Chapter:	9	
Title:	Renewable energy in the context of sustainable development	
(Sub)Section:		
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Remarks:	Second Order Draft rewrite	
Version:	03	
File name:	SRREN_Ch09_SOD_rewrite_final.doc	
Date:	24-Nov-10 13:07	Time-zone: CET Template Version: 13

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Chapter 9 has been allocated a total of 68 pages in the SRREN. The actual chapter length (excluding references & cover page) is 96 pages, a total of 28 pages over target. Government and expert reviewers are kindly asked to indicate where the chapter could be shortened in terms of text and/or figures and tables.

All monetary values provided in this document will need to be adjusted for inflation/deflation and then converted to US$ for the base year 2005.

Chapter 9: Renewable Energy in the Context of Sustainable Development

CONTENTS

EXECUTIVE SUMMARY

Given the heavy reliance of modern societies on fossil fuels, any proposed transformation pathway must be carefully analyzed for feasibility. Both the technological and the economic analyses of renewable energy (RE) in other chapers of this report need to be embedded in the broader context of sustainable development and Chapter 9 extends to include the latter in its assessments. Since the exact nature of sustainable development (SD) is subject to a plethora of definitions and perspectives, the chapter attempts to organize the available literature in a consistent way by choosing four broad criteria. By drawing on different quanitative and qualitiative methodologies, this literature suggests that socio-economic benefits are usually higher and environmental impacts lower with an increased use of renewables, but there are important exceptions to consider. An initial assessment of indicative information available from current IAMs generates important insights about the potentially important future role of RE for SD but also discloses some shortcomings and highlights the need for the inclusion of additional boundaries (e.g. environmental) and more complex energy system models that can represent specific local conditions and variability. Discussing barriers to and opportunities of RE in the context of SD, it is shown how well integrated RE policies and deployment can contribute to positive and multi-dimensional progress for sustainable development.

Linking RE and SD practices requires both an integration of aspects and impacts from different energy technologies, considering also the possibility of non-substitutability between natural and man-made capital. The many different concepts of SD emphasize the distinction between the weak (substitutability between natural and man-made capital) and strong (non-substitutability, either for production purposes or for the intrinsic value of natural capital) sustainability paradigms, as well as how REs relate to these paradigms. REs, as a fossil fuel replacement strategy, can be linked to weak sustainability, but may have their own social, economic and environmental impacts that this chapter is asked to assess. However, attempts to amalgamate various types of indicators into one overall score have shown uncertainties so high that they preclude decision-making. This chapter therefore structures the available literature around four broad criteria to define SD with respect to RE: sustainable social and economic development, increased energy access, enhanced energy security and reduced environmental impacts. Drawing on different methodologies – based on existing literature – the chapter assesses the performance of RE with respect to these criteria according to SD indicators that are introduced (9.2).

Countries at different levels of development have different incentives to advance RE. Despite the goal of developing and transition economies to limit their energy use by adopting modern and highly efficient (energy) technologies (and thus ‘leapfrog’ resource-intensive development stages), the more immediate incentives to advance RE deployment often include, providing affordable and reliable access to energy for the poorest (particularly women), creating employment opportunities and reducing costs of energy imports. Even if the hypothesis for industrialized countries holds that economic growth can continue without increasing energy consumption, economies based on fossil fuels face a number of serious sustainability concerns, including environmental impacts and energy security issues. Their incentive to advance RE thus includes reducing GHG emissions to mitigate climate change, enhancing energy security and actively promoting structural change in the economy (9.3.1-9.3.3).

Environmental impacts are usually lower with the use of renewables, but there are important exceptions to consider. Despite its limitations life cycle assessment (LCA) is an important tool for comparison of technologies: For electricity generation, a LCA literature review suggests that GHG emissions per unit of electrical output from renewables are in general considerably less than those from non-renewable resources. For transportation fuels, studies suggest that both existing and next-generation biofuels have lower GHG emissions compared to fossil fuels, although with wide ranges (9.3.4.1). Impacts on *water* occur in terms of quantity and quality: While non-thermal RE technologies use relatively little water, thermo-electric power generation, renewable or not, consumes significant amounts of water. Water is also required for bioenergy, with impacts highly dependent on the crop, site and production methods utilized. *Water Pollution* is an important issue for comparison, considering both normal operations and accidents in different stages of their life cycle (9.3.4.2). *Local air pollutants* have impacts that depend on factors like concentrations, toxicity and pathways of substances. Most RETs and nuclear power have only minor upstream emissions. All RETs (except biomass in some cases) have advantages over combustion-based technologies concerning air pollution (9.3.4.3). *Indoor air pollution*, mainly due to the use of fuelwood and other traditional solid fuels in primitive systems, is a major health problem at global scale that needs improved technologies. Other impacts are related to *nuisances* (e.g. noise) and to *toxic releases* (e.g. spills) (9.3.4.4). *Land use changes*, direct and indirect, may have significant adverse impacts mainly from unsustainable bioenergy deployment, although the indirect LUCs are complex and therefore very difficult to quantify. Land use has connected *impacts on ecosystems and biodiversity* (9.3.4.4/5). RETs exhibit distinctly lower fatality rates than fossil chains; comparable to hydro and nuclear in highly developed countries. Damages caused by severe accidents in the energy sector are significant, although mostly still small in comparison to large natural disasters or the expected consequences of climate change and air pollution (9.3.4.7).

The scenario literature that describes global pathways for RE deployment considering climate targets (e.g. IAMs) has only begun to incorporate SD aspects into the models and thus offer limited results. This is because IAMs were originally designed to assess energy portfolios of fairly large world regions and emissions trajectories implied by changes in those energy portfolios over time. Even though there has been some progress recently in the models, the IAMs provide little insights about distributional issues within regions or countries which would be crucial for the assessment of SD impacts, such as rural-urban differences. For example, models thus do not give a clear answer whether or not renewable energies might play a central role for the electrification of poor or of rural areas with respect to off-grid facilities (9.4.2). Some conclusions can still be drawn from IAMs with respect to SD aspects: Constraining the implementation of renewable energy increases mitigation costs considerably, thus leading to lower GDP levels in the future and to difficulties at achieving low stabilization targets (9.4.1). IAMs also suggest that RE help to diversify the energy supply sources despite the fact that the most flexible fossil fuels (e.g. oil) will be difficult to substitute independent of the climate target mainly due to the inflexible transport sector (without electrification). The future role of biomass in the transportation sector is also determined by the availability of CCS, which in combination with biomass can produce negative emissions in other sectors that might generally ease the transformation costs (9.4.3). Concerning environmental impacts, IAMs might well be suited to include some of the most important indicators in addition to GHG emissions (e.g. local air pollution, water use etc.), but available literature is scarce. Apart from the land use constraints on bioenergy deployment due to terrestrial carbon and N_2O emissions, no renewable energy implications can yet be clearly spelled out (9.4.4). To derive more valid conclusions about the interaction of renewable energy deployment and sustainable development pathways in a global context, the scenario literature will have to take into account some of the research gaps that are elaborated on in this chapter. One area that is conceptually straightforward is to include results from LCA of material, energy and water consumption for various technologies to reach a better insight regarding their longer-term environmental impacts (9.6).

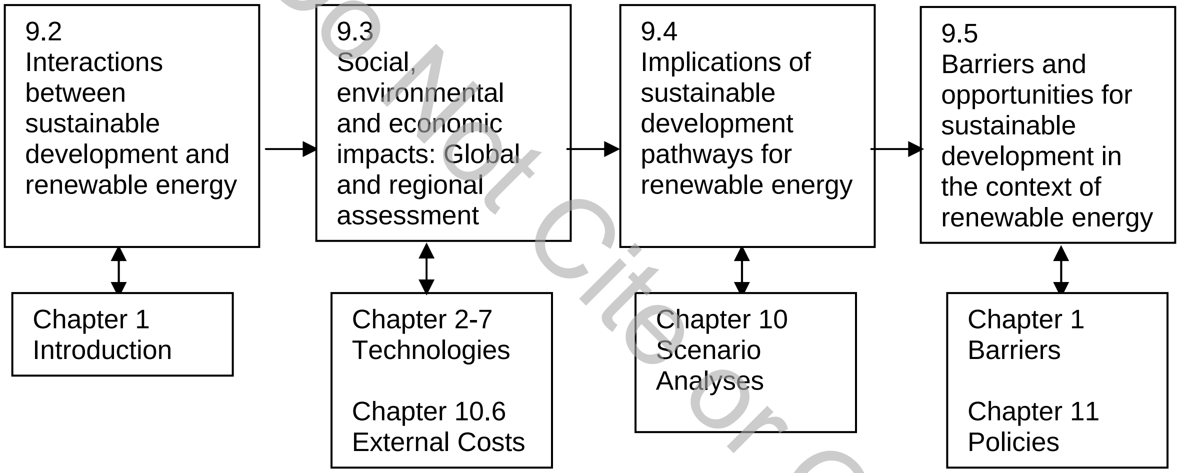
Anticipating and overcoming potential barriers to RE through clear and integrated policy implementation and planning processes allow for sustainable RE deployment taking environmental, social and economic effects explicitly into account and arriving at multi-benefit results. In the context of SD, barriers include environmental concerns and social acceptance, information and awareness barriers, as well as economic barriers. Integrating RE policy into national SD strategies (explicitly recognized at the 2002 World Summit on Sustainable Development) provides a framework for countries to select effective SD/RE strategies and to align those with international policy measures. To that end (and to realize potential leapfrogging opportunities) national SD strategies should include (i) removal of existing financial mechanisms that work against sustainable development; (ii) adaption of existing market mechanisms and (iii) introduction of new financial mechanisms that internalize environmental or social externalities in order to provide a level playing field for the different mitigation options. Since shifting to sustainable energy requires replacing a complex and entrenched energy system, as well political will and strong, sustained policies, the private sector's guidance and good practice documents may help to achieve sustainable RE deployment – taking into account local level requirements (9.5).

We can conclude that our knowledge regarding the interrelations between sustainable development and renewable energy in particular is still very limited and does not fully account for the complexity of the issue. One of the key points that emerges from the literature is that the evaluation of energy system impacts (beyond greenhouse gas emissions), climate mitigation scenarios and sustainable development goals have for the most part proceeded in parallel without much interaction. Effective, economically efficient and socially acceptable transformations of the energy system will require a much closer integration of insights from all three of these research areas. However, it is important to note that all energy technologies, especially when deployed at scale, will create environmental impacts, determined in large measure by the design and integration into local contexts. This is particularly applicable with respect to very localised impacts such as on biodiversity. Hence, integrated assessments at the global and generic level can not take the place of local evaluations and considerations and the evaluation of trade-offs. (9.6, 9.7)

9.1 Introduction

This Chapter provides an overview of the role that renewable energy can play in advancing the overarching goal of sustainable development (SD). Whereas Chapter 1 of the SRREN introduced renewable energy and made the link to climate change mitigation, Chapters 2 through 7 assess the potential and impacts of specific renewable energy technologies in isolation. Chapter 8 focuses on the integration of renewables into the current energy system, and Chapters 10 and 11 will discuss the economic costs and benefits of renewable energy and climate mitigation, and of renewable energy policies, respectively. As an integrative chapter, the present chapter assesses the role of RE from a SD perspective by comparing and reporting the SD impacts of different energy technologies, by drawing on still limited insights from the scenario literature with respect to SD goals, and by discussing barriers to and opportunities of RE deployment that are related to SD. Figure 9.1.1 illustrates the links of Chapter 9 to other chapters in the SRREN.

