2 Cost assessment of mitigation measures

7.8.2.1 Current levelised costs

To compare the competitiveness of energy supply technologies, the concept of “levelised costs of energy” (LCOE, also called levelised unit costs or levelised generation costs) is often applied (IEA, 2005a, 2010d, 2011a; Rogner et al., 2011). A basic description of this concept, including its merits and shortcomings, are discussed in detail in Annex Methodology.

The levelised costs of many low carbon energy supply technologies have changed considerably since the release of the AR4. Even compared to the data recently published in the IPCC’s SRREN (IPCC, 2011a)[14], the decline of LCOE of important renewable energy (RE) technologies has been significant. Figure 7.12 depicts the LCOE evolution of those electricity supply technologies that Bloomberg New Energy Finance has been tracking in the past three years. These numbers are intended to represent global policy-neutral trends and they do not incorporate any policy mechanisms, other than standard taxes faced by the companies. Actual costs in specific regions could fall outside of the range shown, and a variety of other recent sources also report the LCOE of low-carbon supply options (DOE NETL, 2010; IEA, 2010d; Branker et al., 2011; IPCC, 2011a and the references therein; WorleyParsons, 2011; ZEP, 2011a; De Roo and J Parsons, 2011).

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

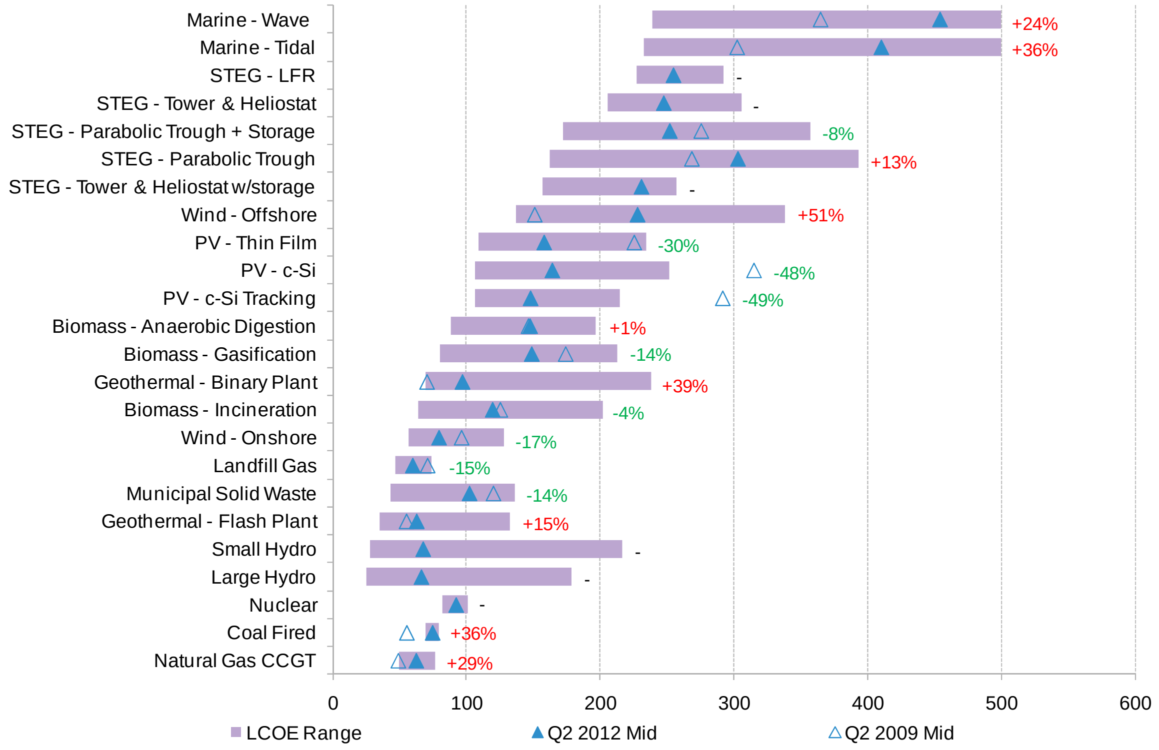


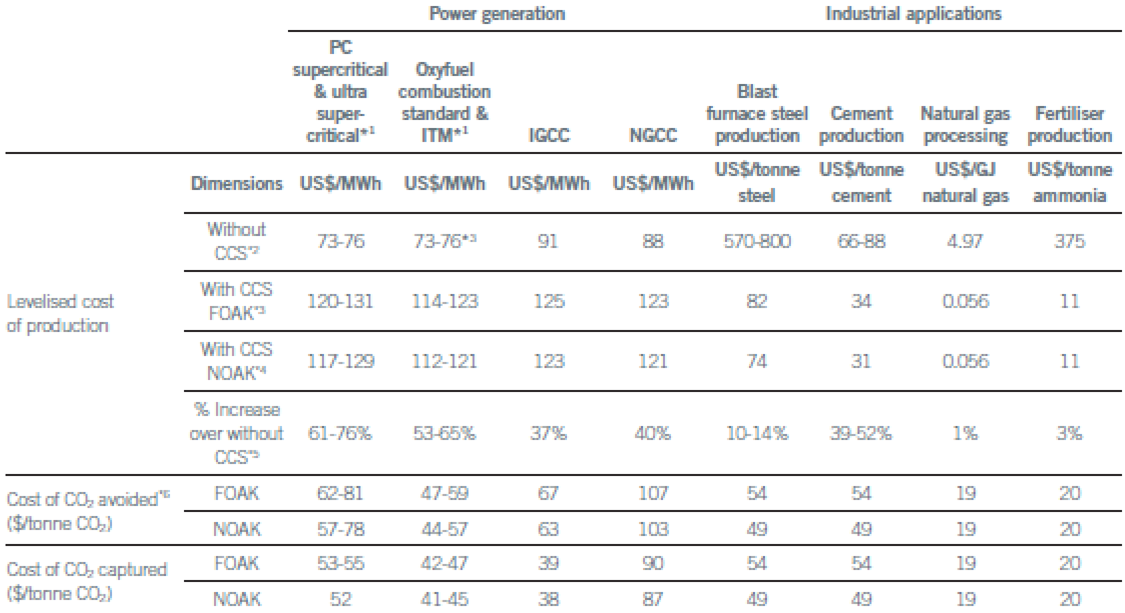
Figure 7.12. Levelised cost in $/MWh of electricity for commercially available fossil and nuclear power plants as well as renewable energy technologies as observed for the second quarter of 2012 (and for the second quarter of 2009). The percentage change is from Q2 2009. A dash denotes no significant change, or insufficient data. The data presented here assume a major technology-agnostic developer or an integrated utility requesting a 10% equity internal rate of return. The diagram is an updated version of a figure published in UNEP and Bloomberg New Energy Finance, 2012. Source: Bloomberg New Energy Finance (2012).

The LCOE ranges are rather broad as values may vary across the globe depending on the site-specific renewable energy resource base, on local fuel and feedstock prices as well as on country specific costs of investment, financing, and operation and maintenance. A direct economic comparison between different technologies should therefore not be based on the cost data provided in Figure 7.12; instead, site-, project- and investor specific conditions should be considered.

For RE technologies, the largest decline in LCOE since the release of the AR4 has been observed for photovoltaics. PV module prices fell from $4/W in 2008 to $1/W in 2011. As a result, although the technology remains significantly more costly than electricity produced from gas or coal, the gap is narrowing. In 2009, Bloomberg New Energy Finance estimated that the LCOE of PV in a sunny location was at least $250/MWh; as of mid-2012, this had fallen to $123/MWh. The previous cost differential between thin film and crystalline technology is also no longer very significant (see Figure 7.12). As this figure shows, a similar, albeit less extreme trend towards lower LCOE from 2009 to 2012 has been observed for onshore wind (-17%), land fill gas (-15%), municipal solid waste (-14%), and biomass gasification (-14%). The main factors contributing to the estimated 8% LCOE reduction of parabolic trough plants (including thermal storage) between 2009 and 2012 was the combined effect of specialized component cost reductions and increased use of thermal energy storage, resulting in greater utilization of the power block and balance of plant assets (Bloomberg New Energy Finance, 2012). In contrast, the LCOE of offshore wind has increased since 2009 due to a shift towards deeper-water projects and a shortage of competition among key suppliers, for instance, suppliers of high-voltage cables and installations ships. A variety of other renewable electricity technologies are also estimated to have, on average, witnessed increased LCOE from 2009 to 2012.

A detailed discussion of levelised costs of renewable power plants is provided in various chapters (especially 1.3.2, 2.3, 2.7, 3.8, 4.8, 5.8, 6.7, 7.8, 10.5, Annex III) of the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) (IPCC, 2011a)). Taking additional information into account (IEA, 2007a, 2010a; c), the IPCC SRREN notes: “Some RE technologies are broadly competitive with existing market energy prices. Many of the other RE technologies can provide competitive energy services in certain circumstances, for example, in regions with favorable resource conditions or that lack the infrastructure for other low-cost energy supplies. In most regions of the world, policy measures are still required to ensure rapid deployment of many RE sources” (IPCC, 2011a, p. 841). Based on the information provided in the IPCC SRREN (IPCC, 2011a), which is consistent with various publications of the IEA (2007a, 2010a; c),the following technology specific assessments can be made: “Under favorable conditions, inter alia, modern combustible biomass to produce heat (IEA, 2007a), solar thermal energy (e.g., solar water heaters in China (IEA, 2010a), selected off-grid PV applications (IEA, 2010e), large-scale hydropower (IEA, 2008a), larger geothermal projects (>30 MW_{el} (IEA, 2007b)) and (if the cost of carbon is reflected in the markets) wind onshore power plants (IEA, 2010c) are already competitive” (IPCC, 2011a, p. 841). “In PV, analysis suggests that the cost of producing power from rooftop panels for domestic use is already competitive with the retail (but not the wholesale) electricity price in several countries” (Bloomberg New Energy Finance, 2012, p. 35) .Although the gas prices went down in the last few years in many regions, the increase in capital expenditures and operation and maintenance costs is explaining the raising LCOE of natural gas combined cycle power and coal-fired power plants.

Applied to fossil-fuelled power plants, CCS reduces the fuel efficiency of those plants. Typical efficiency differences projected for 2015 are on the order of 8 - 11 % points. Due to the lower net output and the cost for the additional equipment needed to capture the CO_2, the specific investment costs of CCS plants are significantly higher compared to conventional ones. In addition, due to the efficiency loss, additional fuel costs must be incurred (IEA, 2010d). The cost of CO_2 capture from various power plants and industrial facilities reported in the SRCCS (IPCC, 2005), and excluding the cost of CO_2 transport, storage, and monitoring (which are provided below), are in keeping with more recent published estimates of the cost of capture. Example costs of CO_2 capture for the fossil fuel fired power sector include \$40-\$70/tCO_2 for post combustion CO_2 capture from a coal power plant (MR Hamilton et al., 2009; Finkenrath, 2011; HJ Herzog, 2011); \$30-\$60/tCO_2 for pre-combustion CO_2 capture from coal fired power plants (Huang et al., 2008; Edward S Rubin et al., 2010; Finkenrath, 2011), and \$35-72/ tCO_2 for coal fired oxycombustion based capture (Finkenrath, 2011).



		Power generation				Industrial applications			
		PC supercritical & ultra super-critical[*1]	Oxyfuel combustion standard & ITM[*1]	IGCC	NGCC	Blast furnace steel production	Cement production	Natural gas processing	Fertiliser production
	Dimensions	US$/MWh	US$/MWh	US$/MWh	US$/MWh	US$/tonne steel	US$/tonne cement	US$/GJ natural gas	US$/tonne ammonia
Levelised cost of production	Without CCS[*2]	73-76	73-76[*3]	91	88	570-800	66-88	4.97	375
	With CCS FOAK[*3]	120-131	114-123	125	123	82	34	0.056	11
	With CCS NOAK[*4]	117-129	112-121	123	121	74	31	0.056	11
	% Increase over without CCS[*5]	61-76%	53-65%	37%	40%	10-14%	39-52%	1%	3%
Cost of CO_2 avoided[*6] ($/tonne CO_2)	FOAK	62-81	47-59	67	107	54	54	19	20
	NOAK	57-78	44-57	63	103	49	49	19	20
Cost of CO_2 captured ($/tonne CO_2)	FOAK	53-55	42-47	39	90	54	54	19	20
	NOAK	52	41-45	38	87	49	49	19	20

Figure 7.13. Levelised cost in $/MWh, cost of CO2 avoided and cost of CO2 captured for various CCS power plants and industrial applications (FOAK = first-of-a-kind, NOAK = nth-of-a-kind, ITM =ion transfer membrane). Source: Global CCS Institute (2011a).

Figure 7.13 depicts LCOE costs of various power plants together with the cost of CO_2 avoided and cost of CO_2 captured (Global CCS Institute, 2011a). Projected costs in specific regions could fall outside of the range shown, and a variety of other recent sources also report projected LCOE for CCS power plants (MR Hamilton et al., 2009; HJ Herzog, 2011; IEAGHG, 2011; Versteeg and E.S. Rubin, 2011; E.S. Rubin and Zhai, 2012). The additional LCOE costs exhibited by CCS plants (compared to traditional fossil fueled power plants) are to be compared with the LCOE increase of the latter once significant CO_2 costs (e.g., via carbon taxes or permit prices) are to be taken into account.

According to the IEA, "nuclear plants are characterized by very large up-front investments, technical complexity, and significant technical, market and regulatory risks, but have very low operating costs and can deliver large amounts of base-load electricity while producing almost no CO_2 emissions" (IEA, 2011a, p. 455). The levelised cost of nuclear energy is included in the estimates of Figure 7.12, but those estimates can only be considered indicative, because of the difficulty of accurately estimating cost elements such as disaster insurance (often provided only implicitly by governments, as the Fukushima crisis has shown), and long-term nuclear waste storage.

According to other sources (IEA, 2010d) the *projected* levelised costs[15] of nuclear electricity generation in OECD countries are in the range of 42 USD/MWh (Korea) to 137 USD/MWh (Switzerland). The fuel costs for this assessment include both front- and back-end costs. Front-end costs refer to uranium mining, conversion, enrichment and fuel fabrication and amount to $7 per MWh_{el}. Back-end costs include spent fuel storage, reprocessing and disposal and are estimated at $2.33 per MWh_{el}. Nuclear fuel costs do not distinguish between open once-through and closed fuel cycles, which reflect the assumption that the additional cost involved in fabricating fuel elements from mixed (i.e. uranium-plutonium) oxide fuel is broadly offset by the savings on mining, conversion and enrichment (Crossland, 2012). Not included in the levelised costs presented here are

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[15] Taking a discount rate of 10% into account. The *projected* costs refer to those costs that are expected to occur in 2015.

the costs associated with low probability - high consequence events such as nuclear accidents and limited operator liability.

The short-run marginal costs of well-run nuclear power plants (i.e., existing plants with sunk or depreciated capital costs) are generally very low. The economic assessment is different for prospective plants that are yet to be built. In liberalized markets, high upfront capital costs, long construction periods preceded by extended planning, licensing, and public hearing periods expose investors in nuclear power to sizable economic risks (IEA, 2011a).

Altering future energy supply to reduce GHG emissions may require investments in ancillary infrastructures beyond those needed in a business-as-usual (BAU) future. This additional ancillary infrastructure can impose additional costs not yet captured in the levelised cost data presented above. These costs often increase with the level of supply from mitigation options, but future infrastructure costs are often uncertain and difficult to define. As will be discussed in the following paragraphs, infrastructure needs and costs will vary by energy sector, mitigation technology, deployment level, region, and other factors.

Infrastructure costs in the electricity network, as described in Section 7.6.1, include the need for flexibility to maintain balance between supply and demand, the need for adequate generating resources to ensure reliable operation, and the need for transmission and distribution of electricity. Infrastructure costs are generally higher for variable and location dependent RE supply options than for other sources of energy supply (e.g., Sims et al., 2007; Hoogwijk et al., 2007; Delucchi and Jacobson, 2011), with the recent literature tending to focus on wind power in OECD countries. Based on estimates from this existing literature, providing the additional balancing reserves required for wind power increases costs by approximately USD 1 to 7/MWh for penetrations of up to approximately 30% (IEA, 2010a, 2011f; Wiser et al., 2011; Holttinen et al., 2011). Inflexible operation of nuclear and CCS plants can also add balancing costs or conversely be less valuable relative to resources that are more flexible, unless modifications are made to facilitate the flexible operation of those plants (Fenton, 1982; Chalmers et al., 2009; S Cohen, G Rochelle, et al., 2011; S Cohen, H. Chalmers, et al., 2011). Additionally, variable RE technologies like wind, contribute a smaller fraction of their nameplate capacity to meet the peak demand – though conventional capacity can still be avoided, the amount of avoided capacity will be lower than conventional supply options. While determining the cost of additional conventional capacity needed to ensure that peak demands are met is contentious, estimates of this cost for wind power range from USD 0 to 10/MWh (IEA, 2010a, 2011f; Wiser et al., 2011). Because of the coincidence of solar generation with air conditioning loads, on the other hand, solar at low penetration levels can in some cases displace a larger amount of capacity, per unit of energy generated, than other supply options, yielding estimates of infrastructure savings as high as USD 23/MWh greater than the savings from base load supply options (Mills et al., 2011). Finally, estimates of the additional cost of transmission infrastructure for wind energy in OECD countries are often in the range of USD 0 to 15/MWh depending on the amount of wind energy supply, region, and study assumptions (IEA, 2010a, 2011f; Wiser et al., 2011; Holttinen et al., 2011). Nuclear and CCS facilities will also require additional transmission costs if power plants are not sited close to demand centres. If mitigation technologies can be deployed near demand centres on the distribution network or if these are intended to serve isolated autonomous systems, those technologies may defer or avoid transmission and distribution needs, potentially reducing infrastructure costs relative to a BAU scenario.[16]

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

Infrastructure costs are not restricted to the electricity network. Infrastructure costs related to heating/cooling and fuels networks, for example, can include transportation, cleaning and blending, storage, and distribution. Whether costs will be higher for low-GHG options than for BAU options depends on the specific context in question (R Sims et al., 2011). CCS, meanwhile, 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 cost of this infrastructure was not included in the cost of CO_2 capture (including compression to pipeline pressures) from various fossil fuel power plants reported earlier, but it is unlikely to exceed \$15/ton-CO_2 for the majority of CCS deployment scenarios (H. Herzog et al., 2005; HJ Herzog, 2011; ZEP, 2011b) and some estimates are below \$5/ton-CO2 (McCoy and Edward S. Rubin, 2008; Dahowski et al., 2011).

7.8.2.2 Historic costs and potential future costs evolution

Although recently detailed studies on CCS costs have been published by the IEA (2010d), WorleyParsons (2011), DOE NETL (2010), and ZEP (2011b), the assessment of the cost of large scale plants is still plagued by many difficulties. With a limited number of commercial-scale CCS projects in operation in some sectors, and none yet in operation for coal-fired power generation, steel or cement production, the estimation of the costs of future large-scale plants has to be carried on the basis of design studies and few existing pilot projects. According to the Global CCS Institute “The initial cost estimates for new technologies based on experience from smaller-scale projects or pilot plants are typically lower than the costs subsequently observed for the initial large-scale applications (S. Yeh and E.S. Rubin, 2010). Costs are often added through design changes and product performance improvements in the early stages of commercialization (Neij, 1997). However, it is then equally common for costs to subsequently decline as technologies mature and learning is incorporated into subsequent designs” (Global CCS Institute, 2011b).

Klara and Plunkett (2010), van den Broek et al. (2009), Rubin et al. (2007) and others, for instance, have pointed out that the cost of CO_2 capture can be potentially reduced through a combination of technological push (e.g., directed R&D investments to allow solid oxide fuel cells to be integrated with IGCC+CCS facilities) as well as learning-by-doing. Rochelle (2009) notes that while most analyses of CO_2 capture assume a capture rate of 90% of the CO_2 in the flue gas “there are few fundamental barriers to higher removal rates” which is something that could be quite important in scenarios where CO_2 levels are being stabilized at levels close to those which exist today (Wise and Dooley, 2004).

“The cost of most RE technologies has declined and additional expected technical advances would result in further cost reductions. Significant advances in RE technologies and associated long-term cost reductions have been demonstrated over the last decades (Figure 7.14), though periods of rising prices have sometimes been experienced (due to, for example, increasing demand for RE in excess of available supply)” (IPCC, 2011a, p. 13). “Further cost reductions are expected, resulting in greater potential deployment and consequent climate change mitigation. Examples of important areas of potential technological advancement include: new and improved feedstock production and supply systems, biofuels produced via new processes (also called next-generation or advanced biofuels, e.g., lignocellulosic) and advanced bio-refining; advanced PV and CSP technologies and manufacturing processes; enhanced geothermal systems (EGS); multiple emerging ocean technologies; and foundation and turbine designs for offshore wind energy” (IPCC, 2011a, p. 13).