Figure 9.1.1 Framework of Chapter 9 and Linkages to other chapters of the SRREN.



Energy technologies, economic costs and benefits, and energy policies, as described in other chapters of this report, depend on the societies and natural environment within which they are embedded. In the context of climate change mitigation, it is clear that renewable energy will play a central role, but climate mitigation strategies must also be technically feasible and economically efficient so that any cost burdens are minimized. Knowledge about technological capabilities and models for optimal mitigation pathways are therefore important. However, sustainable development of a future energy system encompasses several additional concepts that are not typically included in, for example, life-cycle assessments (LCA) or integrated assessment models (IAMs). Thus, one key point of Chapter 9 is to point to the need for additional metrics for sustainable development that go beyond the purely technical-economic indicators that are used in the other chapters of this report.

As a consequence, this chapter provides an overview of the scientific literature on sustainable development (SD) goals and the additional boundary conditions these goals place on renewable, fossil and nuclear energy technologies. Sustainable development aspects which need to be included in future assessments to arrive at an integrated overall picture are outlined in a quantitative as well as in a qualitative and more narrative manner. However, for a comprehensive assessment of all mitigation options these criteria have to be integrated within scenarios of the future and, to the extent possible, quantitative models. As such, Chapter 9 could provide guidelines for the discussion of scenario results in Chapter 10, and guide researchers toward the important criteria that are beginning to be included in IAM analyses. A starting point in this direction is the realization that IAMs do not generally consider the results of full LCAs in their scenarios.

The following paragraphs describe the assessments carried out in the individual sub-sections of the chapter. In Section 9.2, different concepts of sustainable development and how they relate to the use of renewable energy are described. Emphasis is given to the distinction between the weak and strong sustainability paradigms, and their link to the three pillar approach of environmental, social and economic development, is addressed. To provide a conceptual framework for the discussion of renewable energy in the context of sustainable development and to organize the literature throughout the chapter, four criteria are introduced: sustainable social and economic development, increased energy access, enhanced energy security, and reduced environmental impacts. A set of indicators are presented briefly that will be used in the following sections to assess the contribution of RE to these criteria in a quantitative manner.

In Sections 9.3.1 - 9.3.3 actual indicator data that apply and quantify the conceptual socio-economic criteria of 9.2 and that describe the relationship between growth, development and energy use in general and RE in particular are presented and discussed in detail. Section 9.3.1 analyzes these interactions using conventional economic growth metrics as well as the broader concept of the Human Development Index, and then expands on the particular motivation of countries in different development stages to use RE. Sections 9.3.2 and 9.3.3 analyze the meaning of energy access for development and the diverse components of energy supply security, and conclude by evaluating the contribution of RE to all these specific aspects.

Section 9.3.4 discusses the environmental impacts of RE technologies and makes comparisons to currently dominant energy technologies. Impacts are assessed through the use of LCA methods, focusing on greenhouse gas (GHG) emissions, water use and pollution, local and regional air pollution, and land use and land use change. In addition, health impacts are explicitly considered and a section with a comparative assessment of accident risks is included. Additional impacts such as soil contamination, biodiversity and ecosystem losses are addressed in a more qualitative manner.

Whereas the discussion in Section 9.3 concentrates on current conditions, Section 9.4 focuses on the interactions of future renewable energy deployment and sustainable development pathways. Pathways are primarily understood as scenario results that attempt to address the complex interrelations among the different energy technologies on a global scale. Therefore the chapter mainly refers to global scenarios derived from integrated assessment models (IAMs)), that are also at the core of the analysis in Chapter 10. Section 9.4 gives an overview of the insights those models can provide regarding the interaction of future renewable energy deployment and different sustainable development indicators. As the models have only begun to explicitly take sustainable development into account, the section predominantly aims at identifying gaps in the current scenario literature. It also discusses whether and how models can be modified in order to address sustainability pathways, as well as the role of renewables in this context.

Section 9.5 aims to analyzes barriers to and opportunities of RE in the context of sustainable development. Barriers addressed include environmental concerns and social acceptance, lack of capacity building, cost-effectiveness and appropriateness of the technology, as well as distributional aspects with respect to shared benefits. For RE to contribute to the overarching goal of sustainable development, it is important to address such barriers in an integrative manner. Hence, environmental, social and economic constraints and concerns need to be clearly considered during the planning, construction and operational phases of RE projects. A section on opportunities describes what measures should be taken, on both the national and international as well as local level, to ensure that all possible SD benefits from RE deployment can be realised.

To conclude the chapter, Section 9.6 synthesizes the material in the earlier sections and distils the information to arrive at knowledge gaps that are then presented in more detail in Section 9.7.

9.2 Interactions between sustainable development and renewable energy

The concept of sustainable development (SD) is – in varying forms – deeply rooted in human history, addressing concerns about relationships between human society and nature. Sustainable development was relaunched into the political, public and academic discourse in 1972 with the Founex report and in 1987 with the publication of the World Commission on Environment and Development (WCED) report “Our Common Future” – also known as the ‘Brundtland Report’.

Sustainable development was tightly coupled with climate change (and thence the IPPC) at the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro, Brazil in 1992 that seeked to stabilize atmospheric concentrations of greenhouse gases at levels considered to be safe. The IPCC’s First Assessment Report focused on the technology and cost-effectiveness of mitigation activities. The Second Assessment Report (SAR) included equity concerns in addition to social considerations (Bruce et al. 1996). The Third Assessment Report (TAR) addressed global sustainability comprehensively (Metz et al. 2001) and the Fourth Assessment (AR4) included chapters on SD in both WG II and III reports with a focus on a review of both climate-first and development-first literature (Parry et al. 2007)(Metz et al. 2007).

In the context of this Special Report, the Section 9.2 will outline different SD concepts and their implication for the assessment of RE. Furthermore, it will introduce a set of SD criteria and related SD indicators that will allow to structure the assessment of RE around the existing literature.

9.2.1 The concept of sustainable development

Many competing frameworks for sustainable development have been put forward (Pezzey 1992)(Hopwood et al., 2005). For working purposes, we start with Brundtland and define sustainable development as meeting the needs of the present without compromising the ability of future generations to meet their own needs (Bojo, Maler, and Unemo, 1992; World Commission on Environment and Development. 1987) Concepts of sustainable development can be oriented along a continuum between the two paradigms of weak sustainability and strong sustainability. The two paradigms differ in assumptions about the substitutability of natural and human-made capital (Pearce, Kirk Hamilton, and Atkinson 2008)(Neumayer 2003)(Hartwick 1977).

Weak sustainability has been labelled the substitutability paradigm (Neumayer 2003) and is based on the belief that only the aggregate stock of capital needs to be conserved - natural capital can be substituted with man-made capital without compromising future well-being. As such it can be interpreted as an extension of neoclassical welfare economics (Solow 1974)(Hartwick 1977). For example, one can argue that non-renewable resources, such as fossil fuels, can be substituted, e.g. by renewable resources and technological progress as induced by market prices (Neumayer 2003). Weak sustainability also implies that environmental degradation can be compensated with man-made capital such as more machinery, transport infrastructure, education and information technology.

Whereas weak sustainability mostly assumes that the economic system flexibly adapts to varying availability of forms of capital, strong sustainability starts from an ecological perspective with the intent of proposing guardrails for socio-economic pathways. Strong sustainability can be viewed as the non-substitutability paradigm (Pearce, Kirk Hamilton, and Atkinson 2008) (Neumayer 2003), based on the belief that natural capital cannot be substituted, either for production purposes or for environmental provision of regulating, supporting and cultural services (Norgaard 1994). As an example, sinks such as the atmosphere’s capacity to absorb GHG emissions, may better be captured by strong sustainability constraints (Neumayer 2003; Metz et al. 2007). In one important interpretation, the physical stock of specific non-substitutable resources (so-called “critical natural capital”) must be preserved (not allowing for substitution between different types of natural capital) (Ekins and et al. 2003). Guardrails for remaining within the bounds of sustainability are often justified or motivated by non-linearities, discontinuities, non-smoothness and non-convexities (Pearce, Kirk Hamilton, and Atkinson 2008; Dasgupta 2004). As a typical correlate, natural scientists warn of and describe specific tipping points, critical thresholds at which a tiny perturbation can qualitatively alter the state or development of earth systems (Lenton et al. 2008). In a related approach to sustainability, some environmental ethicists rely on the precautionary principle (according to which the burden of proof for the non-harmful character of natural capital reduction falls on those taking action) to argue for strong sustainability (Ott 2000).

Spatial and cultural variations are another important factor in coherently addressing sustainable development. Sustainability challenges and solutions crucially depend on geographic setting (e.g. solar radiation), socio-economic conditions (e.g. inducing energy demand), inequalities within and across societies, fragmented institutions, and existing infrastructure (e.g. electric grids) (National Research Council 1999)(Holling 1997), but also on a varying normative understanding of the connotation of sustainability (Lele and Norgaard 1996). Analysts, hence, call for a differentiation of analysis and solution strategies according to geographic locations and specific places (e.g., (Wilbanks 2002; Creutzig and Kammen 2009) and a pluralism of epistemological and normative perspectives of sustainability (e.g., Sneddon, Howarth, and Norgaard 2006).

Sustainability in the context of renewable energy can be evaluated in the light of the opposing paradigms of weak and strong sustainability. Non-renewable energy, such as fossil fuels and uranium, all reduce natural capital directly and sometimes indirectly (e.g., environmental impact of mining). Renewable energy technologies, in contrast, sustain natural capital as long as the resources they draw upon are not reducing potential for future harvest.

Renewable energy may be a substitute for fossil fuels (for example if electricity is the product), and as such comprise a solution to both weak and strong sustainability concerns. There are two qualifications:

- Renewable energy can also be a complement to the current energy mix and therefore not reduce harmful environmental impacts of existing non-renewable energy production. Hence, renewable energies can be regarded as a solution strategy to climate change (see also the Box on Sustainable development, renewable energy and climate change), if (and only if) fossil fuel consumption is simultaneously reduced.
- Renewable energies may have their own environmental impact and reduce natural capital, e.g. by upstream GHG emissions, destroying forests, binding land that cannot be used otherwise and consuming water – all of which can be evaluated again from weak and strong sustainability paradigms.

For some renewable energy technologies a strong sustainability perspective beyond considerations of climate change alone will be relevant to capture the full impact of specific technologies. In chapter 10 of this report, the future of renewable energy is evaluated within a scenarios framework. To complement this integrated, yet more basic approach of global energy models with climate change as primary constraint, this chapter will focus on non-climate indicators and criteria for sustainable energy systems. In addition to Section 9.4's focus on the treatment of SD indicators in these global energy models, Section 9.3.4 assesses life-cycle assessments (LCA) that represent one well-known bottom-up approach to quantifying some aspects of the sustainability and wider impacts of renewable (and other) technologies. Future research should combine these detailed life-cycle assessment of fuels and their corresponding infrastructures with global energy assessments to fulfill multiple targets and constraints such as equitable and regional specific energy access and global GHG emission restrictions.

Regardless of whether weak or strong sustainability is the relevant framework, it is clear that exhaustible resources can only be used within a finite time window. To manage the transition to a non-carbon economy, renewable energy sources must be deployed, and sufficient capital accumulated to enable future deployment of renewable energy (see chapter 10). The relevance of both sustainability paradigms in specific circumstances is not always precisely known. Hence, specific criteria and indicators are needed that connect the use of (renewable) energy to sustainability.

Traditionally, sustainability has been framed in the three-pillar model: Economy, Ecology, and Society are all considered to be interconnected and relevant for sustainability (BMU, 1998). The three-pillar model explicitly acknowledges the encompassing nature of the sustainability concept and allows a schematic categorization of sustainability issues. The United Nations General Assembly aims for action to promote the integration of three components of sustainable development – economic development, social development and environmental protection – as interdependent and mutually reinforcing pillars (UN 2005). This view subscribes to an understanding where a certain set of action can fulfill all three development goals simultaneously – the three pillars are not mutually exclusive and can be mutually reinforcing. The three pillar model has been criticized for diluting a strong normative concept with vague categorization and replacing the need to protect natural capital with a methodological notion of transsectoral integration (Brand and Jochum 2000). The three pillars of sustainability, however, can also be nested, and subsumed under the concept of strong sustainability (Ott 2009).

Figure 9.2.1 shows schematically the relationship between the three pillars of sustainability and a set of cross-cutting goals for a sustainable renewable energy system. The figure emphasizes the fundamental limits imposed by environmental constraints; both society and the economy operate within the bounds set by the environment. Starting with this schematic, renewable energy technologies can be evaluated with respect to four criteria: sustainable social and economic development, increased energy access, enhanced energy security, and decreased environmental impacts (WDR 2010). The potential of the renewable energy system to increase access to modern energy technologies can facilitate economic and social development. Energy access and economic and social development measures relate to current well-being and to some extent to intra-generational equity and sustainability, for example through an emphasis on energy-related equity questions, including gender equity and empowerment. Energy security and assessments of environmental impacts address more explicitly the intertemporal well-being aspect inherent in sustainability. Assessments of environmental impacts of sustainability are most closely related to the strong sustainability paradigm discussed above, whereas the focus of energy access and energy security concerns can be considered under the weak sustainability paradigm.

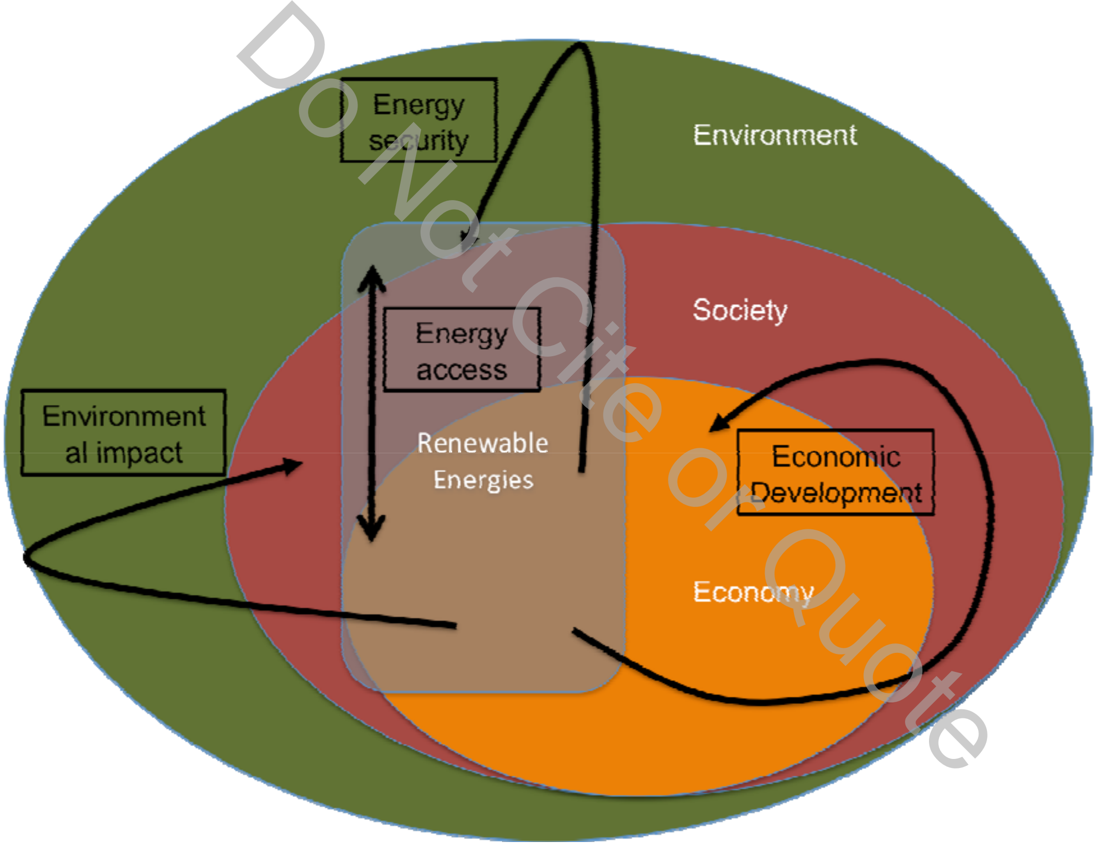


Figure 9.2.1 Embedded dimensions of sustainability. The size of the economy symbolizes the magnitude of material throughput. The arrows illustrate schematically the linkages across dimensions represented by the evaluative criteria used in this chapter.

In the next subsection, a set of tentative indicators for evaluating renewable energy technologies in sustainable development is introduced. The aim of the remainder of this chapter is not to develop new sustainability indicators, but to follow a pragmatic approach of empirical assessment, structured to suitably organize existing literature.

Box - Sustainable Development, Renewable Energy and Climate Change

One clear negative consequence of the historical combustion of fossil fuels has been the increase of greenhouse gases, chiefly carbon dioxide, to levels unprecedented in human history. (Metz et al. 2007). A “business as usual” scenario of continuing on the current emissions trajectory could lead to global average temperature increases as high as 6°C by 2100 (Metz et al. 2007). Although land-use change also plays an important role in increasing net carbon flux to the atmosphere, yearly emissions from fossil-fuel combustion have been steadily increasing for more than a century and are currently five to six times greater than the contribution from land-use change. (McGranahan et al; Houghton, et al.). Geographically, countries responsible for the majority of fossil-fuel emissions are those in the industrialized world, with a 25% population share, and over 50% of current emissions (BP, WRI) and a much larger share of cumulative emissions over the course of the past century.

Since the IPCC AR4 report there has been an increasing realization that it may be necessary to use temperature guardrails as goals for climate policy. One proposal for quantifying “allowable” future emissions is that of a carbon budget (Meinshausen et al. 2009) Total cumulative carbon dioxide emissions since the beginning of industrialization play the key role in determining final temperatures of the global climate system. As one example, to avoid with a probability of 50% breaking through a 2°C temperature guardrail, a total of approximately 1000 Gt CO_2 can be emitted from 2010 to 2050. This carbon budget represents a significant reduction in yearly emissions worldwide, and should developing countries be privileged in the distribution of shares of the carbon budget, correspondingly greater reductions will be required of developed countries. Cumulative carbon emissions constitute a crucial and widely recognized guardrail in the strong sustainability sense. Renewable energies are commonly understood as substitutes of fossil energy sources that allow maintaining energy consumption while staying within a total carbon emission budget.

On the other side of the geographical distribution, higher GHG concentrations and temperatures will be accompanied by rising sea levels and ocean acidification on a global scale. Perhaps more important are the projections for both climate change impacts and extreme weather events. Although there is still significant uncertainty as to the exact magnitude of negative climate impacts in a given region (Parry et al. 2007), some general conclusions are clear. Roughly 10% of the world’s population lives in low-elevation coastal zones (LECZ), defined as areas with elevation less than 10 meters and contiguous with the coastline (McGranahan et al. 2007). Using another measure, 40% of the world population lives within 100km of a coastline, thereby placing this fraction within an area of “coastal pressure” as defined for the Millennium Ecosystem Assessment. In the face of rising sea-levels, this fraction of world population is vulnerable and likely to be impacted by not only long-term sea-level rise, but also by extreme events such as tropical storms and flooding. Of those living in a LECZ, over 85% are in developing countries (McGranahan) and therefore likely to be especially at risk. Furthermore, the strength of larger tropical storms is also projected to increase in a warming climate (Knutson 2010), compounding the risk to these populations.

Overall there is large variability in the capacity for societies to respond to a changing climate. Although all countries will be affected to some extent, even moderate climate change can be a challenge for developing countries (Yohe et al. 2006).

9.2.2 Indicators for Sustainable Development and Renewable Energy

Sustainable development indicators for renewable energy should present a balanced set of measures that will allow sustainable development to be assessed. Energy indicators can assist countries in monitoring progress made in energy subsystems consistent with sustainability principles, although there are many different ways to classify indicators of sustainable development (Sathaye et al., 2007). Vera and Langlois (Vera and Langlois, 2007) provide an overview of progress made over the past two decades toward developing a uniform set of Energy Indicators for Sustainable Development (EISD). A subset of the tentative set of thirty indicators discussed by Vera and Langlois will be used in this chapter; these indicators are organized within the broad themes of the three pillars of sustainable development, economy, society and environment.