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of distributed generation, additional distribution infrastructure may be required (e.g., Cossent et al., 2011).

Starting from the middle of the decade and onwards, the LCOE for offshore projects are expected to fall as a result of improved installation expertise, increasing competition in the supply chain, and the introduction of more efficient turbines (Bloomberg New Energy Finance, 2012). By 2020, grid parity (i.e., competitiveness with grid retail prices) of PV can be expected in many countries provided that sufficient policy support is available (IPCC, 2011a).

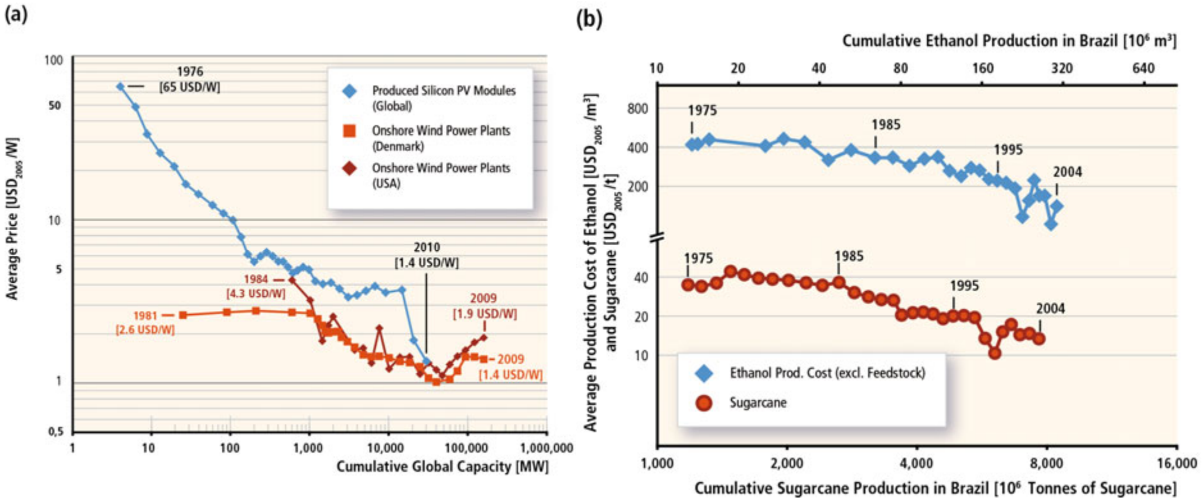


Figure 7.14. Selected experience curves in logarithmic scale for (a) the price of silicon PV modules and onshore wind power plants per unit of capacity; and (b) the cost of sugarcane-based ethanol production. Source: IPCC (2011a, Figure SPM6).

According to the IEA, “Post-Fukushima Daiichi, the relative economics of nuclear power compared with other generating technologies may deteriorate. Finance providers may demand tougher financing conditions, driving up the cost of capital, and some may decide to discontinue investing in nuclear projects altogether. More stringent safety regulations may lengthen lead times for construction and increase construction and operating costs, as could more vigorous action by opponents of nuclear power (…). In liberalized markets, it may not always be possible to recoup the cost increases through higher tariffs” (IEA, 2011a, p. 456).

Learning and cost reductions are not always a given, as illustrated by the recent developments in costs of wind off-shore and nuclear power plants (increasing safety demands and changing design). Also raw material prices impact the development of costs of energy technologies considerably, as was visible around 2008, although this does not mean that actual technological learning stalls. In general, stable and consistent policies with a long term time horizon facilitate innovation and investment and thus technological learning. Also progressive incentives that stimulate technological learning (e.g. declining support over time targeting improved performance) and the use incentives that fit the phase of development and commercialization of technologies is important (Junginger et al., 2010).

7.8.3 Economic potentials of mitigation measures

Energy supply cost curves summarize existing estimates of resources and reserves of major energy fuels or of renewable energy sources into a production cost curve on an annual or cumulative basis. Such production cost curves entail considerable uncertainties over the relationship between confirmed reserves and speculative resources, the impact of unconventional sources of fuels, the costs of future extraction under future technological change and energy market structures, and the uneven global distribution and data availability on energy resources. A useful comparator is 2009 global energy demands of 12,132 Mtoe or 508.0EJ (IEA, 2011a).

Energy resources and reserves and their associated uncertainties are discussed in detail in section 7.4, with the following cost curves falling within these uncertainty ranges. Total resources of hard coal and lignite (IEA, 2011g) are very large (Table 7.2), and are estimated to cover future demand for many decades at up to 400,000EJ. Technically recoverable reserves of oil (summarized in **Figure 7.**8) and Table 7.2) have been classified into a production cost curve with 18,300EJ at a cost of <$40/barrel to 39,700EJ at a cost of <$100/barrel (IEA, 2010c). Natural gas central estimates of conventional resources (detailed in Table 7.2 and in IEA (2005b)) are around 370 trillion cubic metres (14,650EJ) with considerable uncertainties in the additional large unconventional resource baseg. One example of an attempt to classify production cost curves for natural gas, gives 14,650EJ at a cost of<$4.5/GJ, rising to up to 40,000EJ at a cost of <$10/GJ (Remme et al., 2007). Nuclear resources (detailed in Table 7.2) have been estimated into a cost curve with 2,630EJ at a cost <$80/kgU to 7,280EJ (10.4 million tonnes of uranium) at a cost of <$260/kgU (NEA and IAEA, 2010). Very large speculative uranium resources exist at costs >260kgU, but these require substantial new exploration efforts.

Renewable resources are discussed via **Figure 7.**9, with a full discussion of renewable energy resource cost curves given in section 10.4 in Fischedick et al. (2011). Studies of wind potentials (Bert J.M. de Vries et al., 2007; M Hoogwijk and Graus, 2008) find a global economic potential of between 29 and 155EJ/yr, which is highly dependent on assumptions on wind conditions, transmission distances and system integration. De Vries et al. (2007) estimate PV electricity generation technical potential at 4,780EJ/yr in 2050 at a cost of $16.7 - 69.4/GJ. The analyses of biomass resource cost curves depend on discount rates, technology assumptions and different land use scenarios (including energy vs. food production trade-offs). Hoogwijk et al. (2009) find that biomass can supply 130 to 270EJ/yr by 2050 at production costs below $2/GJ. However cost estimates for final energy biomass products are much higher with de Vries et al. (2007) giving an estimated potential for liquid biomass fuels of 108 to 310EJ/yr in cost steps from £12/GJ to $20/GJ.

A broader approach to energy supply cost curves are marginal abatement cost (MAC) curves. MAC curves discretely rank energy supply technologies according to their (GHG) emission abatement cost (in US$/$tCO_2$) for a given amounts of emission reduction (in million tCO_2). MAC curves have become a standard policy tool in assessing climate change mitigation options as they give a simple communication of the complex issue of cost-effective emissions reductions (Kesicki and Ekins, 2011). One method to construct MAC curves is expert-based assessment of abatement measures, with the (subjective) inclusion of market barriers and opportunities. The second method is to use a modelling approach (either top-down [TD] or bottom up [BU]), and consider system interactions. Weaknesses of a MAC approach include the poor consideration of both inter-dependencies between measures and intertemporal dynamics (path dependency). Furthermore there is often a lack of transparency in assumptions (including baselines, spatial boundaries, ancillary benefits, and implementation costs). Wider social cost of mitigation options are discussed in section 7.9.

The majority of MAC curve studies remains grey literature, and there is considerable heterogeneity in the method of construction, the year the MAC is applied to, and the country or region. The use of consistent and transparent scenarios (Chapter 6) is one mechanism to make the MAC more transparent to policy makers. Table 7.5 presents a set of recent MAC curve studies with overall mitigation potentials ranging from 10%-100% of the baseline for costs up to $100/$tCO_2$. MACs are a useful summary mechanism but more sophisticated modeling of how supply and demand markets work and interact with each other is required for an analytical underpinning of mitigation policy.

Table 7.5: Summary of recent MAC curves, with marginal abatement costs at $100/tCO2

Country / Region	Review	Method	Year of MAC	Reduction as % of baseline	Source
Global	Grey literature	Expert	2030	54%	Nauclér and Enkvist (2009)
Global	Peer review	BU model	2030	15-30%	van Vuuren et al. (2004)
Global	Grey literature	BU model	2050	35-40%	IEA (2008b)
World regions	Grey literature	TD/BU models	2020, 2030, 2040, 2050	20-100% in 2050	Clapp et al. (2009)
USA, Japan, EU	Grey literature	TD model	2020, 2050	33-50% in 2020 50% in 2050	Morris et al. (2008)
USA	Grey literature	TD model	2050, 2100	20-30% in 2050 10-50% in 2100	Clarke et al. (2007)
China	Peer review	BU model	2030	18%	Chen et al. (2007)
Russia, Turkey	Grey literature	Expert, TD model	2030	35% (Russia) 40% (Turkey)	EBRD (2011)
UK	Grey literature	Expert, BU model	2020	14%	DECC (2009)

7.9 Co-benefits, risks and spill-overs

7.9.1 Socio-economic effects

7.9.1.1 Energy security

The provision of secure and reliable energy services constitutes a key element of every nation's energy policy of ensuring that the energy sector remains robust against disruptions of energy supply (Michael Grubb et al., 2006), while taking steps to identify and select a suitable set of mitigation technologies. Policies for improving energy security tend to focus on the interconnected factors of availability of resources, affordability of energy services, efficiency of energy use, and minimizing energy-related environmental degradation (Kruyt et al., 2009; JC Jansen and Seebregts, 2010; Vivoda, 2010; J. Sathaye et al., 2011; BK Sovacool and Mukherjee, 2011). In meeting these criteria of energy security holistically, there will be trade-offs between technology options that are effective along one dimension, which will have implications for other aspects of security. Such trade-offs include the construction of regional interstate natural gas pipeline and hydroelectric projects that are aimed at enhancing availability of supply, but may be accompanied by unintended social and environmental impacts (Simpson, 2007). Other examples include shifting from coal to natural gas in the power sector intended to reduce greenhouse gas emissions but having the effect of increasing dependence on imported liquefied natural gas (BK Sovacool, 2008).

The challenges to achieve energy security differ for developed and developing countries (Cherp et al., forthcoming). In addition to securing energy services in the expanding industrial and service sectors, the drive for improved energy services for increasing food security, health, education, and living conditions of the poorest is an important dimension of energy security in developing countries (Kuik et al., 2011). As a consequence, the degree to which low carbon options may or may not contribute to energy security is dependent on the local resource situation and specific national economic and social priorities. With renewable energy resources more evenly distributed around the globe than fossil fuels (WEC, 2007) and being, in general, less traded on the world market, renewables can contribute to diversify the portfolio of supply options. This would limit an economy's vulnerability to price volatility and reduce the heavy reliance on fossil fuels, such that existing reserves are conserved and maintained further into the future (Awerbuch, 2006; Kruyt et al., 2009b). At the same time, however, the integration of higher shares of variable renewable energy resources into existing electricity networks places higher demands on their stability (R Sims et al., 2011).

7.9.1.2 Economic and social development, energy affordability and access

Differences in modern energy consumption across countries partly explain the wide disparity in economic and social development, both within and between countries. As shown in Figure 7.15, countries with higher Human Development Index (HDI) are generally the largest energy consumers with higher per capita carbon emissions. However, beyond a certain level of quality of life (as expressed in HDI), increased energy consumption exhibits a decreasing marginal return whereby additional increase in modern energy consumption per capita results in comparatively small increases in HDI. Furthermore, for constant energy and carbon levels the HDI increases over time, indicating that certain levels of human development are achievable in an increasingly efficient manner (Steinberger and JT Roberts, 2010).

Apart from improving energy efficiency, the deployment of low-carbon technologies is another option for decoupling development from carbon emissions. In off-grid remote and rural areas, small-scale hydro or solar photovoltaic installations can be cost-competitive options to increase energy access (Bhuiyan et al., 2000; M Kolhe et al., 2002; Nguyen, 2007; Casillas and D.M. Kammen, 2010; Thiam, 2010). For grid-based applications, fossil fuel based generation along with nuclear and large hydroenergy systems (Asif, 2009; Chang et al., 2010) are often the less costly options (Nouni et al., 2008; Ahearne, 2011; Deichmann et al., 2011) – if external costs are not accounted for. Still, the levelized cost of many renewable energy technologies remains higher than existing energy prices (2011) and may thus be seen as impeding development. For example, when the share of energy costs to income approaches 3-4% for an average family, the energy affordability threshold is reached (Bashmakov, 2007), and a threshold of 10% energy cost against income is the most widely accepted definition of a fuel poor household (Boardman, 2010). Energy affordability and fuel poverty has now entered into the European Union's regulatory and policy domains as some Member States struggle to provide affordable and sustainable energy services to low income households (Bouzarovski et al., forthcoming).

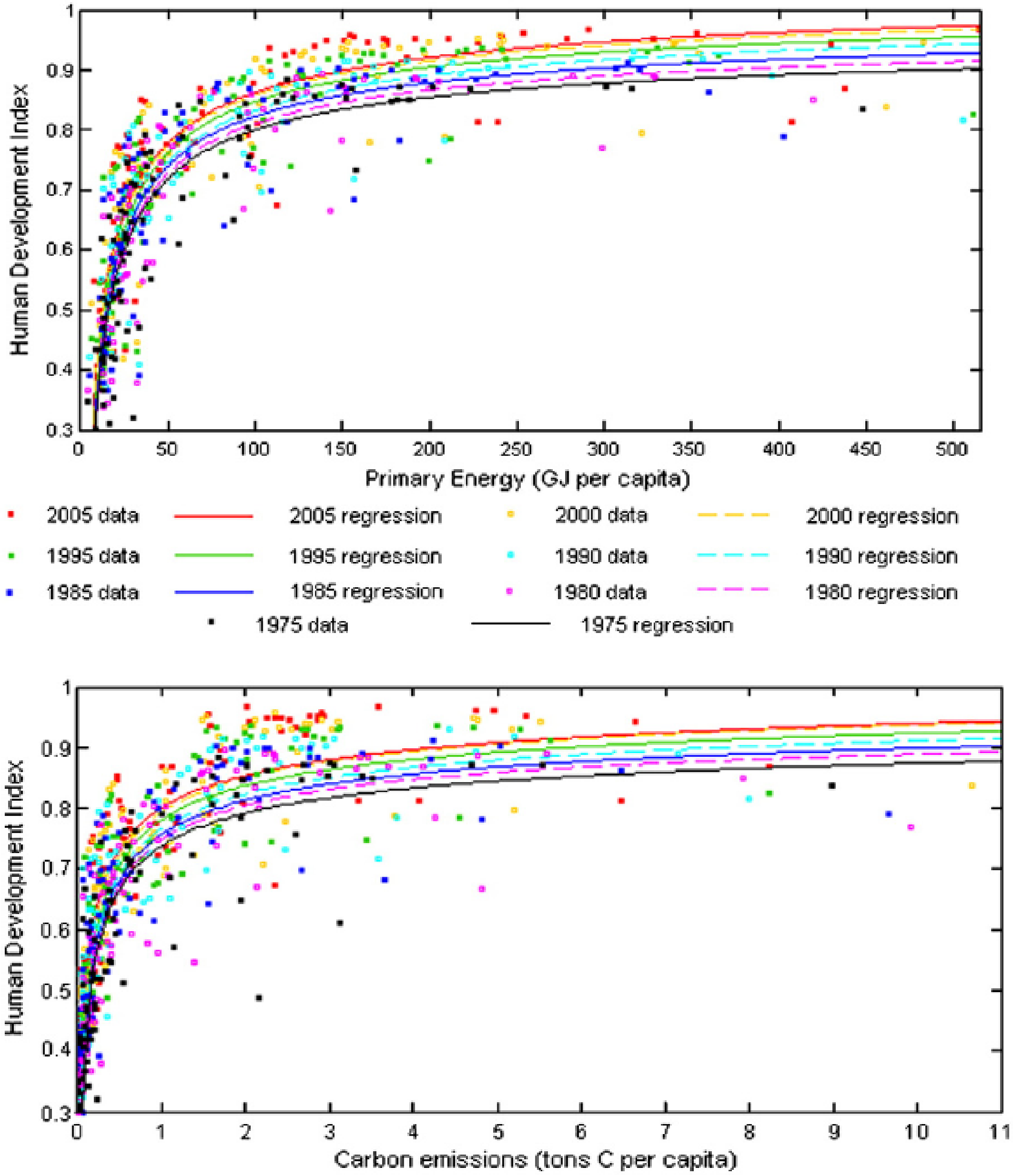
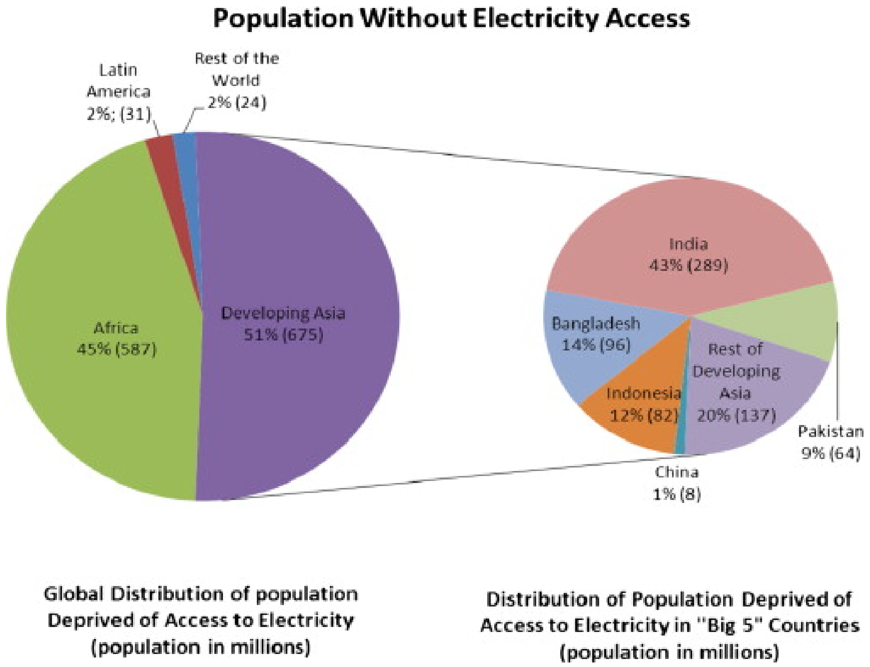


Figure 7.15 Correlation between a) primary energy use per capital and b) carbon emissions per capita and the Human Development Index (Steinberger and JT Roberts, 2010).

Providing clean, affordable and reliable modern energy services is also at the heart of the development challenge in many developing countries (Brew-Hammond, 2010; Mulugetta and Urban, 2010; Sokona et al., 2012). More than 1.3 billion people worldwide, especially the rural poor in Sub-Saharan Africa and developing Asia, are estimated to lack access to electricity and between 2.7 to over 3 billion people are estimated to lack access to modern fuels for heating and cooking (IEA, 2010a, 2011a) (Figure **7.16**). The target of increasing access to modern affordable energy services has triggered a number of major national programmes (H Winkler et al., 2011; IEA, 2011h). With renewables already playing an important role in some of these programmes as well as in smaller local initiatives (ARE, 2011; Gurung et al., 2011; REN21, 2011; Behrens et al., 2012), improvements in energy access do not need to entail significant changes in GHG emissions (IEA, 2011h).