Sustainability indicators for renewable energy technologies rely on a similar list noted above for energy technologies. A recent study evaluated a range of SD indicators using data obtained from the literature (Evans et al. 2009). The indicators used were price of generated electricity, greenhouse gas emissions during full life cycle of the technology, availability of renewable sources, efficiency of energy conversion, land requirements, water consumption and social impacts. The social impacts were assessed qualitatively. Another approach is to develop a figure of merit (FOM) to compare the different RE systems based upon their performance, net energy requirement, greenhouse gas emissions, and other indicators. FOM combines the ranking of each technology with respect to selected indicators and provides a common platform to compare the various energy or RE systems. Varun and Bhat (2009) use this approach to compare selected RE technologies globally. Measurement and reporting of indicators is an important aspect of the implementation of sound renewable energy technologies. Measurement not only gauges but also spurs the implementation of sustainable development and can have a pervasive effect on decision-making (Meadows, 1998; Bossel, 1999), requiring updated methodologies (Creutzig and Kammen 2009). However, measuring energy sustainability is surrounded by a wide range of conceptual and technical issues (Wilbanks, 2010).

This section uses the four goals of energy policies, as outlined in Figure 9.2.1, as broad criteria to define sustainable development with respect to renewable energies. For each of these qualitative criteria, quantitative indicators can be used to evaluate scenarios for future energy-system development within the context of sustainable development. The indicators chosen reflect a suitable framework to assess the existing literature, but cannot close the considerable gaps in achieving a comprehensive and consistent measure of sustainable development.

Sustainable social and economic development

Gross Domestic Product (GDP) or per capita GDP have been used as proxies for economic development for several decades (such as in IAMs, see Section 9.4.1). In expanding the notion of economic development, a variety of indicators of sustainability, and sustainable development, have been suggested. Consistent with the principle of weak sustainability, green net national product (NNP) and genuine savings have been proposed (Hamilton 1994; Dasgupta 2001). Other aggregate indicators of weak sustainability include the index of sustainable economic welfare (ISEW) and the genuine progress indicator (GPI) (e.g., (Daly 2007) which were proposed as intermediate steps by proponents of strong sustainability. Indicators more consistent with strong sustainability, such as carrying capacity, ecological footprint and resilience have also been put forward (Pearce, Kirk Hamilton, and Atkinson 2008). More strict measures have also been proposed as ‘sustainable national income’, and as ‘sustainability gaps’(Hueting 1980; Ekins and Simon 1999).

Sustainability indicators should in principle be intertemporal, in contrast to commonly-used indicators of human well-being, such as GDP – measuring economic growth – or HDI – the Human Development Index. Measures that extend GDP (e.g. ISEW and GPI) tend to deviate qualitatively from the GDP since the 1970s or 1980s (stagnating, or in case of UK decreasing) in many OECD countries (Lawn 2003). Another indicator of weak sustainability, genuine savings, has been systematically related to natural resource exploitation by the World Bank (Kirk Hamilton and Clemens 1999).

In addition, many or all of the proposed sustainability indicators are difficult to measure. Resulting values are indexed with high uncertainty and are often challenged on methodological and epistemological grounds (Neumayer 2003). Crucially, sustainability is an open-boundary concept, and confronted with tipping elements of unknown probability, giving rise to principled doubts that a coherent quantitative evaluation is possible. This chapter evaluates renewable energy in terms of bottom-up measures while being cognizant of their limitations.

As a general matter, there are some conceptual challenges with using aggregated indicators for economic development (e.g. HDI or ISEW) as described in (Fleurbaey 2009, 1055). First, it is difficult to make a rigorous justification for specific choices of weighting the components of aggregate indicators. Second, it is often difficult to obtain reliable and internationally consistent data series across components of the composite indicator.

In spite of these shortcomings, and because of the correlation between HDI and per-capita energy use, and due to the availability of data time series for these parameters, these will both be used as indicators in this chapter (Sections 9.3.1.1 and 9.3.1.2). A further rough indicator of technological development is decreasing energy intensity, i.e. a decrease in the amount of energy needed to produce a dollar of GDP.

Increased energy access

Access to modern energy services, whether from renewable or non-renewable sources, is closely correlated with measures of development, particularly for those countries at earlier development stages. Indeed, the link between adequate energy services and achievement of the Millennium Development Goals (MDG) was defined explicitly in the Johannesburg Plan of Implementation which emerged from the World Summit on Sustainable Development in 2002 (OECD/IEA Report 2010). Over the past few centuries industrialized societies have transformed the quality of life by exploiting non-renewable fossil energy sources, nuclear energy and large-scale hydroelectric power. However, in 2010 almost 20% of the world population, mostly in rural areas, still lack access to electricity. Twice that percentage cook mainly with traditional biomass, mainly gathered in an unsustainable manner (WEO 2010). In the absence of a concerted effort to increase energy access, the absolute number of those without electricity and modern cooking possibilities is not expected to change substantially in the next few decades. Increasing energy access without violating the precepts of weak or strong sustainability constraints is an essential component of sustainable development (Pezzey 1997).

Concrete indicators to be discussed in more detail in Section 9.3.2 are per capita final energy consumption, as well as breakdowns of electricity access (divided into rural and urban areas), and data for the number of those using coal or traditional biomass for cooking. Implicit in discussions of energy access is a need for models that can assess the sustainability of future energy-system pathways with respect to decreasing the wide disparity between rural and urban areas (e.g. in terms of energy forms and quantities used or infrastructure reliability) within countries or regions (see Section 9.4.2).

Enhanced energy security

There is no commonly accepted definition of the term ‘energy security’ and its meaning is highly context dependent (Kruyt et al., 2009). At a macro-level it can best be understood as robustness against interruptions of any one source of energy (Grubb et al., 2006). Thinking broadly across energy systems, one can distinguish between different aspects of security that operate on varying temporal and geographical scales (Bazilian and Roques, 2008). Four broad themes can be identified that are relevant to energy security, whether for current systems or for the planning of future high-penetration renewable energy systems: availability of resources, risk of disruption of domestic or external energy supply, diversity of energy supplies and potential for compensation of temporally fluctuating sources. Given the interdependence of economic growth and energy consumption, access to a stable energy supply is a major political concern and a technical and economic challenge facing both developed and developing economies, since prolonged disruptions would create serious economic and basic functionality problems for most societies.Many developing countries also include providing adequate and affordable access to all part of the population as part of their definition of energy security and in this way links the access and security issues, while broadening the concept to include stability and reliability of local supply.

The potential for fossil fuel scarcity and decreasing quality of fossil reserves represent an important reason for a transition to a sustainable worldwide renewable energy system. One link between the concepts of weak and strong sustainability is that fossil fuel supplies are finite, and can represent only a temporary (even if for many decades) foundation for the energy system. By definition, if fossil fuels are a temporary solution, then that solution is not sustainable.

Avoidance of disruptions to energy supplies is a critical component of energy security for sustainable development and the role of renewable energy. For example, the response of member states of the International Energy Agency (itself created in response to the first oil shock of the 1970s) (Scott 1994) to vulnerability to oil supply disruption has been to mandate that countries hold stocks of oil as reserves in the amount of 90 days of net imports. While this stock buffer clearly reduces the vulnerability of some, mostly wealthier, nations to oil supply disruptions, it does not remove the risk completely and it is an open question as to how much of the vulnerability is in fact mitigated. [reference to be supplied later] For countries who are not members of the IEA, such requirements have little effect. Dependence on energy imports, whether of fossil fuels or the technology needed for implementation of renewable energy, represents a measure of energy (in)security for both developing and industrialized countries.

One avenue to enhance energy security is thus increasing the diversity of energy supply. All else being equal, the more reliant an energy system is one single energy source, the more susceptible the energy system is to serious disruptions. Examples would be disruptions to oil supply, unexpectedly large and widespread periods of low wind or solar insolation (for example due to weather), or the emergence of unintended consequences of any supply source. The extent to which RET contributes to the diversification of the portfolio of supply options represents a contribution to enhanced energy security at the global, the national as well as the local level (Bazilian and Roques, 2008).

The introduction of renewable technologies that vary on different time-scales, ranging from minutes to seasonal, adds a new concern to energy security. Not only will there be concerns about disruption of supplies by unfriendly agents, but also the vulnerability of energy supply to the vagaries of chance and nature. Renewable energy forms are particularly vulnerable to extreme events such as for example, abnormally long periods of calm air for wind turbines. Solar is potentially vulnerable to abnormal cloud cover. Hydro power and bioenergy are potentially vulnerable to extensive periods of drought. A diverse portfolio of energy sources, together with good management and system design can help to enhance security.

Specific indicators for security are difficult to identify. Based on the four topics described above, the indicators used to provide information about the energy security criterion of SD in Section 9.3.3 are the magnitude of reserves (also discussed in Section 9.4.3), production and imports of fossil fuel energy, the share of imports in total primary energy consumption, and the reserves-to-production ratio.

Reduced environmental impacts

As discussed in Chap. 1 and in the Box “Sustainable Development, Renewable Energy and Climate Change,” reducing greenhouse gas emissions with the aim of mitigating climate change is one of the key driving forces behind a growing demand for renewable energy technologies. However, to evaluate the overall burden from the energy system to the environment, other impacts and categories have to be taken into account as well. Comparison of mass emissions to water and air, and usage of water, energy and land per unit of energy generated must be evaluated across technologies. Whereas some environmental impact parameters can be rigorously quantified, for others comprehensive data may be lacking. In addition, impacts are always specific to given sites and circumstances, and can therefore not be discussed generically. In particular, in this chapter impacts on human health, ecosystems and biodiversity are discussed more qualitatively.

While deployment of RE will also entail environmental impacts, the comparative advantage of renewable over fossil fuel energy sources with respect to reduced GHG emissions and other long-term impacts is significant. Life-cycle assessments are a particularly useful methodology for determining total system impacts of a given technology, as a basis for comparison. There are multiple other methods to assess environmental impacts of energy technologies. Many, such as environmental impact statements/assessments and risk assessments, require site-specific data or plans and thus are difficult to generalize for a global review such as this report. Many methods also only evaluate environmental impacts associated with operation of the facility. These context-specific approaches are very difficult to relate to the integrated assessment model results from Chapter 10 that are to be discussed in Section 9.4. While recognizing that LCA does not give the only possible answer as to the sustainability of a given technology, empirical data presented in Section 9.3.4 will be largely based on Life Cycle Inventories.

Literature on full Life Cycle Impact assessments is scarce, as are sources reporting aggregate sustainability indicators. Partly, this is due to the incommensurability of different impact categories (for example litres of polluted water versus tonnes of greenhouse gases) posing problems for interpretation. Attempts to amalgamate various types of LCA indicators (or other sort of indicators) into one overall score (for example by joining their impact pathways into a common endpoint, or by monetisation; (Heijungs et al. 2003) have shown that the uncertainties associated with such scoring approaches are often so high that they preclude decision-making (Hertwich, McKone, and Pease 1999; Rabl and Spadaro 1999; Schleisner 2000; Krewitt 2002; Sundqvist 2004; Lenzen 2006). Nevertheless, external costs are discussed in chapter 10.6, and part of the analysis in 9.4.4 is based on monetization of impacts. The latter section will analyse the extent to which environmental impacts are represented in scenario analyses for renewable energy deployment, with indicators being total and per-capita greenhouse gas (GHG) emissions (of which some also have local pollution effects) and measures of land-use change.