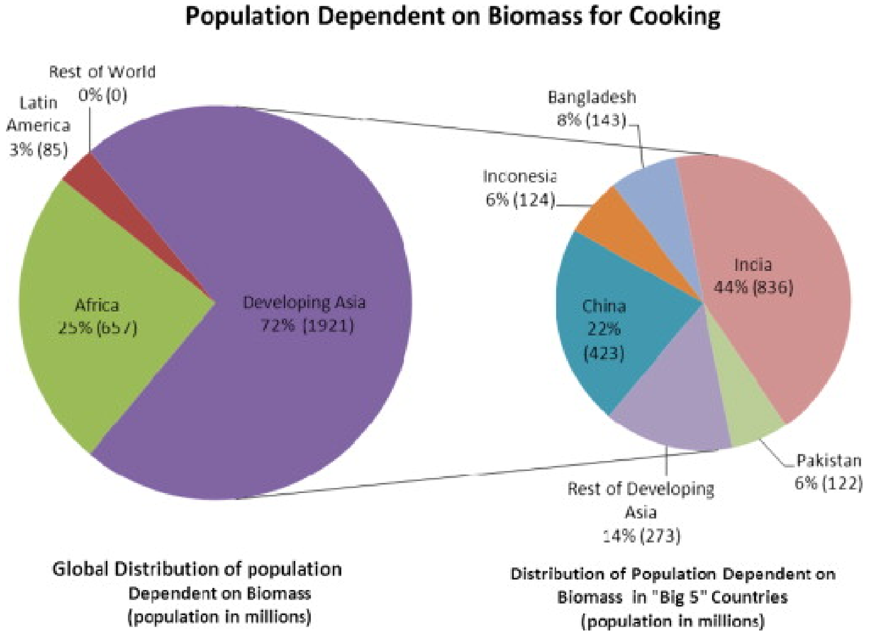


Figure 7.16. Population a) without electricity and b) dependent on biomass for cooking (global and "Big 5" countries) (IEA, 2011a)

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

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

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

Combustion-related emissions cause substantial human and ecological impacts: particulate matter formed from products of incomplete combustion, sulphur and nitrogen oxides are an important cause of respiratory damages (Pope et al., 2009; GEA Chapter 4); sulphur and nitrogen oxides are involved in the acidification of fresh water and soils and nitrogen oxides in the eutrophication of water ways, both threatening biodiversity, and the formation of photochemical oxidants (summer smog, ozone)(EG Hertwich et al., 2010). Coal is an important source of mercury and other toxic metals. About half of the impact categories commonly traced in life cycle assessment are well correlated with fossil fuel use (MAJ Huijbregts et al., 2010). Reducing fossil fuel combustion, especially coal combustion, can hence yield co-benefits for health and ecosystem impacts (Aunan et al., 2004; KR Smith and Haigler, 2008; Creuzig and D He, 2009; Shrestha and Pradhan, 2010). Depending on the technology, other ecological and health concerns can emerge (J. Sathaye et al., 2011).

Ecological and health impacts of renewable and nuclear energy have been comprehensively assessed in SRREN. Hydropower, wind power, solar power, and nuclear power, in particular, perform favourable compared to fossil fuels on a wide range of indicators. These systems have higher material requirements than fossil based system; metals and cement production cause various air pollutants. On a life cycle basis, however, modern renewable energy technologies generally have impacts comparable to clean natural gas systems and much lower than coal or oil based systems. Renewable technologies also have a range of ecological impacts related to land use and habitat change which - depending on site characteristics and the implementation of the technology – can be higher than those of fossil fuel based systems (J. Sathaye et al., 2011).

Renewable energy technologies, however, require additional materials, and the demand for steel, copper and critical materials can be significant compared to current production levels and maybe even geological reserves (Kleijn and E. van der Voet, 2010; Graedel, 2011). While current life-cycle assessments are based on current ore grades, a move towards lower ore grades which is likely to occur in the future will increase the energy cost and pollution associated with material production (Graedel and E. van der Voet, 2009).

While reducing atmospheric emissions from energy generation, CCS will increase environmental burdens associated with the fuel supply chains due to the energy cost of capturing and storing CO_2 and the additional equipment required, thereby increasing the pressures on human health and ecosystems through chemical mechanisms by 0- 60% compared to the best available fossil fuel power plants (Singh, et al., 2011). Uncertainties and risks associated with long-term storage also have to be considered (Chapter 7.9.1; JM Ketzer et al., 2011; Koorneef et al., 2011). *For an overview of mitigation options and their unresolved challenges, see section 7.5.*

A crucial issue that is not well represented in the literature is the vulnerability of thermal generation to cooling water availability and temperature, in particular for large centralised structures with high cooling loads (Bates et al., 2008; Dai, 2011). Reduced water availability or substantial temperature increases of water bodies will lower cooling system efficiency, and may ultimately result in thermal power plants running at lower capacities or shutting down completely, as experienced during the 2003 heat wave in France (Poumadére et al., 2005). Water availability is also an issue for solar-thermal electricity generation, which is often located in hot, dry climates (Damerau et al., 2011; J.J. Burkhardt et al., 2011). Air cooling systems reduce water use substantially but decrease efficiency and increase costs.

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

7.9.3 Technical Risks

This section builds heavily upon the risk assessment presented in chapter 9 of the IPCC SRREN report (IPCC, 2011a). Each technology carries specific operational risks including accidents. The comparative assessment of accident risks associated with current and future energy systems is thus a pivotal aspect in a comprehensive evaluation of energy and sustainability. Accidental events can be triggered by natural hazards (e.g., Steinberg et al., 2008; Kaiser et al., 2009; Cozzani et al., 2010), technological failures (e.g., Hirschberg et al., 2004; Burgherr et al., 2008), purposefully malicious action (e.g., J Giroux, 2008), and human errors (e.g., Meshakti, 2007; Ale et al., 2008). In the event of accidents, fatality and injury may occur among workers and residents. Evacuation and resettlements of residents also may take place. With a coal chain, mining accidents are the major component of the accident related external costs. According to the PSI database, over 25,000 fatalities with severe coal-related accidents have been reported in the past. The operation of coal plants can be dangerous as well: "the fine-particulate air pollution they produce kills about 10,000 people each year in the United States alone" (von Hippel et al., 2011). With the oil and natural gas chains, fatalities related to severe accidents at the transport and distribution stage are the major component of the accident related external costs. Over 20,000 fatalities for oil chain and nearly 2,000 for the natural gas chain in the severe accidents are reported. For hydropower, a single event, the Banqiao/Shimantan dam failure in China, accounted for 26,000 fatalities. Total fatalities from hydro chain amount to nearly 30,000 and this makes the hydro chain to have the highest accident related external costs among all the fuel chains. At the time of analysis, there were two severe nuclear accidents, Chernobyl and Three Mile Island. For Three Mile Island no fatality or injuries are reported. For Chernobyl, 31 immediate fatalities and injury of 370 persons occurred. Including longer-term health impacts the accident may ultimately cause premature death between an aggregate of 9,000 to 33,000 people, mostly from cancer. Reliability fatality data for the Fukushima-Daiichi accident are not yet available.

Figure 7.17 shows risk assessment results for a broad range of currently operating technologies. For fossil energy chains and hydropower, OECD and EU 27 countries generally show lower fatality rates and maximum consequences than non-OECD countries. Among fossil chains, natural gas performs best with respect to both indicators. The fatality rate for coal in China (1994 to 1999) is distinctly higher than for the other non-OECD countries (Hirschberg et al., 2003; Burgherr and Hirschberg, 2007), however, data for 2000 to 2009 suggest that China is slowly approaching the non-OECD level (see Annex II of IPCC SRREN (2011a)). Among large centralized technologies, modern nuclear and OECD hydropower plants show the lowest fatality rates, but at the same time the consequences of extreme accidents can be very large. Experience with hydropower in OECD countries points to very low fatality rates, comparable to the representative Probabilistic Safety Assessment (PSA)-based results obtained for nuclear power plants, whereas in non-OECD countries, dam failures can claim large numbers of victims.

Since the dawn of nuclear power more than half a century ago, the world witnessed three major accidents: Three Mile Island (1979), Chernobyl (1986) and Fukushima-Daiichi (2011) over cumulative 14,500 reactor years. Although the causes and consequences of these accidents are fundamentally different, there are far reaching commonalities (other than the impact on public opinion) between them - lessons learned for enhanced safety standards, more stringent regulatory oversight regarding compliance and the development of reactor designs with advanced safety features. Post Chernobyl design improvements resulted in so-called Generation III+ designs with simplified and standardized instrumentation, strengthened containments and some contain “passive” safety systems based on laws of nature that operate automatically even if electrical power to the control system and pumps is lost and make emergency cooling independent of the availability of power for days. Nuclear power plants designs incorporate a 'defence-in-depth' approach, with multiple safety systems both physical barriers with various layers and institutional controls, redundancy and diversification - all targeted at minimizing the probability of accidents, and avoiding major human consequences from radiation when they occur (NEA, 2008).

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

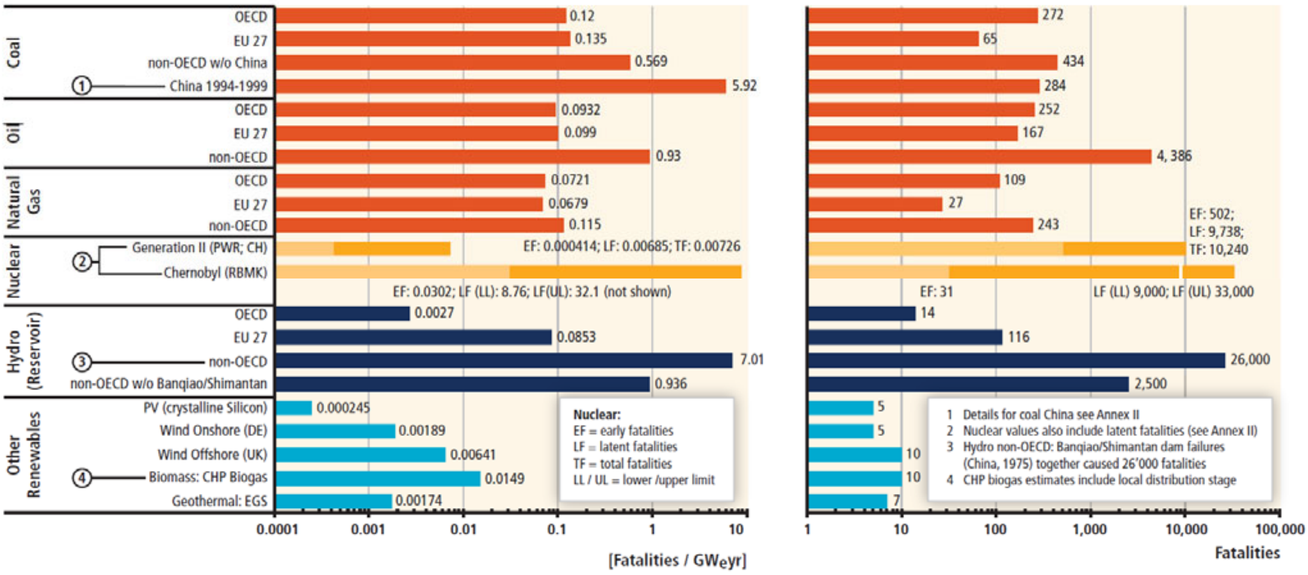


Figure 7.17. Comparison of fatality rates and maximum consequences of currently operating large centralized and decentralized energy technologies. Fossil and hydropower is based on the ENSAD database (period 1970 to 2008); for nuclear PSA is applied; and for other renewable sources a combination of available data, literature survey and expert judgment is used. See Annex II for methodological details. Note: RBMK = reaktor bolshoy moshchnosty kanalny,a boiling water-cooled graphite moderated pressure tube type reactor; PWR = pressurized-water reactor; CHP = combined heat and power; EGS = Enhanced Geothermal Systems. Source: IPCC SRREN (2011a)

As indicated by the IPCC SRREN report, accidents can also result in the contamination of large land and water areas. Accidental land contamination due to the release of radioactive isotopes however, is only relevant for nuclear technologies. Regarding accidental releases of crude oil and its refined products into the maritime environment, substantial improvements have been achieved since the 1970s due to technical measures, but also to international conventions, national legislations and increased financial liabilities (see eg IPCC SRREN, (2011a) or Kontovas et al., (2010)). Still, accidental spills from the extraction and production of petroleum fuel are common and can affect both saline and freshwater resources (Jernelöv, 2010; Rogowska and Namiesnik, 2010). Furthermore, increased extraction of deep offshore resources (e.g., Gulf of Mexico, Brazil) as well as in extreme environments (e.g., the Arctic) provides an additional threat of accidents with potentially high environmental and economic impacts. Spills of chemicals can also occur via hydraulic fracturing during shale natural gas and geothermal operations, which can potentially result in local water contamination (Aksoy et al., 2009; Kargbo et al., 2010). Additional research is needed in this area to better account for a variety of risk aspects that are currently not amenable to full quantification due to limited data and experience or since they cannot be fully covered by traditional risk indicators focusing mainly on immediate consequences.

7.9.4 Public acceptability[17]

Social acceptance for the extraction, conversion, and distribution of higher-emitting fossil energy supplies varies by fuel, technology, location, and other factors. Concerns include a myriad of real or

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[17] Public acceptability related to the use of energy in the end-use sectors is addressed in other chapters of AR5. Although public acceptance issues related to (perceived) environmental (and non-environmental) impacts are addressed here, a discussion of actual environmental impacts is addressed in other sections and chapters.

perceived local, regional, and global environmental and ecological impacts, various risks and hazards, and energy security concerns, each of which are discussed in more detail elsewhere.

Even among lower-GHG-emitting options, social acceptance concerns exist and opposition can impede deployment. For nuclear energy, social acceptance issues often revolve around concerns about health and safety (e.g., accidents, disposal of wastes, decommisioning) and nuclear proliferation (e.g., terrorism, civil unrest); the degree of social acceptance is sometimes found to depend on how nuclear is framed relative to other sources of energy supply (e.g., Bickerstaff et al., 2008; Sjoberg and Drottz-Sjoberg, 2009; Corner et al., 2011; Ahearne, 2011). Among CCS technologies, early concerns include the varied ecological impacts associated with different storage media, the potential for accidental release of stored CO_2 and sequestration effectiveness, and the fact that CCS technologies do not avoid the non-GHG social and environmental impacts of fossil energy sources (e.g., E Miller et al., 2007; de Best-Waldhober et al., 2009; Shackley et al., 2009; Wong-Parodi and I Ray, 2009; Wallquist et al., 2009, 2010; DM Reiner and WJ Nuttall, 2011).[18] For natural gas, the recent increase in the use of unconventional supplies, such as hydrological fracturing to access shale gas, has created concerns about potential risks to local water quality and public health (e.g., US EPA, 2011; IEA, 2012a).

Studies and opinion polls have often found that many RE sources receive relatively wide public support (e.g., J. Sathaye et al., 2011). Nonetheless, as with other forms of energy supply, social acceptance concerns do exist (J. Sathaye et al., 2011). Moreover, the diversity of RE sources, technologies, and applications, and their reliance on sometimes-diffuse energy resources, ensures that these impacts and their potential mitigation vary by technology. The potential of bioenergy, for example, is interlinked with concerns about direct and indirect land use and related GHG emissions, deforestation, and possible competition with food supplies (e.g., Chum, A. Faaij, J Moreira, G. Berndes, Dhamija, H Dong, and Gabrielle, 2011). For hydropower, social acceptance concerns include the possibility of the displacement of human populations and altered recreational opportunities (e.g., Kumar et al., 2011). For wind energy, social acceptance challenges primarily relate to visibility and landscape implications as well as various 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), while for ocean energy those concerns and the potential for competition with other uses extend to the sea (e.g., Lewis et al., 2011). Prominent public acceptance issues for geothermal energy include the possibility of induced local seismicity and impacts on natural areas that might otherwise be used for recreation (e.g., Goldstein et al., 2011).

Though impacts cannot be entirely eliminated for any technology, assessing, minimizing and mitigating these varied impacts are elements of the planning, siting, and permitting processes that occur in many jurisdictions. Technical advancements have also, at times, helped reduce impacts. Moreover, to increase social acceptance, a variety of other procedures have also been shown to be effective, such as: ensuring that accurate and unbiased information about the technology, its impacts and benefits, and its interplay with other technologies is widely distributed and well understood; aligning the expectations and interests of different stakeholders; adjusting to the local societal context; adopting benefit sharing mechanisms; obtaining explicit support at the local and national levels prior to development; building collaborative networks; and developing mechanisms for articulating conflict and engaging in negotiation (e.g., Ashworth et al., 2010; Fleishman et al.,

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[18] Knowledge about the social acceptability of CCS is limited due to the early state of the technologies' deployment. Recent research has, in part, focused on the need to fully educate respondents about CCS if meaningful insights are to be gained about public acceptance issues (de Best-Waldhober et al., 2009; Malone et al., 2010; Ter Mors et al., 2010; Corry and D Reiner, 2011).

2010; Mitchell et al., 2011; Terwel et al., 2011). See also Chapters 2, 6, and 10, which cover issues of public acceptance through complementary lenses.

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

7.10.1 Technical aspects

A number of bottom-up and top-down studies have investigated the principal feasibility and mitigation costs that are associated with ambitious climate protections strategies, e.g., those that are consistent with a stabilization of global mean temperature change at a level below 2°C compared to the pre-industrial state (Chapter 6; IPCC (2011a); Chapter 10 and references therein, Rogner et al., (2011), IEA (2010c); IEA (2010a)).

From a global perspective, the large number of different technologies that are available to mitigate climate change facilitates the achievement of the aforementioned climate protection goals (see section 7.5). As many different combinations of the mitigation technologies are feasible, least cost portfolios can be determined that select those options which interact in the best possible way (see section 7.12).

On a local scale and/or concerning specific technologies, however, various physical and technological barriers might constrain their mitigation potential. These barriers comprise:

- sometimes large distances to energy demand centres which hampers the delivery of electricity from renewable energies (see Section 7.6.1)
- still low energy conversion efficiency values compared to basic physical limits (e.g., conversion efficiencies of power plants, see Section 7.5.1, and the still large “energy penalty” of carbon capture, see Section 7.5.3),
- unnecessary low transmission efficiencies of the existing energy networks (see Section 7.5.2 and Section 7.6),
- limited local CO_2 geological storage potential that might constraint the application of CCS technologies (Section 7.5.3),
- limited local resource potential of some renewable energies (Section 7.5.4) and the limited capability of the *existing* infrastructure to absorb high share of fluctuating renewable energies (see Section 7.6),
- safety aspects concerning the environmental side effects of shale gas exploitation, the reliability of CO_2 storages, operational risks of nuclear power plants and supply chain risks of the nuclear fuel cycle (see Section 7.9.).

7.10.2 Financial barriers and investment barriers and opportunities

Financial and investment barriers to the development and deployment of low carbon energy systems include (i) high initial costs and limits of market capacity, (ii) uncertainty of energy price, (iii) grid integration issues, (iv) uncertainty of policies, (v) technology risks, and (vi) difficulty of achieving a consensus among stakeholders. Deployment of these systems will therefore require a concerted public and private commitment, supported by more ambitious policies (IEA, 2011i).

Various studies indicate that investing in low carbon energy technologies would end up costing less than continuing to invest in older technologies. This is because the new systems would cut energy demand and the cost of operations. For instance, according to the United Nations Framework

Convention on Climate Change, the power sector saves $7 billion, and capital expenditures for fossil fuel drops $59 billion by 2030 under a mitigation scenario (UNFCCC, 2008; ADB, 2009).

The potential savings apply regionally as well as globally in a long term. However the up-front costs for deploying the new technologies are high and developers need to raise funds. These funds could come from commercial banks, bilateral financing, multilateral financial institutions, private stakeholders and governments. Although new investments in sustainable energy have risen worldwide, reaching $184.4 billion in 2007, more investments are required to stabilize climate change (UNEP, 2008a; ADB, 2009).

Financial institutions have a crucial role to play in helping countries transform their energy sector. However, the high risk associated with investing in the early stages makes financial institutions away from projects such as wind farms (ADB, 2009).

Before clear business opportunities appear, climate policies need to support implementing low carbon energy systems. These include (i) financial support, (ii) levying a carbon tax, (iii) building a carbon-trading market, (iv) promoting the clean development mechanism (CDM) and new market mechanisms and (iv) introducing feed-in tariff. With the implementation of specific short-term fiscal incentives, long-term incentives from the banking sector and public investment will become crucial (Liang and W Wu, 2009).

The CDM has worked effectively to deploy low carbon energy technologies in the developing countries. The energy supply technologies account for about 60 % of the registered CDM projects, providing about 180 million tCO2 credits as of April 2012. These include credits generated by introducing hydropower, wind power and biomass-based energy supply (Gillenwater and Seres, 2011; IGES, 2012).

There are many private and public-private initiatives which have succeeded to promote clean energies. For example, in Samsø, Denmark where 100% of its electricity comes from wind power and 75% of its heat comes from solar power and biomass energy, most investment costs come from the people living in the region (EDIN, 2011). Local stakeholder participation through bottom-up institutional mechanisms can enhance renewable energy development (IPCC, 2011a).

Many developing countries need further efforts to alleviate poverty while addressing climate change. There are a lots of opportunities to promote renewable energies where access to electricity is still limited if proper climate policies are implemented to promote electrification. Internationally collaborative development cooperation may be one of keys to promote low carbon energy systems in developing countries (Urmee et al., 2009; Fritsch, 2011).

7.10.3 Cultural, institutional, and legal barriers and opportunities

Transition from a fossil fuel based economy to an economy and energy systems with a large penetration of renewable energy sources (RES), increased access to modern energy services from all energy sources in the case of poor countries, and improved energy efficiency will pose a series of challenges and opportunities in managing the transition. Obviously depending on the status of the regions and the economies, barriers and opportunities may differ dramatically. However the cultural, institutional and legal barriers are universal but approach and solutions will vary dramatically according to the countries and the form of energy source considered. For instance, cultural, institutional and legal barriers to shift from fossil fuels to hydrogen (NERI, 2009) in developed countries will be very different from traditional biomass switching to modern energy services, be they based on renewable or fossil fuels, in many low income countries.

A huge barrier in the case of poor developing countries is the cultural economic and social gap between rural and urban areas. Rural areas are characterized by a very low population density and very low and often irregular income mainly from agriculture which is a seasonal activity. Off grid decentralized options are very expensive be they fossil fuels or renewable based. However the high cost of centralized options may give a comparative advantage to low carbon path particularly with the sharp decrease of PV prices over the last five years. The vast majority of rural population cannot afford to pay for the initial investment, micro finance mechanisms (grants, concessional loans) adapted to the pattern of rural activities (for instance installments correlated with income from agriculture) are necessary to lift rural populations out of the poverty energy trap.

A study finds that the apparent disconnect between how electricity is made and how it is socially perceived perpetuates public apathy and misinformation. As a result, wind farms and solar panels (along with other renewable power systems) are often opposed not because they are a poor alternative to fossil fuels, but because people simply do not comprehend why such technologies may be needed (Sovacool, 2009).

Furthermore energy consumption patterns are influenced by cultures and traditions in addition to availability and affordability. For instance cooking fuels such as firewood, and charcoal are widely used in rural areas because the type of housing, “free” access to cooking fuels in some areas and values such as time which have different perceptions depending on the social and geographical context.

Institutional sustainability is considered as an imperative for achieving sustainable development. Progress in political democracy has opened opportunities in setting up institutions and better governance of energy systems with more participation of the civil society and communities in the energy debate. Adopting a holistic approach encompassing cultural, institutional and legal issues in the formulation and implementation and implementation of energy policies and strategies is increasingly perceived particularly in sub-Saharan Africa as essential to addressing access to modern energy services.

Furthermore legal barriers are often hindering the penetration of modern energy services and distorting the economics of energy systems. For instance informal settlements mean legal barriers to get access to electricity. Land tenancy issues and illegal settlements are indeed barriers to energy access and often are overcome by illegal power connections with an impact on the safety of the end users (dangers of fire) and economic loss for the utility due to meter tampering, electricity theft and vandalism. In addition, in many slums there is a culture of non-payment of the bills (UN Habitat and Global Network for Urban Settlements (GENUS), 2009). Orthodox electrification approaches are inefficient in the context of urban slums. In South Africa, ESKOM, the large utility in Africa, implemented a holistic Energy Losses Management Program (ELMP) (UN Habitat and Global Network for Urban Settlements (GENUS), 2009), which involved community involvement to deal with the problem of energy loss management and infrastructure theft and vandalism. As a result prepayment was successfully implemented as it gives the poor customers a daily visibility of consumption and a different culture and understanding of access to modern energy services.

7.10.4 Human capital capacity building

The lack of human capital is widely recognized as one of the barriers to development, acquisition, deployment and diffusion of technologies required for meeting the CO_2 emissions reduction targets in in the energy sector. Human capacity is particularly critical in providing a sustainable enabling environment for technology transfer in both the host and recipient countries (Barker et al., 2007; Halsnaes et al., 2007). Human workforce development has thus been identified as an important near-term priority (IEA, 2010c). Skilled workforce is needed, in particular, in the areas of renewable energy and smart grids, which form an important part of “green jobs” (Strietska-Ilina et al., 2011). The required skill set differs in detail for different technologies and local context, and people require specific training (W. Moomaw et al., 2011). Developing the skills to install, operate and maintain the renewable energy equipment is exceedingly important for a successful renewable energy project, particularly in developing countries (Martinot, 1998; Wilkins, 2002; UNEP, 2011). In countries where these barriers are overcome, significant installations of renewable systems have occurred (Mondal et al., 2010).

Renewable energy has a high potential for employment generation, including research and development, engineering, consultancy, auditoring, quality control, and installation and maintenance. Many countries, especially developing economies, report shortages of teachers and trainers in subjects related to the fast-growing renewable energy sector (Strietska-Ilina et al., 2011). Globally, it is estimated that in 2006 more than 2.3 million people were employed in the renewable energy sector; about half of which in biomass and the balance in wind, solar thermal and PV (UNEP, 2008b). Given strong and rapidly rising interest in these technology areas, it is projected that by 2030, employment in solar PV alone could soar to as high as 6.3 million, plus 2.1 million in wind and 12 million jobs in biofuels-related agriculture and industry (UNEP, 2008b).

In addition to renewable energy, human capital will also be required on other low-carbon energy technologies and nuclear. And apart from technology-oriented skills, capacity for decision-support and policymaking in the design and enactment stages is also essential, particularly on assessing and choosing technology and policy options, and designing holistic policies that effectively integrate renewable energy with other low-carbon options, other policy goals, and across different but interconnected sectors (e.g. agriculture and water) (Mitchell et al., 2011).

To avoid future skill shortages, countries will need to formulate human capital development strategies based on well-informed policy decisions, and adequate information on labour market and skill needs in the context of green jobs (Strietska-Ilina et al., 2011). Enabling actions to address human capacity development needs include development of academic curricula and training of experts, adapting existing vocational and higher education institutions to develop the needed energy skills, and creating educational incentives and working with industry to foster viable career paths.

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 5.3.3) gives rise to the possibility of path dependent carbon lock-in (Unruh, 2002) where existing (high carbon) energy capital continues to retain a major share of the supply system. Of the 1327GW investments (from 2000-2009) in the global electricity sector (SJ Davis et al., 2010), 416GW (31.4%) were coal, 449GW(33.9%) were natural gas and 47GW (3.6%) were oil. Construction of renewable source power plants together accounted for 231GW (17.4%), with nuclear at only 29GW (2.2%). Therefore high carbon energy capital stock is currently being heavily invested in and will be still in place for decades to come.

Unless expensive premature retirement is carried out, capital turnover rates – together with physical, financial, human capital, institutional and cultural barriers (see 7.10 subsections) – can give an upper bound for the penetration rates of new energy supply technologies. Furthermore, when taking the impact of energy infrastructures (electricity lines, gas pipeline, road transport etc.) on future energy demands into account, estimates of locked-in cumulative GHG emissions increase (Guivarch and Hallegatte, 2011). And when considering the very long lived capital stock embodied in buildings and urban patterns (Jaccard and Rivers, 2007), carbon lock-in estimates increase yet further.

Potential lock-in from long-lived energy capital is a particular issue in 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 and infrastructure in many developing countries bolsters the potential opportunities to develop a low carbon energy system.

Typical lifetimes are shown in Figure 7.18 for key energy supply options. There is considerable uncertainty in these estimates owing to issues of economic vs. technical life (the period in which investments are paid off vs. the engineering expectations of a plant's lifespan), the potentially high costs of prematurely retiring capital intensive assets, as well as the role of additional investments for life extension of existing capital stock.

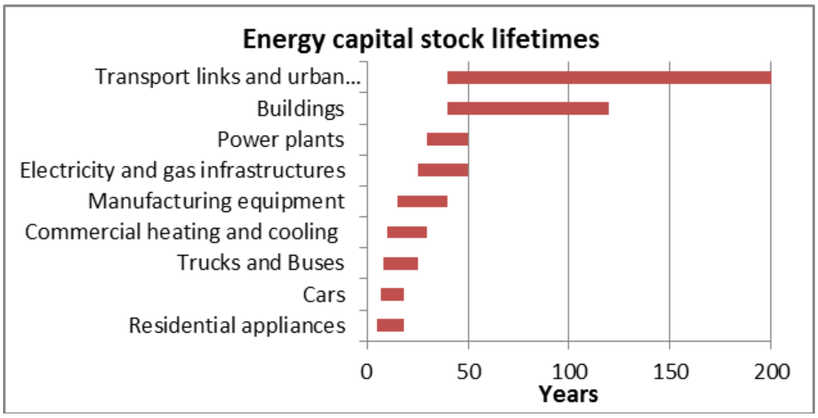


Figure 7.18. Typical energy capital stock lifetimes Source: (Philibert and Pershing, 2002)

7.11 Sectoral policies

Concerns about market failures, local and regional pollution, climate change, energy security and energy poverty have triggered a renewed interest in energy sector policies designed to address these multiple challenges (OFGEM, 2011). Energy policies can be roughly divided into four general categories based on the nature of the instruments invoked to achieve specific outcomes: direct investments in the creation or enhancement of technology, those policies which use financial measures to encourage the development and deployment of technology, those which use regulatory measures, and those which seek to directly change preferences (US DOE, 1989). The following subsections discuss these approaches.

Section 7.11.1 discusses policies designed to correct chronic underinvestment in scientific discovery and technology R&D. Section 7.11.2 is devoted to policies that employ GHG pricing, either through taxes or marketable permits. Section 7.11.3 addresses other fiscal measures to modify behaviour including tax credits and rebates, public financing policies such as subsidies, low-interest loans and policies for renewable electricity (e.g. feed-in tariffs or renewable energy quotas). Section 7.11.4 pertains to enabling conditions that provide a supporting environment for the aforementioned policies. A general discussion of policies designed to address climate change is presented in chapter 15 of this report. The following sections concentrate on the impact of these and additional energy policies on energy markets.

7.11.1 Research, development and demonstration (RD&D) policies

Basic scientific research and R&D play a potentially much larger role in addressing climate change than in addressing other human issues due to the very long-term nature of the mitigation problem, which requires carbon emissions to ultimately peak and decline toward zero for *any* stabilization concentration. Given that mitigation is a long-term commitment rather than a near-term action, improved technologies can play a major role in emissions mitigation even if they do not become available before the middle of the 21st century (RN Schock et al., 1999).

However, the market cannot be anticipated to provide the socially optimal level of scientific research or R&D. Private firms investing in RD&D cannot capture the full value of the knowledge they create through research. This feature of knowledge creation leads to underinvestment in RD&D activities. To correct this public goods problem governments directly support investments in the creation of basic scientific knowledge, with potential benefits distributed across all human enterprise, through national science foundations and RD&D designed to create and/or improve specific technology domains (Philibert, 2011; IPCC, 2011a, Chapter 11 and references therein).

Renewable energy technologies are expected to benefit from additional RD&D activities as discussed in (IPCC, 2011a, p. 13), as are other low carbon technologies. While industrial research generally is carried out for commercial technologies, other technologies often require direct government support. . The development of public RD&D expenditures since the release of the IPCC AR4 has been characterized by a general trend of growing public RD&D funding, incremented by special economic stimulus in the year 2009 – in the context of a deepening of the global crisis–, related with the promotion of renewable energies, high technology activities and value added jobs (IEA, 2012b, p. 11).

Although private RD&D expenditures are seldom disclosed, they are estimated to represent a large share of the overall spending for RD&D activities (at least in some technologies areas) (IEA, 2012b, p. 15). Private RD&D investments are not only stimulated by RD&D policies. Additional policies (e.g. market entry programs) addressing other parts of the innovation chain as well as broad GHG pricing policies might assist in triggering private investments in RD&D (IPCC, 2011a, p. 851; Rogge et al., 2011). As a result of government RD&D expenditures and additional deployment policies (see 7.11.3), some low carbon technologies, such as PV cells and wind energy converters have seen a significant technological progress and an associated decrease in their levelised costs of energy (Sec. 7.8.2.2).

7.11.2 GHG pricing policies

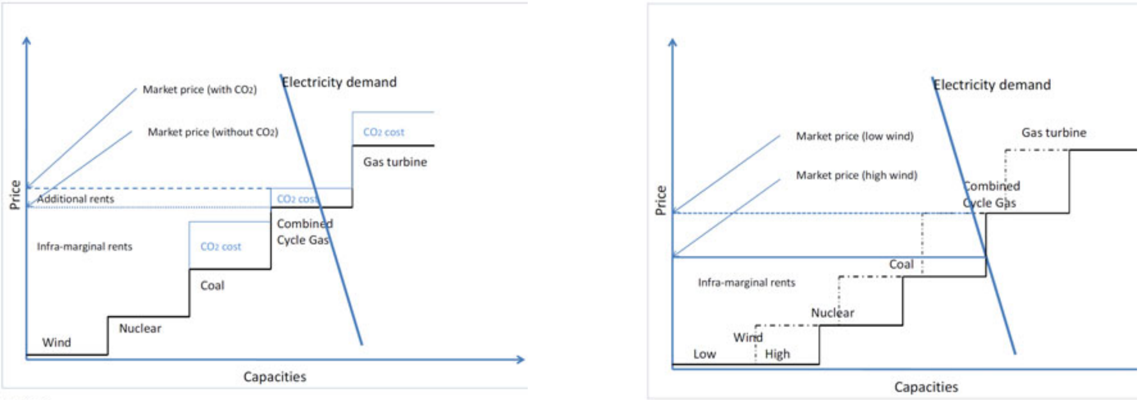
GHG pricing policies, such as greenhouse emissions taxes (e.g. carbon taxes) and tradable GHG emissions permit (EP) regimes have been frequently proposed to address the market externalities associated with global climate change. The two methods are similar in that they place a price on GHG emissions designed to correct the failure of markets to monetize their external costs. They differ in other important regards. Tax regimes fix the tax rate and allow markets to determine emissions, while EP regimes fix emissions and allow markets to determine the EP price. In a world with certainty it is a matter of indifference which approach is taken as both can be implemented so as to deliver the same distribution of economic activates in the economy. However, the two policy instruments differ importantly in their implications for income distribution (NH Stern, 2007; IEA, 2010g, p. 57). EP regimes create permits that are financial assets, with economic value in the market and the pattern of their distribution results in a direct wealth transfer. This property of EP regimes allows instrument designs that can compensate "losers" from the policy by assigning permits to those groups, thus potentially making the approach politically attractive. On the other hand, the same property can impede political implementation. Wealth distribution can be the dominant economic consequence of the policy, overshadowing the economic implications of the emissions mitigation itself (J. Edmonds et al., 1995; J. Edmonds and M. Wise, 1998). Weitzman (1974, 2007) has shown that under uncertainty, tax policies are more efficient instruments.

In the recent years, GHG pricing policies have been implemented in a number of countries either through CO_2 taxes or by introducing emission trading schemes. The world's largest greenhouse gas emission trading system, the European Union Emissions Trading System (EU ETS), was launched on 1 January 2005. It comprises 27 EU member states together with Iceland, Liechtenstein and Norway. The currently covered installations (power and combustion plants, oil refineries and iron and steel works, as well as factories making cement, glass, lime, bricks, ceramics, pulp, paper and board) account for almost half of the EU's CO_2 emissions (OECD, 2012, pp. 40–41). Further ETS exist in Alberta, Canada, New Zealand and in some states of the US (e.g, those belonging to the Regional Greenhouse Gas Initiative (RGGI) - a mandatory trading scheme that caps emissions from power generation in the ten north-eastern US states (Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island and Vermont) (IEA, 2010g). Australia, South Korea and China have all taken steps to mitigate climate change, including the establishment of carbon markets.

Carbon pricing policies increase the marginal cost of electricity production which (with the exception of some so-called super-peak hours; see Joskow (2008)) determines the market clearing price in deregulated markets (see Figure 7.19). The ETS related increase of the marginal costs has several consequences for the performance of competitive electricity markets. First and foremost, the emission trading offset is intended to change the relative position of power plants in the dispatch order and/or to trigger investments in new power plants with lower emissions. Experiences from the EU ETS have shown that the GHG prices observed in the markets were effective in changing operating choices and investments decisions in a way which allowed fulfilling the ETS greenhouse gas reduction goals even in periods of economic growth and the existence of other factors that otherwise would have caused emissions to raise (Ellerman and Buchner, 2007; Ellerman et al., 2010).

A higher market clearing price implies that consumers have to pay more for electricity. "This can result in consumer payments for electricity increasing by substantially more than the actual cost of emissions allowances (Cowart, 2010)" (IEA, 2011j, p. 44). In markets that exhibit some price elasticity (e.g., due to demand response measures (IEA, 2003b)) this might result in a lower demand and consequently in lower emissions as well. In contrast, a higher market clearing price implies higher infra-marginal rents for the electricity producers at least as long as the price effect is not overcompensated by additional EP expenditures (Keppler and Cruciani, 2010). The related transfer of money from consumers to producers is exaggerated, if certificates are allocated for free.

"In competitive markets, free allocation leads to windfall gains for electricity generators and does not prevent electricity price rises for end users. In regulated systems, although free allocation could prevent price rises it can also remove the incentive to move to low-carbon generation. In both cases, if the desire is to offset price rises for end consumers, it is better to compensate consumers directly (or via electricity distribution companies), rather than providing free allocation to generators" (IEA, 2010g, p. 8).



Source: Philibert, 2011.

Source: Philibert, 2011.

Figure 7.19. a) In a competitive wholesale market, CO_2 costs are passed through onto all electricity sold. b) Merit order effect: An increase in renewable energy power generation can lower wholesale electricity prices by shifting the merit order of generating plants. Source: Philibert (2011).

The long-term goal of carbon prices is to lower the emissions of power generation, by changing the relative attractiveness of new investments. To the extent that carbon taxes or EP regimes cover only a subset of the economy, they can introduce market distortions that increase the cost of emissions reductions. Edmonds, et al. (2006) showed that carbon prices applied across the entire energy system resulted in reductions of the price of electricity relative to other end-use fuels, accelerating electrification and decarbonization of power generation. However, application of EP regimes to power generation alone resulted in an increase in the relative price of electricity, substitution of fossil fuels for electricity in end uses, and much higher costs per ton of emissions mitigation.

Whereas ETS are limited to Annex 1 countries (of the Kyoto Protocol), the clean development mechanism (CDM) had an impact on energy systems in non-Annex 1 countries. CDM has the objective to encourage sustainable development in non-Annex 1 countries via emission reductions projects, while at the same time assisting industrialized countries in achieving their GHG emissions reductions commitments (Boyd et al., 2009; van der Gaast et al., 2009). Furthermore, CDM has helped to establish a global price on GHG emission reductions, and established a fairly credible, internationally-recognized, carbon offset market that is worth $2.7 billion with participation from a large number of developing countries and private investors (Gillenwater and Seres, 2011, p. 35).

The relevance of energy related emission mitigation projects within the CDM is shown in Figure 7.20. Renewable energy projects are the most common and account for 68 % of CDM projects. Cumulatively, 35% of emission reduction (CERs) from projects will come from renewable energy projects while 28% will come from industrial hydrofluorocarbon (HFC) and Nitrous oxide (N2O) projects. One reason is that "early in the CDM program, a significant fraction of the emission reduction have come from a few large projects that reduced GHG emissions at low cost, for example industrial HGC and N2O abatement projects, but which delivered limited sustainable development benefits other than reduced GHGs" and low carbon energy supply (Gillenwater and Seres, 2011, p. 30).

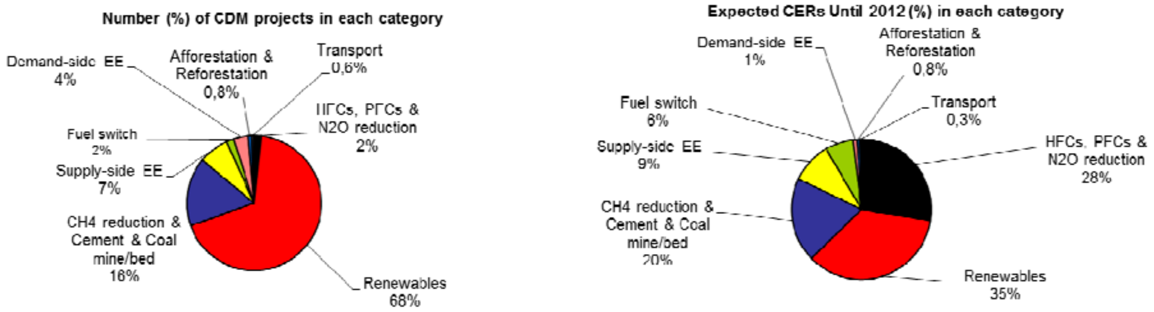


Figure 7.20. Relative Number of CDM Projects and Expected CERs by Project Type. Source: UNEP Risoe CDM/JI Pipeline analysis and database (http://cdmpipeline.org. accessed: 1.7.2012). Note: Data is as of June 2012 and represents all CDM projects in the pipeline (i.e., at the validation, registration or issuance stages).