9.3 Social, environmental and economic impacts: Global and regional assessment

Structured around the four SD criteria laid down in Section 9.2.1, this section will assess the literature on the performance of energy in general and RE in particular with respect to the different SD indicators that were introduced by Section 9.2.2. Since the literature is far from being comprehensive or consistent, different methodologies will be used for different indicators, including empirical and qualitative, as well as life cycle assessments.

9.3.1 Sustainable social and economic development

This section assesses the potential contributions of RE to sustainable social and economic development. Due to the multi-dimensional nature of SD neither a comprehensive assessment of all mitigation options nor a full accounting of all relevant costs can be performed. Rather, the following section identifies key issues and provides a framework to discuss the relative benefits and disadvantages of RE and fossil fuels with respect to development.

9.3.1.1 Energy and Economic Growth

With the ability to control energy flows being a crucial factor for industrial production and socio-economic development (Cleveland *et al.*, 1984; Krausmann *et al.*, 2008), industrial societies are frequently characterized as ‘high-energy civilizations’ (Smil, 2000). Globally, per-capita incomes are positively correlated with per-capita energy use (see Figure 9.3.1) and economic growth can be identified as the most relevant factor behind increasing energy consumption in the last decades (see Figure 1.4). Nevertheless, there is no agreement on the direction of the causal relationship between energy use and increased macroeconomic output, as the results crucially depend on the empirical methodology employed as well as the region and time-period under study (Stern, 1993; Asafu-Adjaye, 2000; Paul and Bhattacharya, 2004; Ang, 2007; Ang, 2008; Lee and Chang, 2008).

Industrialization brings about structural change in the economy and therefore affects energy demand. As economic activity expands and diversifies, demands for more sophisticated and flexible energy sources arise: while agricultural societies derive a large part of primary energy consumption from traditional biomass (Leach, 1992; Barnes and Floor, 1996), coal and liquid fuels – such as kerosene and liquid petroleum gas – gain in importance with rising income, and electricity, gas and oil dominate at high per-capita incomes (Grubler, 2004; Marcotullio and Schulz, 2007; Burke, 2010). From a sectoral perspective, countries at an early stage of development consume the largest part of total primary energy in the residential (and to a lesser extent agricultural) sector. In emerging economies the manufacturing sector dominates, while in fully industrialized countries services and transport account for steadily increasing shares (Schafer, 2005) (see also Figure 9.3.1). Furthermore, several authors (Jorgenson, 1984; Schurr, 1984) have pointed out that electricity – which offers higher quality and greater flexibility compared to other forms of energy – has been a driving force for the mechanization and automatization of production in industrialized countries and a significant contributor to continued increases in productivity.

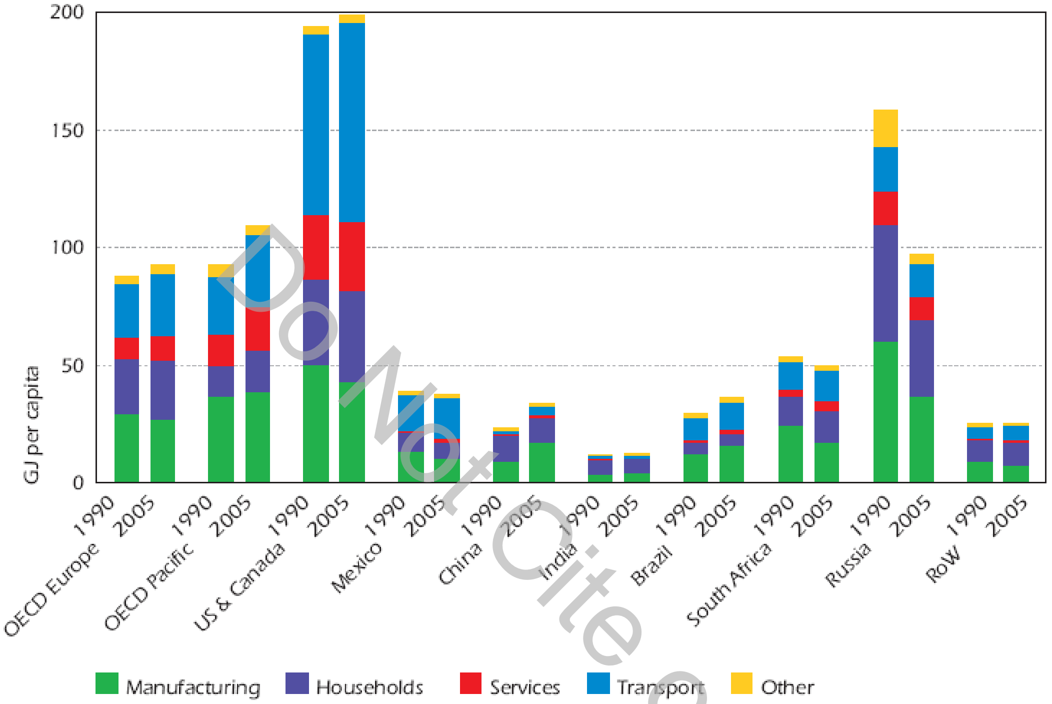


Figure 9.3.1: Energy Use (GJ) per capita by economic sector. Source: (IEA, 2008).

Despite the fact that as a group industrialized countries consume significantly higher amounts of energy per capita than developing ones (see Figure 9.3.1), a considerable cross-sectional variation of energy use patterns across countries prevails: while some countries (such as e.g. Japan) display high levels of per-capita incomes at comparably low levels of energy use, others are relatively poor despite extensive energy consumption, especially countries abundantly endowed with fossil fuel resources, in which energy is often heavily subsidized (UNEP, 2008b). It is often asserted that developing and transition economies can ‘leap-frog’, i.e. adopt modern, highly efficient energy technologies, to embark on less energy- and carbon-intensive growth patterns compared to the now fully industrialized economies during their phase of industrialization (Goldemberg, 1998). For instance, one study for 12 Eastern European EU member countries finds that between 1990 and 2000, convergence in per-capita incomes between fully industrialized and transition economies has been accompanied by significant reductions of energy intensities in the latter (Markandya *et al.*, 2006). For industrialized countries, one hypothesis suggests that economic growth can largely be decoupled from energy use by steady declines in energy intensity as structural change and efficiency improvements trigger the ‘dematerialization’ of economic activity (Herman *et al.*, 1990). However, despite the decreasing energy intensities (i.e. energy consumption per unit of GDP) observed over time in almost all regions (Figure 9.3.2), declines in energy intensity historically often have been outpaced by economic growth and hence have proved insufficient to achieve actual reductions in energy use (Roy, 2000). In addition, it has been argued that decreases in energy intensity in industrialized countries can partially be explained by the fact that energy-intensive industries are increasingly moved to developing countries (Peters and Hertwich, 2008; Davis and Caldeira, 2010) and, as observed energy efficiency improvements are largely driven by shifts to higher quality fuels, they cannot be expected to continue indeterminately (Cleveland *et al.*, 2000; Kaufmann, 2004).

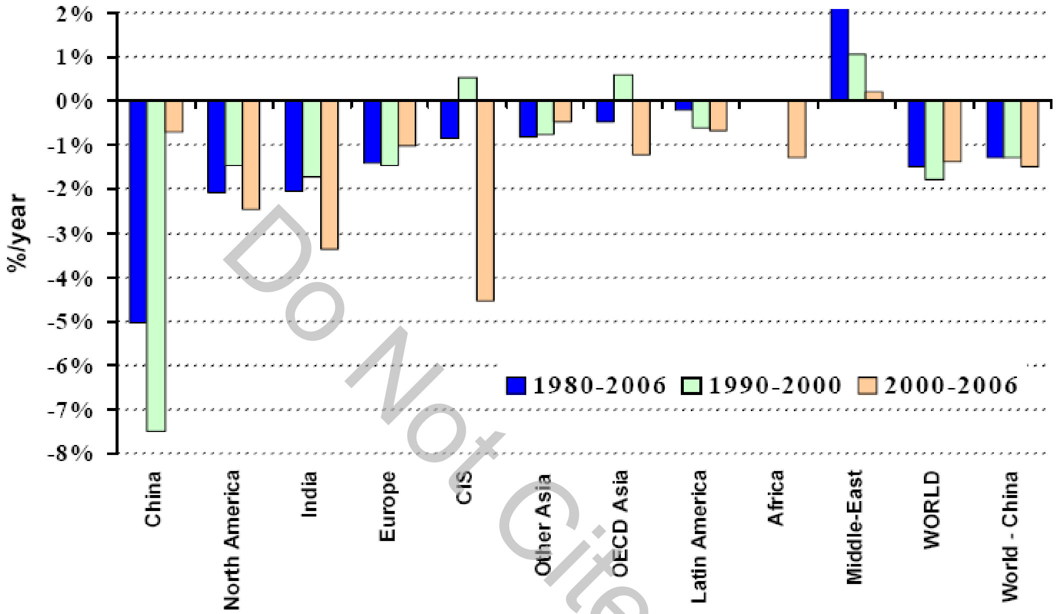


Figure 9.3.2 Changes in energy intensities over time for selected regions. Source: (WEC, 2008).

9.3.1.2 Human Development Index & Energy

As already mentioned in Section 9.2.2, the industrialized societies' improvements in the quality of life where so far mainly based on the exploitation of non-renewable energy sources (even though it should be noted that in early stages of industrialization, as well as for many developing countries today, hydropower has played an important role in development). Apart from its significance for productive purposes, access to clean and reliable energy constitutes an important prerequisite for fundamental determinants of human development including health, education, gender equality, and environmental safety (UNDP, 2007). As the IEA's most recent World Energy Outlook (WEO, 2010) points out, providing access to modern energy for the poorest members of society is crucial for the achievement of any single of the eight Millennium Development Goals (MDGs).

Although the income level is an important determinant of development, human well-being also includes other elements that cannot be captured by a single measure of income. Figure 9.3.3 depicts the correlation between the Human Development Index (HDI) and primary energy use per capita for 115 countries. The HDI is used to assess comparative levels of development in countries and includes purchasing power parity (PPP)-adjusted income, literacy and life expectancy as its three main matrices. The HDI is only one of many possible measures of the well-being of a society, but it can serve as a proxy indicator of development. The graph reveals that countries that have achieved high HDI levels in general (although to varying degrees) consume relatively large amounts of energy per capita and no country has achieved a high (>0.8) or even a medium HDI (between 0.5 and 0.8) without significant access to non-traditional energy supplies (which for the largest part of the last century have been dominated by fossil fuels). However, with rising levels of energy consumption, saturation of the positive relationship between energy use and HDI sets in (Martinez and Ebenhack, 2008), which means that a certain minimum amount of energy is required to guarantee an acceptable standard of living (Goldemberg, 2001) suggests 1 toe/cap), after which raising energy consumption yields only marginal improvements in the quality of life.

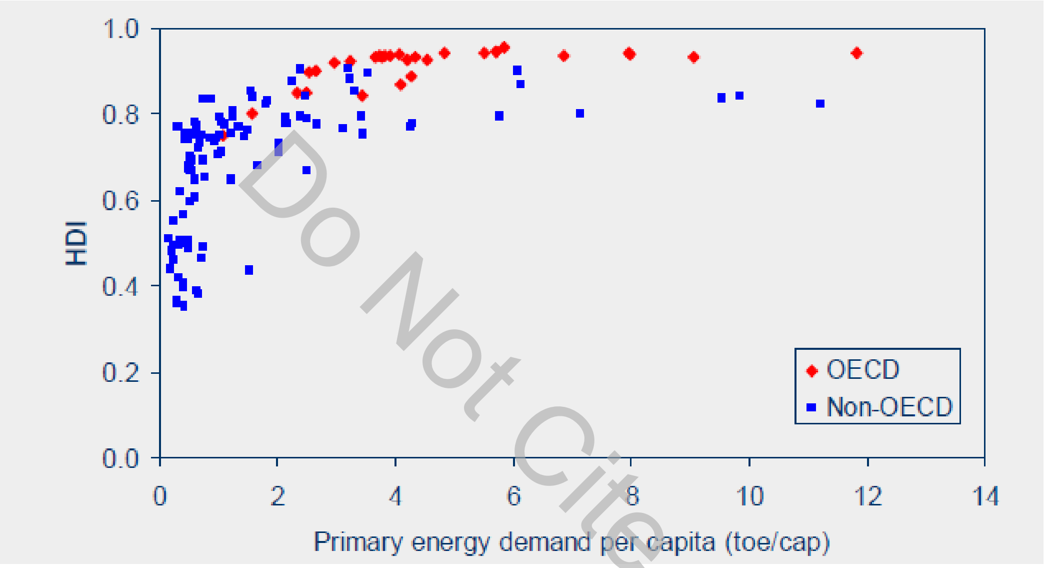


Figure 9.3.3 Correlation between primary energy consumption and the countries' Human Development Index (WEO, 2004).

9.3.1.3 Motivations to promote RE

Countries at different levels of development have different incentives to advance RE. For developing countries the most likely reasons to adopt RE technologies are (i) providing access to energy (see Section 9.3.2.), (ii) creating employment opportunities in the formal economy, and (iii) reducing the costs of energy imports (or, in the case of fossil energy exporters, prolong the life-time of their natural resource base). For industrialized countries the primary reasons to encourage RE include (i) reducing carbon emissions to mitigate climate change (see Chapter 1), (ii) enhancing energy security (see Section 9.3.3.1.), and (iii) actively promoting structural change in the economy, such that job losses in declining manufacturing sectors are softened by new employment opportunities related to RE.

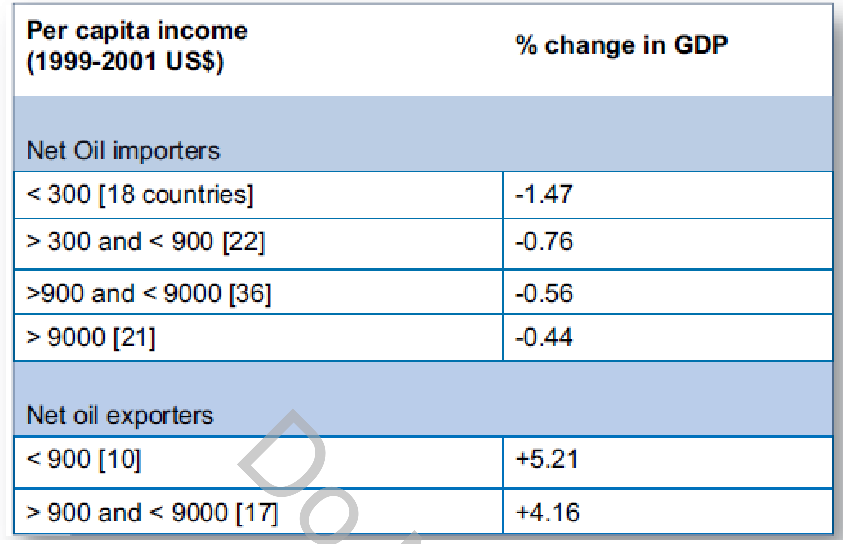
According to a recent study prepared by UNEP (UNEP, 2008a), RE already accounts for about 2.3 million jobs worldwide and in many countries job creation is seen as one of the main benefits of investing in renewable energy sources. A study by the German Environment Ministry finds that in 2006, about 236.000 people were employed in RE, up form roughly 161.000 two years earlier (BMU, 2009). Examples of the use of RE in India, Nepal, and parts of Africa indicate that in many parts of the developing world RE can stimulate local economic and social development (Cherian, 2009) [TSU: will be inserted later]. This is corroborated by case study evidence from the sugar-cane industry in Brazil, which point to increases in levels of employment (Goldemberg *et al.*, 2008) and per-capita incomes (Walter *et al.*, in press). Other studies that also observe possible negative employment effects are more critical in this regard (Frondel *et al.*, 2010) and the assertion of positive employment effects is further weakened by disagreements in the methodology used to calculate them (Sastresa *et al.*, 2009). Evaluating the labour market effects of RE policies is in any case a challenging task that requires an assessment of how value chains and production patterns adjust in the mid-term and how structural adjustment and innovative activity respond in the long-run (Fankhauser *et al.*, 2008) and RE should not be regarded as an instrument that can be employed to cure underlying inefficiencies in labour markets. For a comprehensive assessment, it would be necessary to factor in all social costs and benefits of a given technology (including interactions with labour market frictions) to be able to appropriately compare RE and fossil fuels on a level playing field. This includes the costs of support schemes for RE as well as subsidies for fossil fuels. Yet, this has not yet been accomplished satisfactorily.

Numerous governments have included substantial spending on clean energy technologies in their stimulus packages that were put into place in response to the financial and economic crisis (Bauer *et al.*, 2009; Bowen *et al.*, 2009). For the US, one study (Houser *et al.*, 2009) suggested that for every US $ 1 billion [TSU: 2005$?] spent on green fiscal measures, there was the potential to create about 30,000 jobs; another one, prepared by the Center for American Progress (Pollin *et al.*, 2008) estimated that a green stimulus of US $ 100 billion [TSU: 2005$?] could save roughly 2 million jobs. From a more long-term perspective, many national green-growth strategies e.g. in China, Korea, Japan, EU and US (UNEP, 2010) have stressed the deployment of RE as an important contribution to job creation and one study (Barbier, 2009) argues that a 'Global Green New Deal' could in the long run create more than 34 million jobs in low-carbon transportation and related activities alone.

As noted above, many developing and transition economies are highly dependent on imports of energy. For a number of countries (Moldowa, Pakistan, Trinidad and Tobago, Madagascar, India, Ukraine, Tajikistan) the share of energy imports in total imports exceeded 25% for the period 2000-2005 and it was as high as 45% for Bahrain and 40% for Sierra Leone (WDI, 2007). A related indicator is the share that energy import constitutes of export earning and overall GDP. For example, Kenya and Senegal spend more than half of their export earnings for importing energy, while India spends over 45% (GNESD, 2010; Jain, 2010).

The Energy Sector Management Program (ESMAP) of the World bank has studied the impacts of higher oil prices on low income countries and the poor (ESMAP, 2005) and the finding about macro level effects on GDP is illustrated in the table below. It should be noted that the data is based on a large number of country case studies and do not claim to be universally valid. It illustrates, however, that oil importing developing countries are affected significantly by oil price increases and the poorest countries are affected the most as shown in Table 9.3.1. Increases in important commodity prices will always affect importers of these products. What makes energy unique is both the scale of the cost as a share of national imports, and the volatility of prices compared to most other commodities. The ESMAP national case studies also showed the poorest households experienced the highest percentage changes in expenditure for commercial energy purchases of e.g. kerosene, LPG and diesel.

Table 9.3.1 Percentage change in GDP by a US$10 a barrel rise in oil prices (analytical results grouped by income levels) (ESMAP, 2005).



Per capita income (1999-2001 US$)	**% change in GDP**
Net Oil importers	
< 300 [18 countries]	-1.47
> 300 and < 900 [22]	-0.76
>900 and < 9000 [36]	-0.56
> 9000 [21]	-0.44
Net oil exporters	
< 900 [10]	+5.21
> 900 and < 9000 [17]	+4.16

ESMAP has also analyzed the national policy responses (ESMAP, 2005; ESMAP, 2006; ESMAP, 2008) and it was found that many governments try to limit the impacts of international price increases in the short term by adjusting subsidies or providing targeted cash support to poorest households, rationing supply or forcing supply companies to absorb some of the short term effects. This may however have significant effects both on state budgets and companies' ability to maintain stable delivery (UNEP, 2008b). Longer term responses are more focused on diversification and efficiency measures and are dealt with in section 9.3.3.1.

For these countries increased uptake of RE technologies could be a promising avenue to redirect highly needed foreign exchange flows away from energy imports towards imports of goods that cannot be produced locally, such as high-tech capital goods. For other developing countries which are net exporters of energy, promoting the domestic use of RE can extend the life-time of their fossil resource base and prolong the time to diversify the scope of economic activities by decreasing the dependence on resource exports while strengthening their manufacturing and service sectors.

9.3.2 Increased energy access

The traditional link between economic development and energy requirements, as discussed above, takes on a different meaning when the focus is on the significant parts of the global population that have no or limited access to modern and clean energy services. From a development perspective, any sustainable energy expansion should increase the availability of energy services to groups that currently have no or limited access to them: the poor (measured by wealth, income, or more integrative indicators), those in rural areas and those without connections to the grid. Within households the impacts on women of lack of clean and efficient energy services are often singled out (Reddy *et al.*, 2000; Brew-Hammond, 2010) (Agbemabiese, 2009).

As noted in Section 9.2.2, the provision of modern energy services is widely recognized as critical foundation for promotion of sustainable development and the link was defined explicitly in the 2002's Johannesburg Plan of Implementation (UN, 2002 para 9). This is consistent with a number of studies and Section 9.3.1.2 has already noted that there is a link between adequate energy services and the achievements of the various MDGs. Their achievement is critically dependent on energy inputs (Modi *et al.*, 2006; GNESD, 2007a; Brazilian *et al.*, 2010).