In terms of geographical distribution, CDM projects are unevenly distributed across host countries with China, India and Brazil accounting for 75% of all project activities and 78% of expected CERs (Francois and Hamaide, 2011). African countries have been lagging behind with a 2.7% of the total registered CDM projects worldwide, with majority of the projects concentrated in South Africa and Egypt (UNEP Risoe, 2011; Gujba et al., 2012). The reasons that explain why some developing countries don’t reach their full potential to capture the benefits from CDM are discussed in (Lokey, 2009).

With respect to technology transfer the assessment of CDM projects is mixed. While the contribution of CDM to the evolution of energy systems in least developing countries (LDCs) has been minimal, CDM may be supporting the spread of existing technologies in emerging economies (Decezlepretre et al., 2008). For example, Brazil's abundant hydro and biomass resources have meant higher diffusion of renewable energies based on these resources (Bodas-Freitas et al., 2012). In an empirical study of 1000 CDM projects Das (2011) found that the contribution of the CDM to technology transfer is minimal, but in the present revision of this mechanism improvements can be expected.

7.11.3 Technology policies to complement carbon pricing

In addition to GHG pricing, additional technology related policies (e.g., feed-in tariffs, competitive public auctions, obligation for electricity providers to buy and supply a specific percentage of renewable energy, or various financial and tax incentives) can be justified from a macroeconomic point of view if market failures in the field of innovation could be avoided by exploiting technological learning (or if other goals beyond climate mitigation are pursued) (IPCC, 2011a, p. 870; IEA, 2011j).

Although technology specific government policies were responsible for the substantial growth of renewable energies observed in the recent years, not all of these policies have proven to be effective and efficient in increasing the share of renewable energies in the power mix (IPCC, 2011a, p. 869). "Several studies have concluded 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" (IPCC, 2011a, p. 869). Often supported by government policies, the electricity production based on renewable energies, which is characterized by often low (or even zero) variable costs, can reduce wholesale electricity prices in the short term by displacing power plants with higher marginal costs (S. Bode, 2006; Sensfuß et al., 2008). This "merit order effect" is visualized in Figure 7.19. "In the long term, this suppression of prices may not be sustainable, as generators need to be able to recover their costs to justify investment. This has led many to conclude that current wholesale electricity market designs need to be re-evaluated with the goal of supporting a least-cost decarbonisation of the power sector. These discussions are reviewed in Hood (2011)" (IEA, 2011j, p. 44).

7.11.4 Enabling policies

The success of energy policies and measures depends at least in part on the development of an efficient system to facilitate their implementation. Property rights and contract enforcement are essential to successful policy implementation. The most elegantly crafted policy is impotent if it cannot be enforced, or if its measures are undercut by other policies and measures or if property rights go undefined. For example, a well-defined emissions mitigation crediting environment is essential to deployment of CO_2 capture and storage. Without defining the basis upon which emissions storage will be assigned and the long-term responsibility for its disposition, CO_2 capture and storage cannot be deployed effectively. Similarly, a consistent treatment for emissions accounting purposes of bioenergy is essential to its widespread deployment in a mitigation strategy.

According to (IEA, 2011k), the phase-out of fossil fuel consumption subsidies would reduce global energy-related carbon emissions by about 6% (see also Bruvoll et al., 2011). In order to facilitate a least cost integration of fluctuating renewable energies, further issues are to be addressed. These comprise (1) the enhancement of the currently rather low price elasticity of demand by technical means (IEA, 2003b), (2) the often existing lack of local price elements that reveal network constrains (Neuhoff et al., 2011), and (3) the rising difficulties of back-up power plants to capture their investment costs for increasing shares of renewable energies under the conditions of “energy-only markets ” (Sven Bode and Groscurth, 2009; Hood, 2011). Demand response measures, nodal pricing schemes and capacity markets (Joskow, 2008) have been proposed to cure these failures. While increasing demand response is generally seen as beneficial (IEA, 2003b), the necessity of nodal pricing schemes and capacity markets (Joskow, 2008) is still under debate. A recent issue in regulatory field is the regulatory support for the development of “smart grids”. What is at stake is to examine how regulation could help to enhance the contribution of the electric grid to meeting the energy needs in an efficient, reliable and environmentally responsible manner (Pérez-Arriaga, 2009).

Considering different aspects and measures, coherence and better interactions among policies and their instruments are indispensable. Recent studies have emphasized this problem (Cédric Philibert, 2011) and have tried to develop a unified framework, e.g. in the electricity sector, to assess different policy options. Fisher and Newell (2008) in their application to the US electricity sector note that an optimal portfolio of policies achieves emissions reductions at a significantly lower cost than any single policy.

Finally, energy policies are not isolated instruments. They are enacted within a “regulatory framework” that needs a solid legal foundation. Regulatory stability is another condition: agents and participants in the process must know how the system works, its administrative requirements, the time delays, the implementation and changes in the process. Regulatory agencies could be required to delegate some tasks to other governmental or nongovernmental entities. In some countries, a rural electrification agency functions as a “de facto” regulator, imposing certain requirements in return for giving grants or subsidized loans: it may specify a maximum tariff, a required technical quality for new installations, or technical and commercial quality for post-installation service. That agency will almost always have a better appreciation of the cost implications of imposing different regulatory requirements, it will facilitate coordination and it will reduce the risk of duplication and over-regulation (Reiche et al., 2006).

Beyond issues of regulatory stability, there is an emerging evolutionary economic growth literature which emphasizes that “in order to rise, states must prevent vested interests from blocking structural change. States that are unable to do this will get locked into yesterday’s technologies, industries and energy systems, effectively consigning themselves to stagnation and decline” (Moe, 2010).

7.12 Sectoral implication of transformation pathways and sustainable development

This section reviews long-term integrated assessment scenarios and transformation pathways with regard to their implication for the global energy system. Focus is given to energy-related CO_2 emissions and the required changes to the energy system needed to achieve emissions reductions compatible with a range of long-term climate targets.[19]

The assessment builds upon more than 400 greenhouse gas emissions scenarios, which were collated by Chapter 6 in the AR5 scenario database.[20] The scenarios were grouped into baseline scenarios and GHG mitigation scenarios, corresponding to different levels of ambition to reduce GHG emissions. The most stringent mitigation scenarios (category 1) correspond to a long-term total

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[19] Other non-CO_2 greenhouse gases (eg, CH4 and N2O) are primarily emitted by other sectors than energy. Their share is thus relatively small in the energy sector.

[20] AR5 database: https://secure.iiasa.ac.at/web-apps/ene/AR5DB

radiative forcing targets of below 2.7 W/m^2, which is broadly compatible with stated objective of the Copenhagen Accord to limit global average temperature change to below 2°C. Similarly, scenarios in the highest category (6) correspond to modest mitigation efforts leading to radiative forcing levels greater than 6.7 W/m^2 with temperature outcomes of approximately 4°C (See Chapter 6 for details).[21]

7.12.1 Energy-related greenhouse gas emissions

In absence of climate change mitigation policies, energy-related CO_2 emissions are expected to continue to increase. Estimates from the integrated assessment scenarios indicate that this growth might be particularly rapid over the next decades with the energy & industry sector reaching 55-75 $GtCO_2$ by 2050 (20th-80th percentile of the scenarios in the AR5 database, see Figure 7.21).[22] This corresponds to an increase by a factor of 1.8 to 2.5 compared to emissions of about 30 $GtCO_2$ in the year 2010. In the very long term by 2100 emissions may reach even higher levels of about 95 $GtCO_2$ (80th percentile), or an increase of a factor of three compared to 2010. [23] The full uncertainty range of the AR5 databases includes high emissions scenarios approaching 80 $GtCO_2$ by 2050, and almost 120 GtCO2 by 2100.

The stabilization of GHG concentrations requires policy interventions in the energy sector to depart from the business as usual pathway. For example, in scenarios compatible with a long-term target of below 2.7 W/m^2 (category 1) energy-related emissions peak already by 2020, and decline thereafter to about 12-17 $GtCO_2$ by 2050 (Figure 7.21). This corresponds to emissions reductions by 2050 of 45-60% compared to the year 2010, and 70-85% compared to the business as usual (20th-80th percentile). As discussed in Section 7.12.4, CO_2 emissions must eventually decline to zero in order to stabilize CO_2 concentrations. In order to achieve stringent climate targets, that is Category 1, CO_2 emissions from energy need to approach or decline below zero.

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[21] Category 2 scenarios correspond to stabilization of total radiative forcing between 2.7-3.2 W/ m^2, category 3: 3.2-3.7 W/ m^2, category 4: 3.7-4.7 W/ m^2, and category 5: 4.7-6.7 W/ m^2.

[22] Note that energy & industry emissions are mostly dominated by energy-related emissions. A split of this category is not available in the AR5 scenario database. Some models do include in this category emissions from fossil fuel feedstocks for industrial processes (fossil fuel use for eg lubricants, asphalt, cement production, etc.).

[23] If not otherwise mentioned, ranges refer to the 20th-80th percentile of the AR5 database.

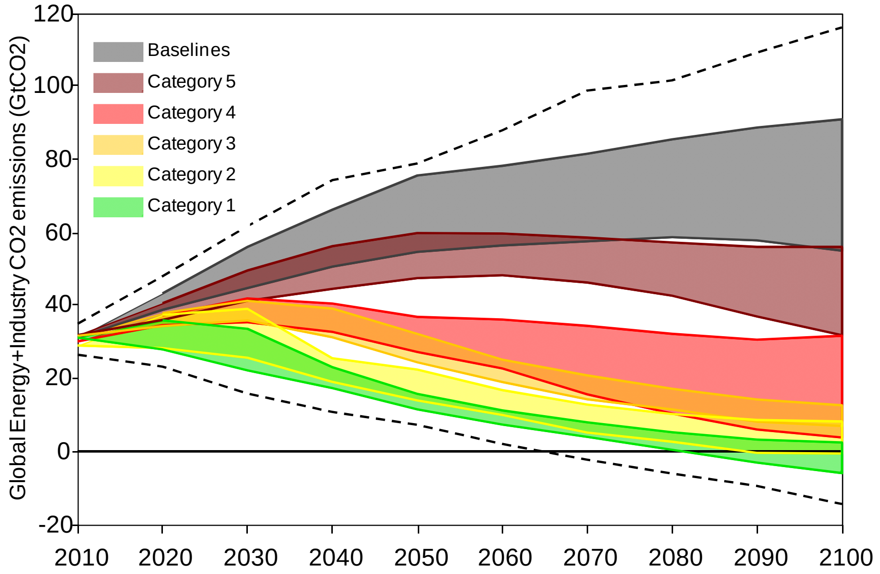

Figure 7.21. Development of global CO2 emissions in the energy and industry sector. The baseline emissions range (grey) is compared to the range of emissions from mitigation scenarios grouped according to their long-term target (C1 to C5). Shaded areas correspond to the 20th-80th percentile across scenario categories of the AR5 scenarios database (see Chapter 6 for details). Dashed lines correspond to the full range of emissions scenarios in the AR5 database. Source: AR5 scenario database (Chapter 6).

7.12.2 Energy supply in low stabilization scenarios

Achieving the stabilization of GHG concentrations at low levels requires fundamental changes to the energy system. As discussed in Section 7.5 as well as in chapters 8 to 10, a portfolio of measures is available in the energy system to achieve this objective, including the reduction of energy demand through enhanced efficiency or behavioural changes as well as the introduction of low-carbon supply options such as renewables, nuclear, and carbon capture and storage in combination with fossil or biomass energy conversion processes. Figure 7.22 shows an array of alternative energy system configurations that are consistent with Category 1 mitigation levels.

The scenarios from three selected models shown in Figure 7.22 are broadly representative of different strategies for the transformation of the energy system to achieve the stabilization of GHG concentrations at low levels (category 1: 2.7 W/m^2 by the end of the century). In absence of policies to reduce GHG emissions, the energy supply portfolio of the scenarios is dominated by fossil fuels, increasing their contribution from presently about 420 EJ to about 700-900 EJ by 2050 (left-hand panel of Figure 7.22). Stabilization at low levels will require the rapid and pervasive replacement of this fossil fuel share (right-hand panel of Figure 7.22). 60-300 EJ of fossil fuels are replaced across the three scenarios over the next two decades (by 2030), and the effort needs to increase to replace fossil energy in the order of 230-670 EJ by 2050.[24]

While the pace of the transformation differs across the scenarios (and depends also on the carbon-intensity and energy demand development in the baseline), all three illustrative scenarios show the importance of measures to reduce energy demand over the short term. For instance by 2030, between 40-90% of the emissions reductions are achieved through energy demand saving, thus reducing the need for fossil fuels. The long-term contribution of energy demand savings differs,

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

however, significantly across the three scenarios. For instance, in MESSAGE more than 1200 EJ of fossil fuels are replaced through efficiency and demand-side improvements by 2100, compared to about 400 EJ in the GCAM scenario. Generally, improving efficiency increases the flexibility for energy supply, requiring the less pervasive and rapid up-scaling of the supply-side options (see right-hand panel of Figure 7.22).[25]

Achieving the stabilization of GHG concentrations at low levels (category 1) requires the massive up-scaling of low-carbon energy options. Deployment ranges across the scenarios of the AR5 scenarios database for 2050 are shown in Figure **7.23**. As illustrated, for most technologies the deployment needs for low-carbon options increases when energy demand is relatively higher. Even at very low stabilization levels a significant fraction of energy supply may be provided by freely emitting fossil energy (without CCS). The need for fossil CCS however, increases substantially by 2050.

Energy system response to a prescribed climate policy varies across models and regions. Figure 7.24 shows the response in 2050 reported by a variety of energy system models participating in the Asia Modeling Exercise to a carbon tax that begins at $30 and rises at 5%/y for various Asia regions. Note that most stabilization scenarios in the literature are medium or low energy demand scenarios with the high category under-represented.

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[25] Efficiency improvements include both demand and supply-side measures. However, in all three scenarios the contribution of demand-side measures are dominating over the effect of supply-side efficiency improvements.

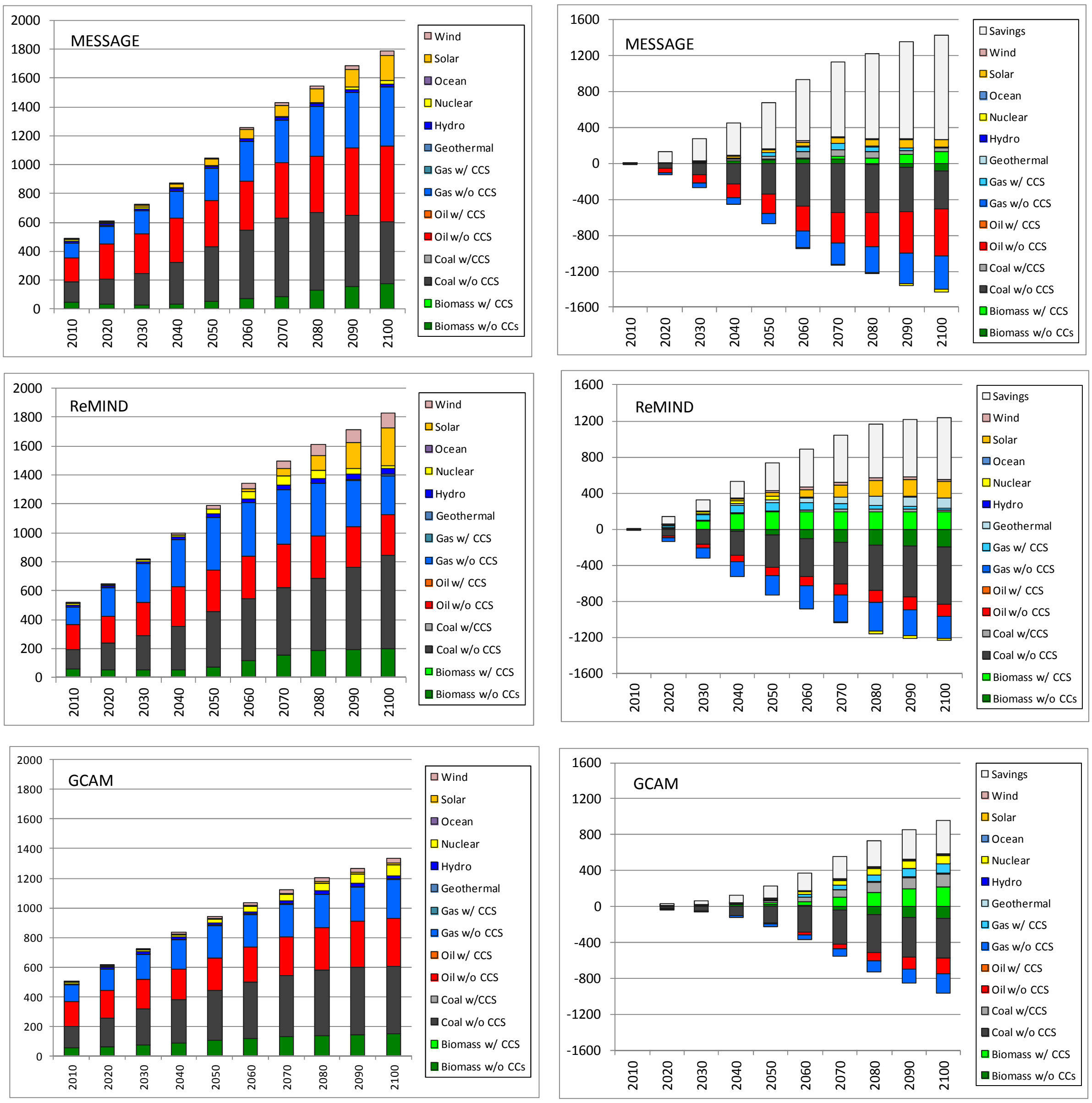

Figure 7.22. Development of primary energy (EJ) in three illustrative baseline scenarios (left-hand panel); and the change in primary energy compared to the baseline in order to meet 450 ppm CO2eq stabilization target (selected scenarios of category 1 of the AR5 scenario database). Data based on chapter 6 scenario database, and three illustrative models: ReMIND (Rose: Kriegler et al, forthcoming); GCAM (AME: Calvin et al, 2012); MESSAGE (GEA: Riahi et al, 2012)26.

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

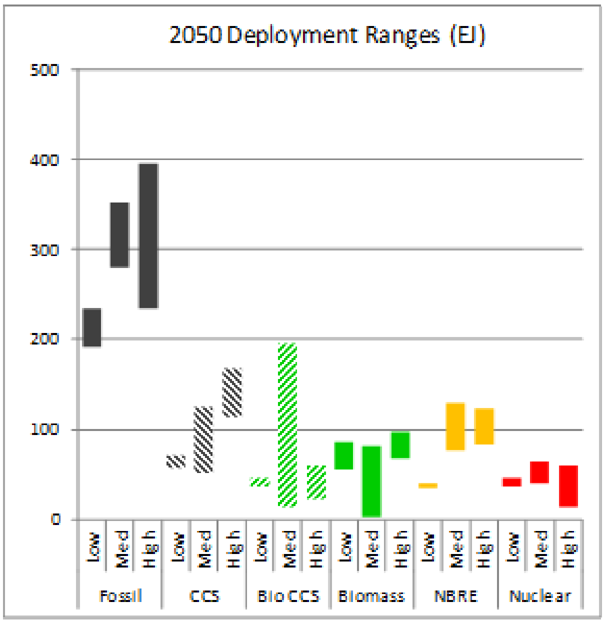

Figure 7.23. Deployment ranges for groups of energy supply technologies in 2050 in order to achieve the stabilization of GHG concentrations at low levels (category 1). Low, Med, and High correspond to scenario groups with alternative levels of energy demand. The bars indicate the 20th-80th percentile of scenarios within each demand category (see chapter 6 for more details of the classification of scenarios for different levels of demand). Fossil = freely emitting fossil technologies; CCS = Fossil CCS technologies, BIOCCS = biomass conversion technologies with CCS; NBRE = sum of non-biomass renewables; Nuclear = nuclear. [Author note: preliminary figure only based on limited set of scenarios for high energy demand projections. Figure will be updated in the next draft with additional scenarios from various presently on-going modeling comparison projects (eg, AME, AMPERE, EMF27).]