Table 9.3.2 provides an estimate of the number of people without access to electricity which totals almost 1.5 billion in 2009. The regional distribution indicates that it is entirely a developing country issue particularly in Sub Saharan Africa (SSA) and South Asia.

Table 9.3.2 Electricity access in 2008 - Regional aggregates (WEO, 2009)[1].

	Population without electricity millions	Electrification rate %	Urban electrification rate %	Rural electrification rate %
Africa	589	40.0	66.8	22.7
North Africa	2	98.9	99.6	98.2
Sub-Saharan Africa	587	28.5	57.5	11.9
Developing Asia	809	77.2	93.5	67.2
China & East Asia	195	90.2	96.2	85.5
South Asia	614	60.2	88.4	48.4
Latin America	34	92.7	98.7	70.2
Middle East	21	89.1	98.5	70.6
Developing countries	1,453	72.0	90.0	58.4
Transition economies & OECD	3	99.8	100.0	99.5
World	1,456	78.2	93.4	63.2

A recent report from the UN Secretary General's advisory group on energy and climate change (AGECC, 2010) stresses the importance for universal access by 2030 to modern energy sources as a key part of enhancing sustainable development.

AGECC also presents an approach to a common understanding of "access" that helps identify the specific sustainable development elements where renewable energy sources and technologies can make specific contributions over and above the effects of energy access expansion based on grid expansion or fossil technologies like diesel plants: The AGECC approach defines energy access as "access to clean, reliable and affordable energy services for cooking and heating, lighting,

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[1] See also: WEO electricity database http://www.iea.org/weo/electricity.asp

communications and productive uses" (AGECC, 2010) and illustrates the incremental process (Figure 9.3.4) involved in moving from servicing basic human needs to creating a self sustaining process of sustainable development.

Even a basic level of energy access that includes lighting and allows for communication, healthcare and education can provide substantial benefits to a community or household, including cost savings. AGECC does, however, suggest a broader definition than basic needs, and proposes that access to sufficient energy for basic services and for productive uses is the appropriate level of energy access needed to improve livelihoods in the poorest countries and drive local economic development.

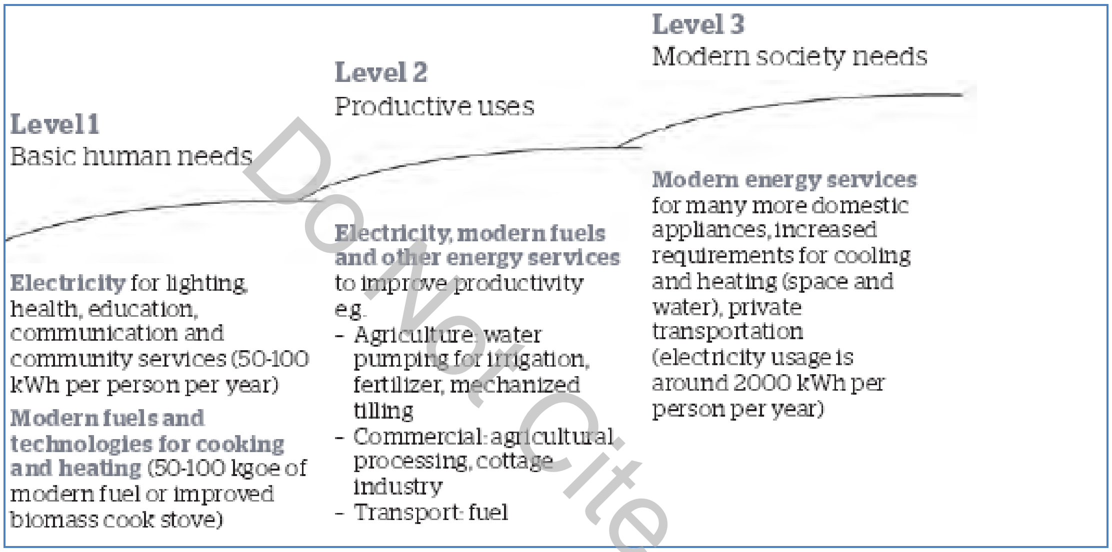

Figure 9.3.4 Incremental level of access to energy services; source: AGECC, 2010.

It is shown in a number of studies (Baumert *et al.*, 2005; Bhattacharyya, 2005; World Bank, 2008; UNDP and WHO, 2009; Brew-Hammond, 2010; IEA, 2010)[2] that access issues need to be understood in a local context and that in most countries there is a marked difference between electrification rates in urban and rural areas. This is especially true in the Sub Saharan African and South Asian regions but the figures illustrate that rural access is still an issue of concern also in developing regions with high overall national electrification rates, illustrating that the rural - urban divide on modern energy services is still quite marked in all developing regions.

Some studies show that decentralized grids based on RE are generally more competitive in rural areas with significant distances to the national grid (Baumert *et al.*, 2005; Nouni *et al.*, 2008; Deichmann *et al.*, 2010) and the low levels of rural electrification offer significant opportunities for renewable energy based mini-grid systems. The role of RE in providing increased access to electricity in urban areas is less distinct, as it is either a question about competitiveness compared with other grid supply options or a local social and economic issue at household or community level where access is hampered by legal land issues or affordability and small scale RE technologies can here play the same role as in rural areas.

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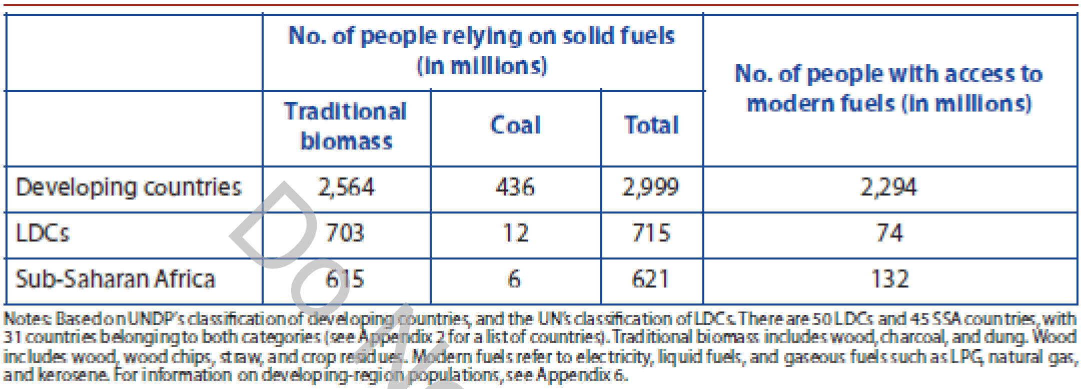
[2] See also: on-line Earth trends database on electricity access http://earthtrends.wri.org/searchable_db/index.php?theme=6

UNDP and WHO (UNDP and WHO, 2009) have assessed the number of people who rely on solid fuels for cooking. As shown in Table 9.3.3 there are around 2.5 billion relying on traditional biomass like wood, charcoal and dung for cooking energy and close to another half billion that uses coal for cooking. Uncertainty in these estimates is high, but the span is limited across the different data sources (IEA, 2010).

Table 9.3.3 Number of people relying on solid and modern fuels for cooking for LDCs and SSA, 2007 (UNDP and WHO, 2009)



	No. of people relying on solid fuels (in millions)			No. of people with access to modern fuels (in millions)
	Traditional biomass	Coal	Total	
Developing countries	2,564	436	2,999	2,294
LDCs	703	12	715	74
Sub-Saharan Africa	615	6	621	132

Notes: Based on UNDP's classification of developing countries, and the UN's classification of LDCs. There are 50 LDCs and 45 SSA countries, with 31 countries belonging to both categories (see Appendix 2 for a list of countries). Traditional biomass includes wood, charcoal, and dung. Wood includes wood, wood chips, straw, and crop residues. Modern fuels refer to electricity, liquid fuels, and gaseous fuels such as LPG, natural gas, and kerosene. For information on developing-region populations, see Appendix 6.

This shows that around 1 billion people with some form of electricity access have to rely on biomass, kerosene, coal or LPG for energy demanding services like cooking (Bravo *et al.*, 2008; Karekezi *et al.*, 2008; Dhingra *et al.*, 2009).

More detailed analysis is generally hampered by very poor data about energy consumption among the poor in many developing countries. While an increasing number of national censuses include energy related data, the coverage is still very limited for poor peri-urban and rural households with no official registration or land ownership (GNESD, 2008; Dhingra *et al.*, 2009). The analytical constraints are compounded by the lack of well defined and generally accepted indicators (IEA, 2010).

The very dominant use of biomass fuels for cooking purposes, mainly indoors, has a number of documented negative health effects (Barnes *et al.*, 2009) in addition to social effects related to time spent on gathering fuel or paying high shares of income for small amounts of commercial biomass and environmental aspects like deforestation in areas where charcoal and market based biomass are the dominant fuels. For further information on specific pollutants, please refer to Section 9.3.4.

Figure 9.3.5 illustrates the magnitude of the health problems associated with indoor air pollution and provides a comparison with other major deadly diseases. The figure shows that while many international and national efforts are focusing on the other diseases, household indoor air pollution is projected to exceed other major causes of premature deaths (e.g. HIV/AIDS, malaria and TB) by 2030.

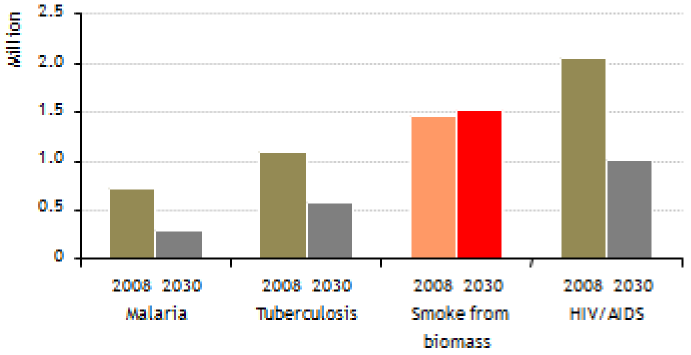


Figure 9.3.5 Premature deaths from household air pollution and other diseases (IEA, 2010).

The health problems like chronic obstructive pulmonary disease and pneumonia are most severe for women and children (Barnes *et al.*, 2009; Haines *et al.*, 2009; UNDP and WHO, 2009). As illustrated by Figure 9.3.6, there is in addition a strong correlation with household income and use of low quality fuels, illustrating that it is the poorest of the poor, who are at risk.