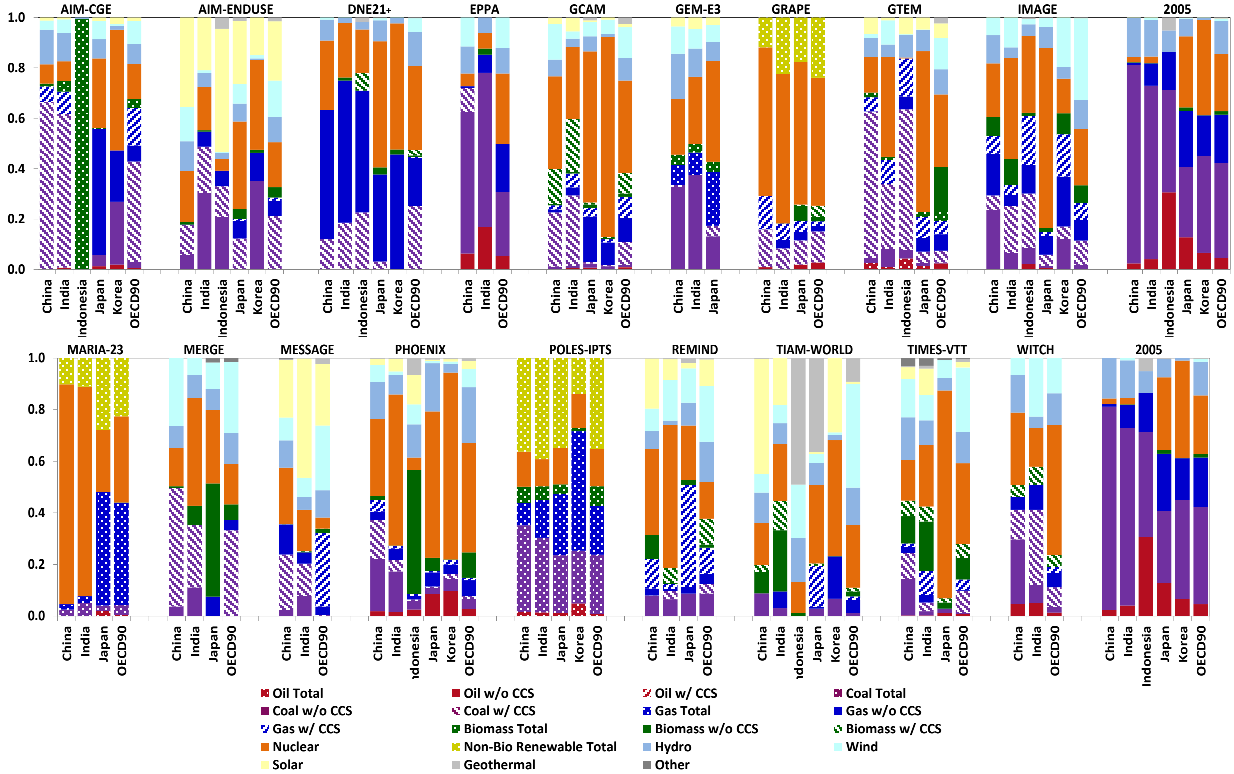

Figure 7.24. Distribution of technology utilization for a $30/tCO2 carbon tax escalating at 5%/y for models participating in the Asia Modeling Exercise for various regions and models.

7.12.3 The role of the electricity sector in emissions mitigation

The supply of reliable, affordable, and clean electricity is vital for economic productivity and sustainable growth. Electrification of the energy system has thus been a major driver of the historical energy transformation from an originally biomass dominated energy system in the 19th century to a modern system with high reliance on coal and gas (the major sources of electricity generation today). Many studies in the AR5 data base use a three-part strategy to reduce energy sector emissions: 1. Decarbonize power generation, 2. Substitute electricity for direct use of fossil fuels in buildings and industry, and sometimes transportation, and 3. Reduce aggregate energy demands through technology and other substitutions.

The vast majority of integrated assessment studies assume that the global electrification trend will continue in the future, and that the share of electricity in final energy may double even in absence of climate policies (Figure 7.25). In baseline scenarios without climate policy most of the demand for electricity is expected to be in the residential, commercial and industry sectors, while transport sectors rely predominantly on liquid fuels. Bioenergy and electricity both have the potential to provide transport services without fossil fuel emissions. The relative contribution of each depends at least in part on the character of technologies that evolve to provide transport services with each fuel.

Power production is the largest single sector emitting of fossil fuel CO_2 in reference scenarios. 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 CCS. By contrast, possibilities to decarbonise energy supply in other central energy conversion facilities, such as refineries, is comparatively limited (and includes mainly biofuels that may be combined also with CCS). The electricity sector plays thus a major role in transformation scenarios with deep cuts of GHG emissions. Mitigation studies show generally an acceleration of the electrification trend as a response to reduce the system's carbon emissions (Figure 7.25). Shares of electricity in total final energy are thus significantly higher in scenarios with climate policies than in no-climate policy scenarios.

Mitigation studies indicate that the decarbonisation of the electricity sector may be achieved at much higher pace than in the rest of the energy system (Figure 7.26). In stringent stabilization scenarios (category 1 & 2), the share of low-carbon energy increases from presently about 30% to more than 80% by 2050. In the long term (2100) fossil-based electricity generation without CCS is phased out entirely in these scenarios. As indicated in Figure 7.26 this trends is comparatively slower in the rest of the system.

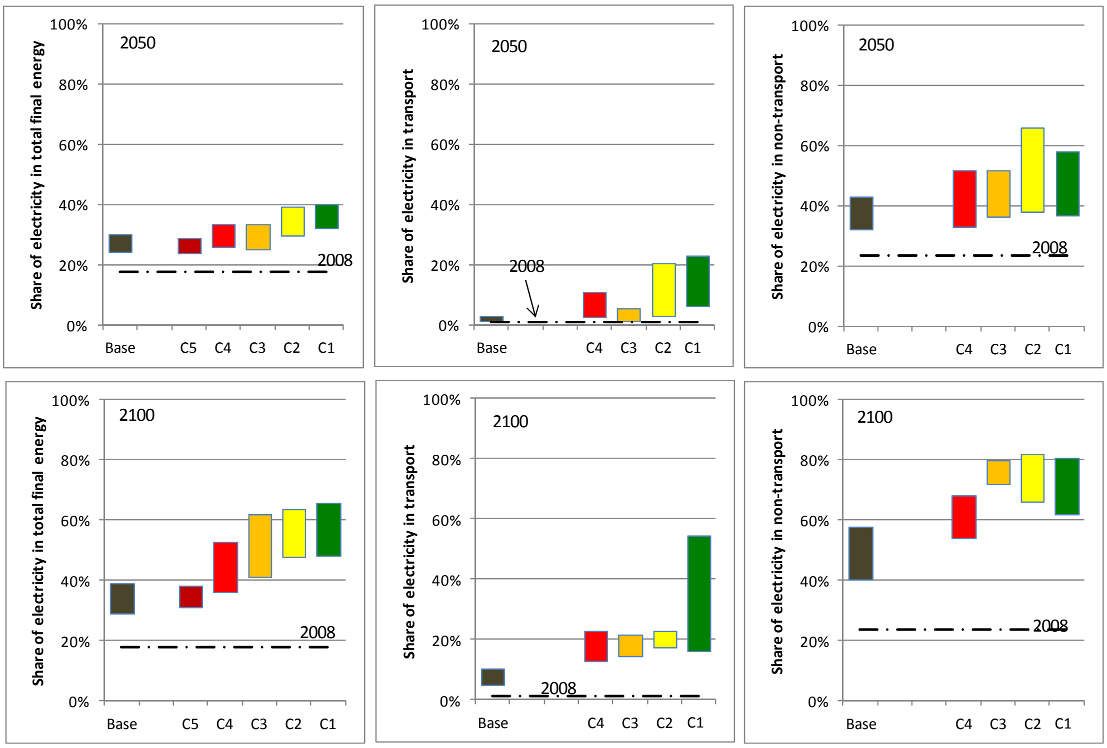

Figure 7.25. Share of electricity in total final energy, final energy transport, and other non-transport final energy (residential commercial and industry). Ranges correspond to the 20th-80th percentile of baseline and stabilization scenario categories of the AR5 scenario database (see chapter 6 and Table 7.6 for more details). Dashed horizontal lines show the electricity share for the year 2008, and bars indicate the share for 2050 and 2100.

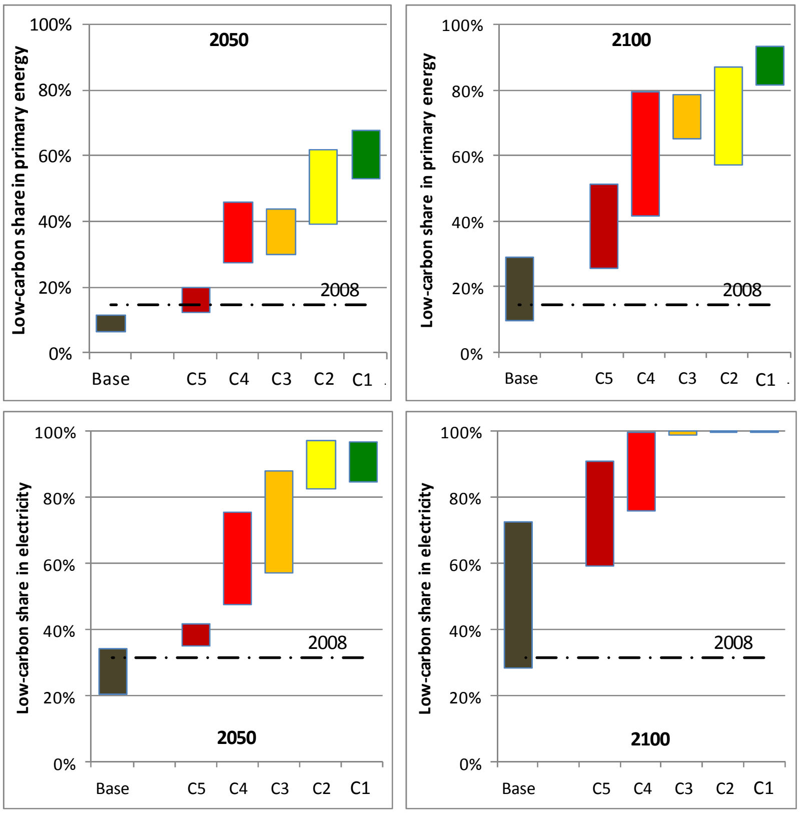

Figure 7.26. Share of low-carbon energy in electricity and total primary energy. Ranges indicate the 20th-80th percentile of the full set of IAM scenarios in the AR5 scenario database (see chapter 6 for more details). Dashed horizontal lines show the low-carbon share for the year 2008, and different panels for the years 2050 and 2100.

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

The relationship between near-term actions and long-term goals is complex and has received a great deal of attention in the research literature. Unlike short-lived species (e.g. CH_4, CO, NO_x, and SO_2) for which stable concentrations are associated with stable emissions, stable concentrations of CO_2 ultimately require emissions to decline to zero (Kheshgi et al., 2005). Two important implications of that biophysics follow directly. First, to a first approximation it is cumulative emissions over the entire century that determines the CO_2 concentration at the end of the century, and therefore no individual year's emissions are critical (for cumulative CO_2 emissions consistent with different targets see chapter 6, and Meinshausen et al (2009). Second, minimization of global social cost implies an immediate, initiation of global emissions mitigation, relative to a reference, no-climate-policy scenario, with a marginal value of carbon which rises exponentially (Hotelling, 1931; Peck and YS Wan, 1996). The consequence of this latter feature is that emissions mitigation and the deployment of mitigation technologies grows over time.

When only a long-term state, e.g. a fixed level of radiative forcing in a specific year such as 2.6 Wm^{-2} in 2100, is prescribed, the interim path can theoretically take on any value before the target year. "Overshoot scenarios" are scenarios for which target values are exceeded during the period before the target date. They are possible because carbon is removed from the atmosphere by the oceans over an extended period of time, and can be further extended by the ability of society to create negative emissions through sequestration in terrestrial systems (section 7.5), production of bioenergy in conjunction with CCS technology, and/or direct air capture (DAC). Even so, the bounded nature of the cumulative emissions associated with any long-term CO_2 limit creates a derived limit on near-term emissions. Beyond some point, the system cannot adjust sufficiently to achieve the goal. Early work linking near-term actions with long-term goals was undertaken by researchers such as Swart, et al. (1998), the “safe landing” concept, and Bruckner, et al., (1999), the “tolerable windows” concept. O’Neill, et al., (2010) assessed the relationship between emissions levels in 2050 and the probability of meeting different 2100 targets. They identified “emissions windows” through which global energy systems would need to pass in order to achieve various atmospheric composition goals. Figure 7.27 shows the 2050 emissions ranges that if surpassed would make the stabilization of CO2e concentrations at specific levels infeasible in the long term. The 2050 ranges show a pronounced shift upwards compared to the AR4, which primarily has focused on optimal pathways with significant early emissions reductions.

The magnitude of long-term emissions mitigation goals tends to distort the associated near-term energy system deployment requirements. Figure 7.28 shows energy system CO_2 capture in a scenario, which stabilizes atmospheric CO_2 concentrations at 550 ppm (3.7 Wm^{-2} when the effects of non-CO_2 GHGs are included) employing the MiniCAM model (L. Clarke, J. Edmonds, et al., 2007). While near-term deployment is large relative to present monitored experiments (though less different than present EOR deployment levels), deployment levels appear small relative to long-term deployment rates.

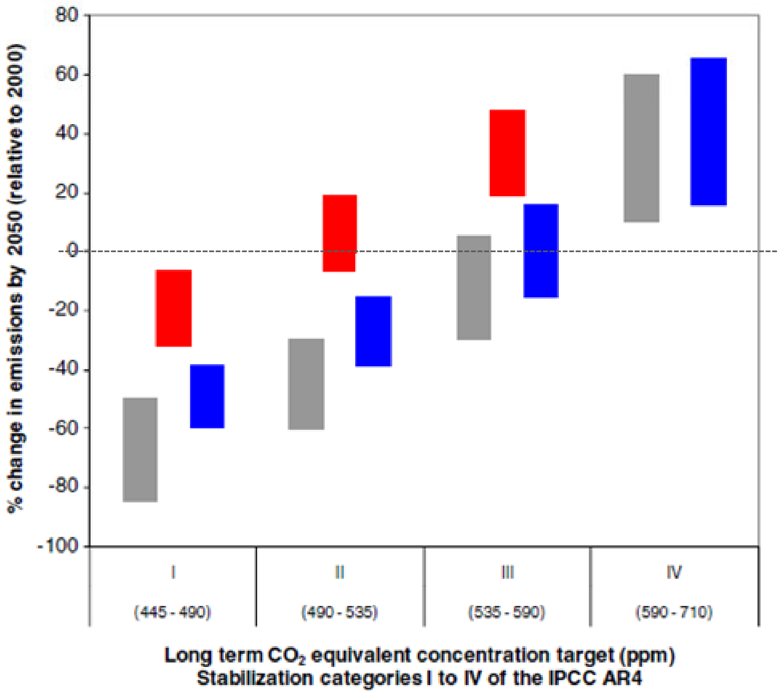

Figure 7.27. Feasibility frontier for the B2 (Red) and A2r (Blue) baseline scenarios compared to ranges of mid-century emissions associated with mitigation scenarios in the literature assessed in IPCC AR4 (Ha-Duong et al., 1997). The B2 feasibility frontier does not apply to the IPCC stabilization category IV, because this target is attainable in the B2 baseline scenario without any mitigation by 2050. Source: O’Neill, Riahi and Keppo (2010).

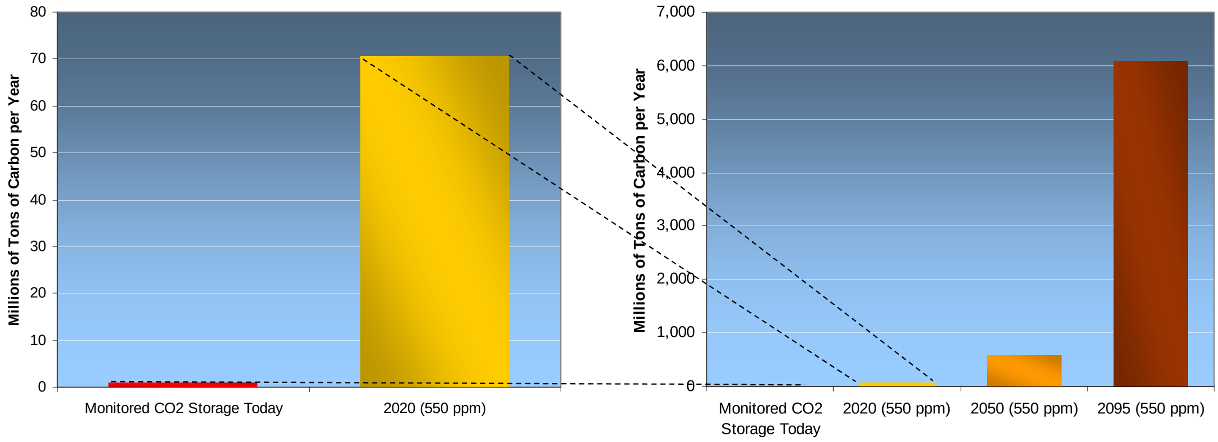

Figure 7.28. Near-term CO2 capture and storage compared with long-term deployment in a scenario which stabilizes atmospheric CO2 concentrations at 550 ppm.

7.12.5 The role of technology for the costs of climate stabilization

The feasibility of achieving stringent limits to radiative forcing, less than 2.7 Wm^{-2} in the year 2100, has been a matter that has come under increasing investigation (EMF 22, EMF 27, IIASA study, Luckow, et al. 2012). As noted above, low long-term radiative forcing levels require dramatic changes to the global energy system, particularly compared to reference, no-climate-policy scenarios. Depending on assumed technology availability, the modeling environment, and other exogenous assumptions such as population and economic development, some models cannot find a transition pathway, while others do. Those that find a transition pathway, however, may need to make ambitious assumptions about energy sector deployment rates for new capital stocks and retirement rates for existing infrastructure. These in turn can produce marginal costs that are relatively high, particularly compared with those required to meet less stringent environmental goals.

Luckow, et al. (2012) explored interactions between technology availability and the international accession regimes where global radiative forcing was limited to no more than 2.6 Wm^{-2} in the year 2100 using carbon taxes. The marginal cost of stabilization for five technology suites, ranging from a full set of options to no use of nuclear power, bioenergy or CO_2 capture and storage technologies in combination with alternatively an idealized policy regime (solid lines) or regime with delays in accession (dashed lines) are shown in Figure 7.29. While this paper successfully limited radiative forcing to not exceed 2.6 Wm^{-2} in all instances, it found that if either all technologies were available or all regions of the world mitigated from the start that marginal costs were contained within a factor of four. Combinations of delay and limitations on technology availability produced non-linear increases in marginal costs. Note that in all instances, land-use policies were invoked to sequester carbon. The study showed a non-linear relationship between stressors and marginal costs.

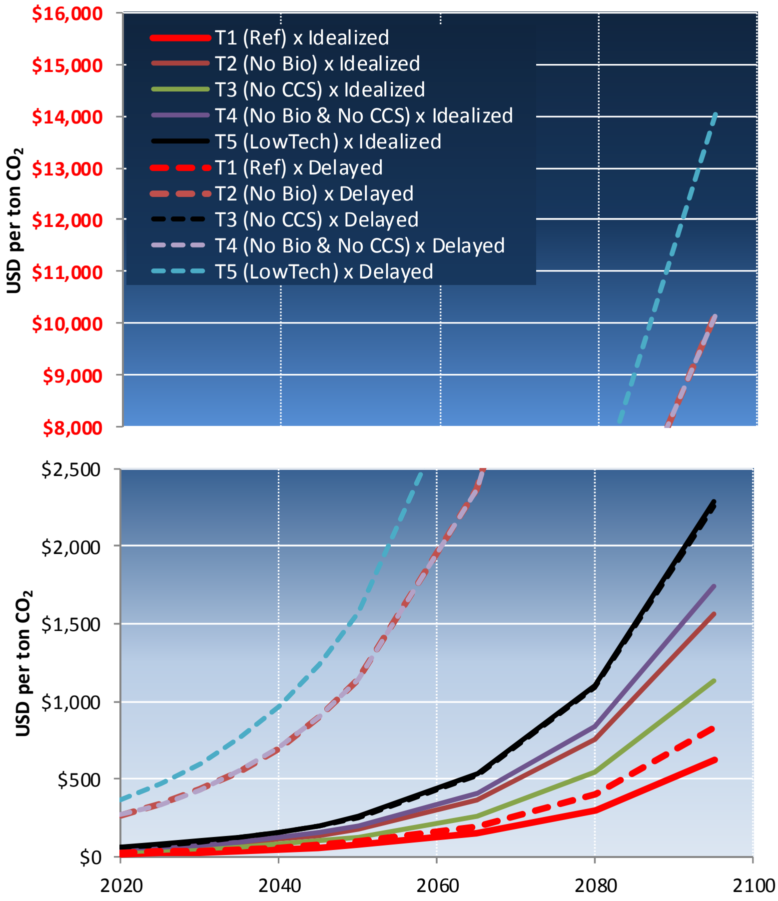

Figure 7.29. Marginal cost in the emissions mitigation coalition for two policy regimes with five alternative technology availability sets—year 2100 radiative forcing limited to 2.6 Wm-2.

7.12.6 Energy investments in low stabilization scenarios

An important characteristic of the energy sector is its long-lived capital stock, with lifetimes for infrastructure and energy conversion facilities of 20–60 years and sometimes longer. This longevity translates into high inertia in energy supply systems, which impedes rapid transformation. There is significant cost to society to allocate resources to the creation of one capital stock and then abandoning it before the end of its useful life. Similarly, the more rapidly new plant and equipment are needed to be installed, the more expensive the new investments will be as short term constraints in human capital and materials availability increasingly impinge. The energy investment decisions of the next several years are thus of central importance, since they will have long-lasting implications and will critically shape the direction of the energy transition path for years to come.

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

Table 7.6 compares the present investment intensity with future investment needs from a range of 41 transformation scenarios of the Global Energy Assessment in order to stabilize radiative forcing at low levels (category 1). Increasing investment in the energy system as depicted by Table 7.6 requires the careful consideration of a wide portfolio of policies in order to create the necessary financial incentives. The portfolio needs to include regulations and technology standards in sectors with relatively low price elasticity, in combination with externality pricing, in order to avoid rebound effects, as well as targeted subsidies to promote specific “no-regrets” options while addressing affordability. In addition, attention must be given to building an enabling technical, institutional, legal, and financial environment to complement traditional deployment policies (particularly in the developing world).

Table 7.6 identifies effective combinations of policies for specific technology options and puts these in the context of the required future investment needs. Different types of technologies and objectives will require different combinations of policy mechanisms to attract the necessary investment. Table 7.6 thus distinguishes among various mechanisms: “essential” policy mechanisms are those that must be included for a specific option to achieve the rapid energy system transformation; “desired” policy mechanisms are those that would help but are not a necessary condition; “uncertain” policy mechanisms are those where the outcome will depend on the policy emphasis and thus might favour or disfavour a specific option; and “complement” policies are those that are inadequate on their own but could complement other essential policies.

Table 7.6: Energy investments across 41 low stabilization scenarios (category 1), and illustrative policy mechanisms to mobilize the necessary resources. Source: (Rogner et al., 2011).

	Investment (billions of US$/year)		Policy mechanisms			
	2010	2010–2050	Regulation, standards	Externality pricing	Carefully designed subsidies	Capacity building
Efficiency	n.a.[1]	290–800[2]	*Essential* (elimination of less efficient technologies every few years)	*Essential* (cannot achieve dramatic efficiency gains without prices that reflect full costs)	*Complement* (ineffective without price regulation, multiple instruments possible)[3]	*Essential* (expertise needed for new technologies)
Nuclear	5–40[4]	15–210	*Essential* (waste disposal regulation and, of fuel cycle, to prevent proliferation)	*Uncertain* (GHG pricing helps nuclear but prices reflecting nuclear risks would hurt)	*Uncertain* (has been important in the past, but with GHG pricing perhaps not needed)	*Desired* (need to correct the loss of expertise of recent decades)[5]
Renewables	190	260–1010	*Complement* (renewable portfolio standards can complement GHG pricing)	*Essential* (GHG pricing is key to rapid development of renewables)	*Complement* (feed-in tariff and tax credits for R&D or production can complement GHG pricing)	*Essential* (expertise needed for new technologies)
CCS	<1	0–64	*Essential* (CCS requirement for all new coal plants and phase-in with existing)	*Essential* (GHG pricing is essential, but even this is unlikely to suffice in near term)	*Complement* (would help with first plants while GHG price is still low)	*Desired* (expertise needed for new technologies)[5]
Electricity transmission and storage[6]	260	310–500	*Essential* (security regulation critical for some aspects of reliability)	*Uncertain* (neutral effect)	*Essential* (customers must pay for reliability levels they value)	*Essential* (expertise needed for new technologies)

1. Global investments into efficiency improvements for the year 2010 are not available. Note, however, that the best-guess estimate for investments into energy components of demand-side devices is by comparison about 300$ billion per year (GEA, 2012). This includes, for example, investments into the engines in cars, boilers in building heating systems, and compressors, fans, and heating elements in large household appliances. Uncertainty range is between US$100 billion and US$700 billion annually for investments in components. Accounting for the full investment costs of end-use devices would increase demand-side investments by about an order of magnitude (see Rogner et al., 2011 for details).
2. Estimate includes efficiency investments at the margin only and is thus an underestimate compared with demand-side investments into energy components given for 2010 (see note 1).
3. Efficiency improvements typically require a basket of financing tools in addition to subsidies, including, for example, low- or no-interest loans or, in general, access to capital and financing, guarantee funds, third-party financing, pay-as-you-save schemes, or

feebates as well as information and educational instruments such as labeling, disclosure and certification mandates and programs, training and education, and information campaigns.
4. Lower-bound estimate includes only traditional deployment investments in about 2 GW capacity additions in 2010. Upper-bound estimate includes, in addition, investments for plants under construction, fuel reprocessing, and estimated costs for capacity lifetime extensions.
5. Note the large range of required investments for CCS and nuclear in 2010–2050. Depending on the social and political acceptability of these options, capacity building may become essential for achieving the high estimate of future investments.
6. Overall electricity grid investments, including investments for operations and capacity reserves, back-up capacity, and power storage.

7.13 Gaps in knowledge and data

Gaps in knowledge and data are addressed to identify the limitations of research. Chapter 7 is confronted by various gaps in knowledge primary those related to methodologies and availability of data. On one hand, the diversity of energy balances construction and GHG emission accounting methodologies leads to some disagreement among statistical sources. Furthermore, a significant knowledge gap arises through the several years of delay of the availability of comprehensive data not only just on CO_2, but as well on global GHG emissions [sec. 7.1 to 7.3]. On the other hand, further knowledge gaps in the climate change research 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 [sec. 7.7]. Moreover, the current literature provides a limited number of comprehensive studies on the economic, social and cultural impacts of threats to energy security such as a major and long disruption of energy supply. This is valid for both importing and exporting countries. Moreover, there are few comprehensive comparative studies on the environmental and health impacts of low carbon technologies and high carbon technologies [sec. 7.10]. Finally, integrated decision making support requires further development of integrated analysis tools and modeling frameworks, accounting for the range of possible co-benefits and trade-offs of different policies in energy sector that tackle access, security and/or environmental concerns, as well as institutional and human capacity for the use of such tools and frameworks [sec. 7.11 and 7.12].

7.14 Frequently asked questions

[TSU note: FAQs will be presented in box format throughout the text in subsequent drafts.]

FAQ 7.1: Is it technically feasible to achieve deep emission reductions in the long-term (e.g. those compatible with the 2°Celsius goal of the Copenhagen Accord)?

Even nowadays, numerous mature technical mitigation options exist which taken together allow for deep GHG emission reductions in the energy sector that are compatible with the 2°C goal of the Copenhagen Accord. Moreover, anticipated advances will continuously expand the solution portfolio over time [7.5, 7.12].

The global technical potential of many of the mitigation options will not limit continued growth in the use of low carbon technologies. However, in the longer term, technical potentials indicate a limit to the contribution of some individual options at higher market penetration levels or at certain sites [7.4].

Various factors such as costs, sustainability concerns, public acceptance as well as system integration and infrastructure issues may constrain the deployment pace and level of some individual low carbon options before technical potential limits are reached [7.6, 7.8, 7.9, 7.10].

Infrastructure and integration issues, which vary by mitigation technology, are not technically or economically insurmountable. However, they must be carefully addressed in energy supply planning and operations to ensure reliable and affordable energy supply [7.6].

FAQ 7.2: Is there a single best solution to achieve deep emission reductions in the energy sector?

There are many potential technology options that can facilitate the de-carbonization of energy supply systems. The mitigation portfolio finally selected will depend on various factors including technology, policy, and social choice [7.5, 7.12].

The available mitigation technologies are in various stages of technical maturity. In addition, they have varying costs and different regional potentials, so that the best solution set is uncertain, will vary regionally and over time, and will be impacted by various societal preferences and decisions – there is no single best solution [7.4, 7.8, 7.9, 7.10, 7.12].

FAQ 7.3: Is it necessary to introduce specific policies in the energy sector in order to achieve a transition to low GHG concentrations?

Without intervention, energy systems way will not show a transition to low GHG concentrations. Specific climate protection policies will be necessary in order to achieve that goal [7.10, 7.11, 7.12].

A number of barriers might constrain the use of mitigation technologies, requiring various policies to encourage deployment while maximizing benefits and minimizing costs/concerns. There are multiple co-benefits from the use of mitigation technologies in the energy supply sector, but also a variety of societal and environmental risks that should be accommodated in policy-making. The co-benefits and risks vary by technology and its use [7.8, 7.9, 7.10].

Energy systems are highly path dependent: short term policy decisions and investments will have a large impact on long term mitigation pathways. Learning technologies, like most renewable energies, for instance might benefit from market introduction programs and associated cost reductions. In addition, the availability of CCS can affect the nature of the energy system in a climate constrained world. If CCS is available, systems with negative emissions from bioenergy CCS and continued fossil fuel use would be feasible; if it is not available, it implies greater deployment of renewables, a phase out of coal use and a smaller energy system [7.8, 7.11, 7.12].

Bioenergy annex: Climate effects, mitigation options, and potential

[TSU note: Bioenergy is a topic that is dealt with in a series of chapters. The synthesis of the various findings has been tentatively provided as an annex to chapter 7. It will be integrated into the body of an appropriate chapter in subsequent drafts. Its final placement is currently under discussion.]

Bioenergy Annex compiled by the bioenergy cross-cutting group: *Felix Creutzig, N. H. Ravindranath, Göran Berndes, Simon Bolwig, Helena Chum, Esteve Corbera, Oswaldo Lucon, Omar Masera, Helmut Haberl, Richard Plevin, Alexander Popp, Steven Rose, Pete Smith, Anders Stromman, Sangwon Suh*

Bioenergy is a versatile form of energy, which can be deployed as biomass power, process heat, liquid fuels gaseous fuel and heat energy for cooking (Fig.1). Bioenergy is subject to climate effects to varying degree, many of them associated with land use. Land use for bioenergy can only be understood in relation to other functions of land including food production, biodiversity, water, nature protection (see Ch. 11), and rural livelihoods. Success of bioenergy for climate mitigation response hinges crucially on sustainable land, water, and other resources management and rapid technological improvements, especially in biomass production and land management. Among all bioenergy applications, first generation biofuel production, especially from starch crops, is most associated with controversies around adverse land use impacts. High productivity sugarcane crops producing multiple products have shown higher sustainability profiles but are nonetheless subject to debates about land-use change. Much ground has been covered in the IPCC's Special Report on Renewable Energy Resources and Climate Change Mitigation (SRREN) (Chum et al., 2011) and multiple chapters of the Global Energy Assessment (2012). This crosscut chapter overviews direct (section 1) and indirect (section 2) climate effects of using terrestrial biomass as a primary resource for bioenergy. Some harmful climate effects have been observed for many presently deployed primary resources of bioenergy. But advanced technologies and management practices, together with sustainability practices and indicators, offer the potential to avoid or minimize detrimental effects and produce climate change mitigation and other environmental and social benefits. Hence, this chapter will then provide an overview of pathways, technologies and land management practices that enable bioenergy deployment with net GHG benefits, specifying possible potential of such options (section 3). A sustainable development perspective focuses on rural livelihood, complementing the dual objectives of climate change mitigation and energy deployment with a third goal (section 4). Understanding bioenergy's aggregated role in climate change mitigation requires a reconciliation of global long-term climate mitigation models, near-term bottom-up observations and models on multiple climate effects, studies on rapidly evolving and competing technologies, and sustainable development (section 5). Specific conversion technologies will be discussed in the sectoral chapters.

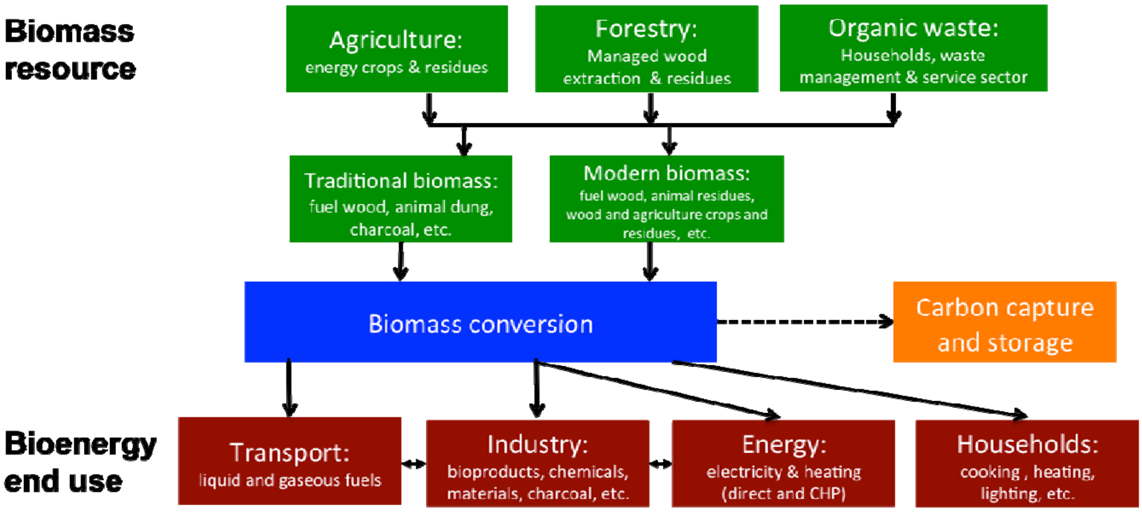

Figure 7.30. Bioenergy pathways.

7.A.1 Direct climate effects of bioenergy systems

Production of bioenergy from biomass sourced from agriculture and forested land or from urban residues can affect the climate system through many complex mechanisms. It is common to distinguish between geochemical (GHG's) and geophysical effects (e.g. albedo and evapotranspiration).

Climate neutrality assumption: Bioenergy systems are often assessed under the assumption that the CO_2 released during the combustion of bioenergy is climate neutral, as the carbon in the CO_2 emission during combustion is originated from atmospheric CO_2 in the first place (Rabl et al., 2007; Ester van der Voet et al., 2010), e.g. also in the global integrated assessment models presented in previous IPCC reports (Creutzig et al., 2012a). In the recent years it has been pointed out that carbon neutrality is not equivalent to climate neutrality (Möllersten & Grönkvist 2007; Searchinger et al. 2009; Johnson 2009; Courchesne et al. 2010). Integrated bottom-up analyses are increasingly coherently considering most or all relevant climate effects (Hillier et al. 2009), but remain spatially and sectorally limited.

Stock dynamics: Taking biomass out of forests induces non-negligible stock dynamics (Schlamadinger and Marland, 1996; Hudiburg et al., 2011; McKechnie et al., 2011). The increased outtake for bioenergy purposes causes a period of increased CO_2 emissions, carbon debt, compared to leaving the forest standing and using fossil fuels (Marland and Schlamadinger, 1997; Fargione et al., 2008; Hudiburg et al., 2011). This period is specific to the individual systems, but for forest based bio-electricity substituting coal, payback times are shorter than those for transportation biofuels replacing gasoline or diesel. The use of easily decomposable residues and wastes for bioenergy can produce GHG benefits even in the near term (Zanchi et al., 2011), whereas the removal of slowly decomposing residues reduces soil carbon accumulation at a site, and can result in net emissions from some residue-based bioenergy systems (Repo et al., 2011). A related problem is the "baseline error" of neglecting the alternative fate of biomass and of the land on which biomass is produced (Searchinger, 2010; Haberl et al., 2012; Schulze et al., 2012). Such dynamics will be discussed in the section on systemic effects (section 2).

Forcings of biogenic CO_2: While net biogenic CO_2 fluxes associated with bioenergy from regenerative biomass generally may be assumed to be zero over the rotation period, the time distribution of the fluxes generate temporary climate forcings depending on the particular biomass regrowth conditions (Cherubini et al. 2011a). The climate impacts of biogenic CO_2 emissions can be characterized in terms of radiative forcings and associated metrics (e.g., GWP and GTP) consistent with other GHG's. GWP of biogenic (from biological sources) CO_2 emissions is higher with increasing rotation times and lower with increasing time horizon (Cherubini, Peters, et al., 2011; Cherubini, Strømman, et al., 2011; Bright et al., 2012). While a pulse of fossil CO2 emissions generates instantaneous warming for millennia, a biogenic CO2 emission pulse generates radiative forcings in timescales equivalent to the regrowth period (Cherubini et al., 2012). The instantaneous (not the cumulative) global surface temperature change caused by biogenic CO2 emissions from regenerative biomass therefore asymptotically tends towards zero over time.

Nitrous oxide (N_2O) emissions: For first-generation crop-based biofuels, as with food crops (see Chapter 11), the release of N_2O from agricultural soils is the single largest contributor to the life cycle GHG emissions for first-generation crop-based biofuels, and one of the largest contributors across many biofuel production cycles (Smeets et al., 2009; Hsu et al., 2010). Emission rates can vary by as much as 700% between different crop types for the same site, fertilization rate and measurement period (Don et al., 2012). Even for the same crop, there is a significant regional variation in N fertilizer application rates (Y Yang et al., 2012). Increased estimates of N_2O emissions alone can convert some biofuel systems from apparent net sinks to net sources (Crutzen et al., 2007; KA Smith et al., 2012). Improvements in nitrogen use efficiency and nitrogen inhibitors can substantially reduce emissions of N_2O (Robertson and Vitousek, 2009). Other non-first-generation bioenergy crops, such as short rotation coppice and Miscanthus, require minimal or zero N fertilization and can reduce GHG emissions relative to the former land use where they replace conventional food crops (Clair et al., 2008), though N_2O and CO_2 emissions from indirect land use change also need to be considered (see below).

Geophysical effects: Forest and agricultural operations also interact with the climate system through changes in surface reflectivity (i.e., albedo), surface roughness, evaporation and other factors influencing fluxes of energy and water between land and atmosphere (Betts 2001; Marland et al. 2003; Betts et al. 2007; Bonan 2008; Jackson et al. 2008; (Anderson-Teixeira et al., 2012)). Radiative forcing of some of these factors (e.g., evapotranspiration and surface roughness) cannot currently be directly quantified (Claussen et al., 2001; Pielke et al., 2002; Davin et al., 2007; Betts, 2011). Albedo is found to be the global dominant direct biogeophysical climate forcing resulting from land use, especially in areas affected by seasonal snow cover (Betts, 2000; Claussen et al., 2001; Bala et al., 2007). The resulting radiative forcings can be comparable and even stronger than those of CO2 fluxes associated with afforestatation or deforestation (Randerson et al., 2006; Bala et al., 2007; Bonan, 2008; Betts, 2011). For example, the global warming disadvantages of slow rotations for forest biomass are partially and sometimes more than offset by cooling from increased reflectivity by snow at logging sites (Bright et al., 2011, 2012).

7.A.2 Systemic effects of bioenergy systems

The net effect of harnessing the bioenergy potential for climate change mitigation depends on (1) the difference between the estimated climate effects of the biomass system harvested for energy and the use of the land in its absence; and (2) the fossil energy system that the bioenergy displaces. Bioenergy systems interact with global markets for agricultural commodities and in forest bioenergy systems depend on the extent of active forest management and geophysical effects (section 1) as well as markets. Each of these interactions can have important consequences for global GHG emissions, which need to be integrated with the LCA standard methodologies. To account for time dependent phenomena, total radiative forcing calculations need to be used to avoid misleading results (section 1).

Land use change: "Indirect land use change" (ILUC) occurs when bioenergy crops displace other crops, triggering the conversion to cropland of lands, somewhere on the globe, to replace some portion of the displaced crops (Searchinger et al. 2008; Hertel et al. 2010; Delucchi 2010). Biospheric C losses associated with LUC from some bioenergy schemes can be, in some cases, more than hundred times larger than the annual GHG savings from the assumed fossil fuel replacement (Gibbs et al. 2008; Chum et al. 2011). Some positive induced land-use changes can also occur: Coproducts of bioenergy can displace additional feedstock production thus decreasing the net area needed (e.g., for corn, Wang et al. 2011; for wheat, (G. Berndes et al., 2011), reducing the net disbenefit of ILUC. As market-mediated emissions are unobservable, the magnitude of these effects must be modeled (Nassar et al., 2011) raising important questions about model validity and uncertainty (Liska and Perrin, 2009; Plevin et al., 2010; Gawel and Ludwig, 2011; Khanna et al., 2011; Wicke et al., 2012). A large number of studies have examined this question in the past four years using economic models (e.g., Searchinger et al. 2008; Hertel et al. 2010; Dumortier et al. 2011; Havlík et al. 2011; Taheripour et al. 2011; Chen & Khanna 2012; Timilsina et al. 2012; Bento et al.), simpler approaches based on historical data and assumptions (Fritsche et al., 2010; Overmars et al., 2011), and statistical analyses of historical data (Arima et al., 2011; Seungdo Kim and Dale, 2011; Wallington et al., 2012). The modeling studies all find positive emissions from ILUC, though the estimates span a wide range, and negative ILUC values are theoretically possible (Njakou Djomo and Ceulemans, 2012).

Owing to the challenges of modeling global economic behavior, the location and magnitude of ILUC, and thus the GHG emissions induced by crop-based biofuels, are highly uncertain (Plevin et al., 2010; Khanna et al., 2011; Wicke et al., 2012). The estimated magnitude of ILUC emissions also varies under alternative policy scenarios and assumptions about fuel prices (Bento et al., In review; Khanna et al., 2011), and is highly sensitive to the treatment of emissions over time (Plevin et al., 2010). Studies to date have mostly examined ILUC in the context of liquid biofuels, but ILUC is equally an issue for biopower and biomaterials (Weiss et al., 2012). Producing biofuels on degraded land, from wastes and sustainably harvested residues, and replacing first generation biofuel feedstocks with lignocellulosic crops (e.g., grasses) can avoid ILUC (Davis et al. 2012; Scown et al. 2012).

Fossil fuel displacement: [THIS SECTION MIGHT BE MOVED TO A PLACE WHERE REBOUND EFFECTS ARE DISCUSSED SYSTEMATICALLY] Economists have criticized the assumption that each unit of bioenergy replaces an energy-equivalent quantity of fossil energy, leaving total fuel use unaffected (Drabik and de Gorter, 2011; Rajagopal et al., 2011; Thompson et al., 2011). Increasing energy supply through the production of bioenergy affects energy prices and demand for energy services, and these changes in consumption also affect net global GHG emissions (Hochman et al., 2010; Rajagopal et al., 2011; X Chen and Khanna, 2012). The sign and magnitude of the effect of increased biofuel production on global fuel consumption is uncertain (Thompson et al., 2011) and depends on how the world responds in the long term to reduced petroleum demand in regions using increased quantities of biofuels, which in turn depends on OPEC's supply response and with China's and India's demand response to a given reduction in the demand for petroleum oil in regions promoting biofuels, and the relative prices of bio- and fossil fuels (Gehlhar et al., 2010; Hochman et al., 2010; Thompson et al., 2011). Notably, if the percentage difference between an alternative fuel and the incumbent fossil fuel is less than the percentage rebound effect (the fraction *not* displaced, in terms of GHG emissions), a net *increase* in GHG emissions will result from promoting the alternative fuel, despite its nominally lower rating (Drabik and de Gorter, 2011). Estimates of the magnitude of the petroleum rebound effect cover a wide range and depend on modeling assumptions. Two recent modeling studies suggest that biofuels replace about 30-70% of the energy equivalent quantity of petroleum-based fuel (Drabik and de Gorter, 2011; X Chen and Khanna, 2012), while others find replacement can be as low as 12-15% (Bento et al., In review; Hochman et al., 2010) Under other circumstances, the rebound can be negative, resulting in greater than 100% displacement (Bento et al., In review). The rebound effect is always subject to the policy context, and can specifically avoided by cap and pricing instruments.

In summary, a large body of recent research indicates a highly uncertain effect of system-wide GHG emissions induced by bioenergy deployment depending on the impact on land-use and the efficiency of the bioenergy production system. The sign of the net effect is uncertain in many cases, but is almost surely negative for some first generation systems (M. A. Delucchi, 2010).

7.A.3 Bioenergy mitigation options

This section will explore opportunities that are likely to provide significant GWP benefits, many of them by reducing land-use competition. These opportunities cover land management, conversion pathways, end-use, and negative emission technologies.

7.A.3.1 Conversion and end-use technologies

End-use technology in households (improved cookstoves): Around 2.7 billion people relied on traditional biomass in 2008, a number projected to increase to 2.8 billion by 2030 (Chum et al., 2011). Global biomass consumption as fuel is estimated between 37-43 EJ in 2008, roughly 15% of global energy use, most of which is used for domestic cooking and heating, with only 10-20% conversion efficiency. Changing to cleaner fuels and more efficient technologies reduces fuel consumption by 50% (Chum et al., 2011) and lowers the atmospheric radiative forcing, reducing both black carbon and CO_2 emissions by 60% in successful case studies (Chum et al., 2011). Co-benefits accrue from improved indoor and local air quality, and time savings for those collecting fuelwood, typically women and children (J. Sathaye et al., 2011). Heterogenity in cultures and consumer preferences lead to highly variable outcome of improved cookstove programs; such heterogenities must be addressed to secure successful adaptation of improved cook stoves (Masera et al., 2000; Jeuland and Pattanayak, 2012).

End-use across sectors: Using biomass for electricity and heat, especially co-firing of woody biomass in the near term and also large heating systems coupled with networks for district heating, and biochemical processing of waste biomass, can be the most cost-efficient and effective biomass applications for GHG emission reduction in modern pathways (Sterner and Fritsche, 2011). Powering electric cars with electricity from biomass has higher land-use efficiency and lower GWP effects than the usage of bioethanol for road transport across a range of feedstocks, conversion technologies, and vehicle classes (JE Campbell et al., 2009; Schmidt et al., 2011), though costs are likely to remain prohibitive in the short-term (Schmidt et al., 2011). Biofuels in aviation which lacks low-carbon intensity fuel options (see Chapter 8.3) can be from the best option for GHG emissions reductions within aviation, but costs need to be reduced significantly (Chum et al., 2011). Many pathways can lead to fuels for aviation; and the development of fuel standards has started, and biofuels have been tested in commercial domestic and transatlantic flights (REN21, 2012). Value added bioproducts are also under development and will both complement and compete with feedstocks for advanced biofuels. Integrated biorefineries continue to be developed; for instance, 10% of the ethanol or corresponding sugar stream going goes into bioproducuts in Brazil (REN21, 2012).

Negative emission technologies: Carbon capture and storage (CCS) of CO_2 emissions from biomass could produce negative emissions if CCS can be successfully deployed. More offsets could be achieved by using crops that improve soil carbon.

Production and conversion technologies: Yield improvements can possibly increase output per area by 20-50% by 2030 for many crops, with most improvement potential in sub-Saharan Africa, Latin America, Eastern Europe and Central Asia where advanced techniques are not yet fully adapted (Chum et al., 2011). Advanced management practices coupling sensors, GIS, and information technologies in planting, fertilizing, and drip irrigation are projected to increase yields of agricultural crops in developed countries (Deutsche Bank Advisers, 2009). Aquatic biomass, i.e. microalgae can offer productivity levels above those of terrestrial plants and can avoid land-use conflicts. Its deployment depends on technological breakthroughs, and its commercial potential and the co-use of products for food, fodder and fuel markets (Chum et al., 2011). Similarly, lignocellulosic feedstocks produced from waste, residues, or on land unsupportive of commercial agriculture do not compete directly with food production. In addition, lignocellulosic sources can be bred specifically for energy purposes, and can be harvested. Various conversion pathways are in R&D, near commercialization, or early deployment stages in several countries (see 2.6.3 in Chum et al. 2011). Biofuels include ethanol and biodiesel and a variety of fuels of composition similar to gasoline, diesel and jet fuels, fully compatible with the petroleum infrastructure. Depending on feedstock and conversion process, cellulosic bioenergy can be associated with significant GHG emissions (e.g. corn stover excessive removal associated with soil emissions) or quite low GHG emissions (e.g. SC Davis et al., 2012; Gramig et al., submitted).

7.A.3.2 Primary resource management

Organic waste and residues: Organic waste and residue flows in the food and forestry sectors represent a potential with few technical constraints on rapid ramp-up for several categories such as animal residues, straws, wood processing by-flows. Primary residues resulting from crop harvest and forestry operations have varying collection and processing costs depending on quality and how dispersed they are. Secondary residues – e.g., sawdust and black liquor in forest industry, rice husk and other food processing waste – often have the benefits of not being dispersed and having relatively constant quality. Organic waste may be dispersed and also heterogeneous in quality but the health and environmental gains from collection and proper management through combustion or anaerobic digestion can be significant. There are large regional variations in the potential from residues, with global estimates ranging from 25 to more than 200 EJ/yr in 2050 (Table 1 - Ch. 11). Negative impacts from the use of residues include excessive removals leading to biodiversity losses and soil degradation, GHG emissions from the displacement of earlier uses (e.g., animal feeding) are displaced or if soil productivity losses require compensating extended/intensified cultivation. Overcoming reduced climate benefits due to long distance transport are biomass densification and storage strategies that enable cost effective collections over longer distances (Chum et al., 2011; U.S. DOE, 2011)

Forestry: This refers to the net annual increment in forests available for wood supply not needed for the production of conventional forest products (see carbon stock dynamics in section 1 for a discussion on the baseline). Biomass potential estimates range from 0-100 EJ/yr in 2050. Realizing higher-end potentials for this category implies increasing the forest output to several times the present global industrial roundwood production, drastically extending the share of global forests that are managed for high biomass output and would requires strong simultaneous efforts to conserve biodiversity, other environmental objectives, and aesthetic/recreation values. The climate outcome depends mostly on carbon stock dynamics, albedo and non-CO_2 GHG emissions and can be both net positive and net negative (Cherubini et al., 2012).

Agriculture: Dedicated annual and perennial energy crops (such as sugarcane, maize, poplar, and miscanthus) can be grown on current or abandoned agricultural land or on degraded lands. The specific energy potential of bioenergy in or degraded lands is difficult to estimate as there is few accurate information on the extent to which these lands are utilized for other purposes, particularly in developing countries (e.g., extensive livestock systems). Investor interest often focuses on the best land in terms of water availability and irrigation potential, soil fertility, proximity to markets or availability of infrastructure, which is not considered to be marginal land (Cotula, 2012). The deployment of large-scale bioenergy systems in degraded lands need then to acknowledge native people´s alternative or traditional uses of the land (see section 4). The potential critically depends on *land availability*, which depends in turn on competing land demand (infrastructure, food, feed and fiber production) and restrictions (e.g., biodiversity conservation) and on what *yield levels* can be achieved. Yield level depends on both the quality of available land (climate, soil, topography) and the land use/technology practices that are implemented. Intensification in agriculture for food/feed production and efficiency in the food sector modify land availability for bioenergy plantations (Stehfest et al. 2009; Popp et al. 2011). Win-win synergistic strategies, such as multiple use of biomass, improve post-harvest biomass use efficiency; wise integration of bioenergy into agriculture and forestry landscapes including watersheds can increase total biomass output from land and also mitigate several of the well documented consequences of present day agriculture and forestry (Chum et al. 2011; see also Chapter 11). The share of animal food products in human diets is a critical determinant of land demand, given the large land requirements associated with livestock production (both cropland and grazing land) (Ch. 11).

7.A.4 Sustainable development and equity

Large-scale bioenergy deployment has a range of implications for sustainable development and equity beyond GHG and ILUC-related impacts. For example, increased production of biofuel will have negative implications on biodiversity due to i) habitat conversion and loss, ii) agricultural intensification, iii) invasive species, and iv) pollution (Sala et al., 2009). Food, soil and water constraints are systematically covered in Chapter 11. This section indicates the relevance of including livelihood itself into comprehensive assessments, in addition to GHG effects, costs and potentials (Creutzig et al. 2012b).

First, it is important to acknowledge that future generations' access to ecosystem services is diminished when forest or smallholder land is converted to large-scale mono-cropping of energy crops, or when residues are harvested at unsustainable levels (intergenerational distribution).

Second, sustainable development and equity require as a precondition the recognition of all affected and interested parties (intra-generational recognition), which in turn implies to accept that the land proposed for bioenergy production (or for the harvesting of residues) may currently be in use by both formal and informal user groups and individuals, including e.g. nomadic pastoralists or informal fuel wood and non-timber resource collectors, or may be actually subject to claims by landless peasants and communities. Subsequently, the development of biofuels requires including all potentially affected stakeholders in decision-making (i.e. intra-generational procedural fairness), specifically on the establishment of large-scale feedstock plantations impacting present and future communities (J Hall et al., 2009; German et al., 2011) and on the development of biofuel policies with interregional spill-overs (Banse et al. 2008; Fabiosa et al. 2010).

Third, it is important to consider the distributional implications of biofuels deployment (i.e. intra-generational distribution of costs and benefits). It can be economically beneficial, e.g. by raising and diversifying farm incomes and increasing rural employment through production biofuels to domestic (Gohin, 2008) or export (Arndt et al., 2011) markets. However, biofuels deployment can also translate into reductions of time invested in on-farm subsistence and community-based activities, thus translating into lower productivity rates of subsistence crops and an increase in intra-community conflicts as a result of the uneven share of collective responsibilities (Mingorría et al., 2010). The establishment of large-scale biofuels feedstock production can cause smallholders, tenants and herders to lose access to productive land, while other social groups such as workers, investors, company owners, biofuels consumers, and populations who are more responsible for GHG emission reductions enjoy the benefits of this production (van der Horst and Vermeylen, 2011). This is particularly relevant where large areas of land are still unregistered or are being claimed and under dispute by several users and ethnic groups (Dauvergne and Neville, 2010). Furthermore, increasing demand for first-generation biofuels is partly driving the expansion of crops like soy and oil palm in countries like Brazil and Argentina, which in turn contributes to promote large-scale agribusinesses at the expense of family and community-based agriculture (J Wilkinson and Herrera, 2010).

Labelling, certification and other information-based instruments to promote ‘sustainable’ biofuels and avoid some of the above mentioned impacts on sustainable development and equity have been developed in recent years (Janssen and Rutz, 2011; Scarlat and Dallemand, 2011). Nevertheless, certification approaches have been scrutinized and challenged on the basis of a lack of legitimacy in their design and a deficient on-the-ground implementation (Partzsch, 2009; J Franco et al., 2010).

7.A.5 Integrated assessment

Altogether, by 2050, global bioenergy primary energy could contribute 20 to 250 EJ (full range of scenarios or 10 to 30% of total primary energy) and by 2100, 10 – 330 EJ (20 to over 35% of total). The end-use disposition of bioenergy is unclear, mostly due to uncertainties about relative penetration of the various technology options and their costs over time. The majority of global bioenergy production is projected in non-OECD countries. Bioenergy’s share of total electricity and liquid fuels can be significant. Bioenergy availability and deployment affects abatement costs and emissions trajectories.

In the IPCC SRREN scenarios, bioenergy is projected to contribute 120 to 155 EJ/yr (median values) to global primary energy supply by 2050 (50 EJ in 2008). Traditional biomass demand is steady or declines in most scenarios from 30EJ/yr. The transport sector increased nearly tenfold from 2008 to 18-20 EJ/yr while modern uses for heat, power, combinations, and industry increase by factors of 2-4 from 18 EJ in 2008 (e.g., Fischedick et al. (2011). Many scenarios coupled bioenergy and CCS mitigation. The GEA (2012) scenarios project 80–140 EJ by 2050, including extensive use of agricultural residues and second-generation bioenergy to mitigate adverse impacts on land use and food production, and the co-processing of biomass with coal or natural gas with CCS to make low net GHG-emitting transportation fuels and or electricity. The 2010 IEA model projects a contribution of 12 EJ/yr (11%) by 2035 to the transport sector, including 60 % of advanced biofuels for road and aviation. Bioenergy supplied 5% of global power generation, up from 1% in 2008. Modern heat and industry doubled their contributions from 2008 (IEA, 2010h).

The size and regional distribution of future biomass supply cannot be estimated accurately as both depend on a number of inherently uncertain factors, including 1) population, urbanization and economic/technology development; 2) how these translate into food, fibre, fodder, and land demand; 3) climate change impacts on future land use; 4) biodiversity and nature conservation constraints; and 4) consequences of land degradation and water scarcity (Chum et al., 2011). Organic waste and residue flows in agriculture and forestry can become an important source of biomass for energy, both in the near term and in the longer term. Residue extraction in agriculture and forestry is bounded by opportunity costs and the requirement to maintain biodiversity, soil quality and ecosystem health, indicating the need of active forest management to increase forest growth. In the absence of growth-enhancing measures, increased biomass extraction reduces forest C stocks. Biomass from dedicated energy cropping systems has a significant supply potential. However, estimates in the range of several hundred EJ/yr presume very favourable productivity development in agriculture, especially concerning livestock production and avoidance of adverse land-use change. Share of animal food products in human diets is a critical determinant, given the large cropland and grazing land requirements to support livestock production. Grasslands and marginal/degraded lands may additionally support substantial bioenergy production, but negative impacts on subsistence farming and equity, biodiversity, and water availability are likely to limit this potential.

The climate change mitigation effect of bioenergy deployment is highly uncertain and dependent on the implementation of global land use policies (e.g., GBEP 2011). Two divergent scenarios of future bioenergy deployment can be imagined. In the optimistic scenario, lignocellulosic feedstock, multifunctional systems and management practices help to minimize negative impacts (see section 3). Relevant mitigation potential is realized, conditional on globally effective policies managing soil and forest carbon stocks (e.g. a price on GHG from land use; strict forest protection), considerable technological advancement, and good land management practices are adapted to various regions and disseminated rapidly. Under those conditions, and assuming effectively climate neutrality of bioenergy, many climate stabilization modeling suggests that bioenergy could play a significant, but uncertain, role in energy system transformation for long-run climate management (Chapter 6.2.8). The climate stabilization modeling further shows an increasing dependence on bioenergy with more stringent climate stabilization targets, both in a given year as well as earlier in time. Coupling fermentation gaseous streams of mostly CO_2 with CCS could be very helpful (and valuable) for getting to lower targets (especially in later half of century). Bioenergy could be the dominant land-related mitigation strategy.

In the more skeptical scenario, global policies restricting adverse land-use change remain more limited. The potential to utilize biomass both sustainably and in a commercial viable manner at large scales might also be compromised. For example, commercial bioenergy farmers may not choose to grow bioenergy crops on degraded land, as it is likely to be relatively unprofitable (Johansson and Christian Azar, 2007). Similarly, maintenance of biodiversity may be difficult with large-scale bioenergy deployment (Sala et al., 2009). In such a scenario, a considerable fraction of economically viable first generation biofuels continue to be deployed, and total GHG balances are mostly undesirable. For example, unfavorable land-use change associated with bioenergy deployment can lead to very high GHG emissions (possibly exceeding 500 Gt) (Melillo et al. 2009; Wise et al. 2009; Creutzig et al. 2012a). With increasing scarcity of productive land, the growing demand for food and bioenergy may incur substantial LUC causing high GHG emissions and/or increased agricultural intensification and higher N_2O emissions unless wise integration of bioenergy into agriculture and forestry landscapes occurs (M. A. Delucchi, 2010). Large-scale energy crop production will likely increase competition for land, water, and other inputs, affecting food security, deforestation, water use and biodiversity loss.

To better explore the solution space within the range of these two scenarios, climate change stabilization modelers need to collaborate closely with those developing bottom-up assessments , covering crucial dynamics such as capturing carbon stock dynamics, albedo or N_2O emissions under imperfect climate policies (Creutzig et al. 2012a).

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