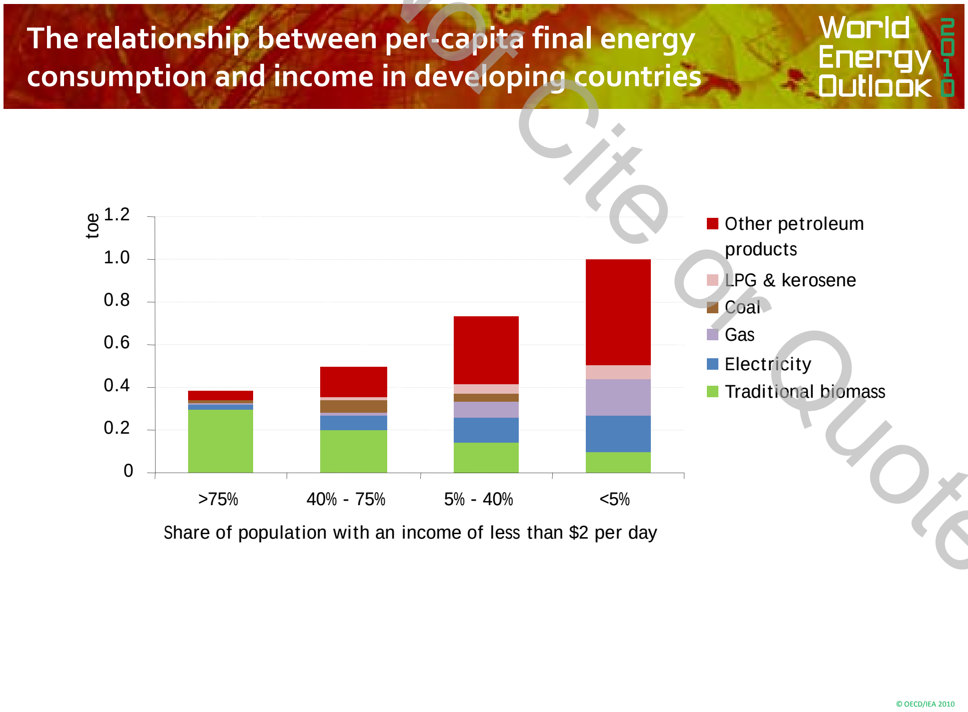


Figure 9.3.6 The relationship between per-capita final energy consumption and income in developing countries (WEO, 2010).

While the importance of access to energy is widely recognized, it is not equally well understood what this actually means in practice and how contributions from renewable energy sources can make a specific difference with regard to providing access in a more sustainable manner than other energy sources. The specific relevance for electrification in remote areas has been mentioned above (Nouni *et al.*, 2008; Deichmann *et al.*, 2010).

A study by the Global Network on Energy for Sustainable Development (GNESD, 2007b) examined the options for RE technologies in making specific contributions to rural development and found that a number of non-electrical technologies like solar drying and water heating, treadle and wind pumps for mechanical power, biogas for cooking and power, etc. were highly relevant for satisfying priority household and productive energy requirements in areas with no access to electricity (cooking, water heating, heating, water pumping). This is also illustrated by the overview in Table 9.3.4 of possible ways RE can provide the basic energy services required. Furthermore, the study found a high potential in relation to these technologies for local job generation and increased economic activity through system manufacture and renewable resource extraction and processing.

Implementation of RE based energy access programs are expanding quite rapidly but there is still quite limited research on the sustainability related aspects and there is hardly any literature on large scale implementation. Instead, one has to rely on a few specific examples of actions where elements of energy access has been provided with a specific focus on the combination of social and productive services utilizing the potential for local job creation through small scale business development (Van der Vleuten *et al.*, 2007; Nouni *et al.*, 2008; Kaundinya *et al.*, 2009; Peters *et al.*, 2009; Urmee *et al.*, 2009; Jonker Klunne and Michael, 2010). The assessment and case examples available, however, show that energy access is key for achievement of the MDGs and for economic development in general. Renewable energy technologies have the potential to make a significant contribution to improving the provisions of clean and efficient energy services. But in order to ensure full achievement of the potential sustainable development benefits from RE deployment it is essential to put in place coherent, stable, supportive political and legal frameworks. The options and barriers for such frameworks are further assessed in Chapter 11 of this report.

Table 9.3.4: Transition to Renewable Energy in Rural (Off-Grid) Areas (REN21, 2010).

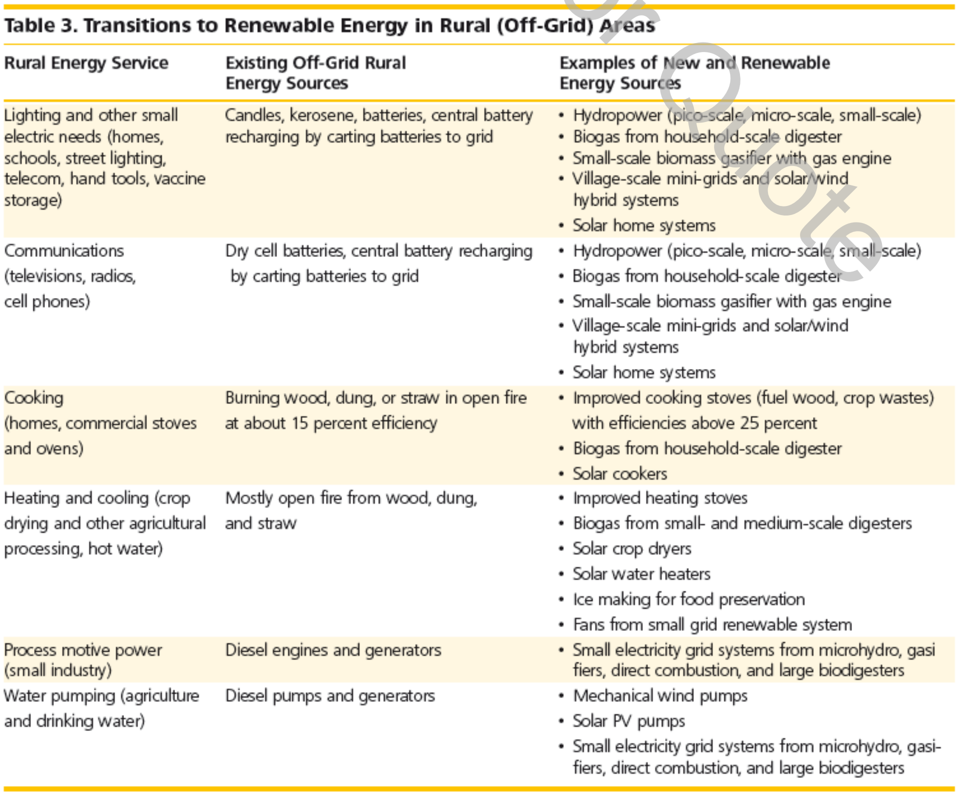


Table 3. Transitions to Renewable Energy in Rural (Off-Grid) Areas

Rural Energy Service	Existing Off-Grid Rural Energy Sources	Examples of New and Renewable Energy Sources
Lighting and other small electric needs (homes, schools, street lighting, telecom, hand tools, vaccine storage)	Candles, kerosene, batteries, central battery recharging by carting batteries to grid	• Hydropower (pico-scale, micro-scale, small-scale) • Biogas from household-scale digester • Small-scale biomass gasifier with gas engine • Village-scale mini-grids and solar/wind hybrid systems • Solar home systems
Communications (televisions, radios, cell phones)	Dry cell batteries, central battery recharging by carting batteries to grid	• Hydropower (pico-scale, micro-scale, small-scale) • Biogas from household-scale digester • Small-scale biomass gasifier with gas engine • Village-scale mini-grids and solar/wind hybrid systems • Solar home systems
Cooking (homes, commercial stoves and ovens)	Burning wood, dung, or straw in open fire at about 15 percent efficiency	• Improved cooking stoves (fuel wood, crop wastes) with efficiencies above 25 percent • Biogas from household-scale digester • Solar cookers
Heating and cooling (crop drying and other agricultural processing, hot water)	Mostly open fire from wood, dung, and straw	• Improved heating stoves • Biogas from small- and medium-scale digesters • Solar crop dryers • Solar water heaters • Ice making for food preservation • Fans from small grid renewable system
Process motive power (small industry)	Diesel engines and generators	• Small electricity grid systems from microhydro, gasifiers, direct combustion, and large biodigesters
Water pumping (agriculture and drinking water)	Diesel pumps and generators	• Mechanical wind pumps • Solar PV pumps • Small electricity grid systems from microhydro, gasifiers, direct combustion, and large biodigesters

The REN study refers to rural (off-grid) applications but other studies (GNESD, 2007b) show that many of the options apply equally to the increasing number of slum communities in peri urban areas where many households are not able to gain legal or economic access to even nearby electricity grids (Jain, 2010). Energy access through some of these technologies allows local communities to widen their energy choices, stimulate economies and incentivize local entrepreneurial efforts as well as meeting basic needs and services related to lightening and cooking and thus reaping ancillary health and education benefits.

As a final caveat, it also should be noted that different RE facilities, i.e. distributed versus central supply, face very different constraints, with the latter experiencing similar barriers as conventional energy systems, i.e. high upfront investments, siting considerations, infrastructure and land requirements as well as network upgrade issues.

9.3.3 Enhanced Energy security

Based on the four broad themes of energy security outlined in Section 2.2 (availability of resources, risk of energy supply disruptions, diversity of energy supply and temporal fluctuations of energy supply) this section will assess the evidence on the potential contribution of renewable energy technologies to energy security goals at a macro level. Additionally, it will briefly discuss energy security issues at the micro-level that go beyond grid stability problems.

9.3.3.1 Macro-level: security of supply

Fig. 9.3.7, which depicts the ratio of proven reserves to current production (R/P), i.e. for how many years production at current rates could be maintained before reserves are finally depleted, illustrates potential fossil fuel scarcities. While scarcity of coal (with a global R/P ratio of more than one hundred years) is not a major issue at the moment, at the current rate of production global proven conventional reserves of oil and natural gas[3] would be exhausted in about 45 and 62 years, respectively[4]. As has been highlighted by the IEA in its World Energy Outlook 2008 (WEO, 2008), accelerated economic growth in many parts of the developing world is likely to raise global energy demand, which could further shorten the life-span of remaining fossil fuel resources. Even though technological progress allows tapping reservoirs of oil from so-called non-conventional sources (such as e.g. oil sands), usually large investments are required, which raise extraction costs and the price of oil and gas (Bentley, 2002). In addition, increasing amounts of energy are needed to produce a given quantity of usable energy from depleted conventional as well as from non-conventional reserves. Published estimates of the ratio of energy output-to-input (Energy Return on Energy Invested, EROEI) for conventional oil indicate that there has been a strong decline over time (Cleveland, 2005), while the EROEI for non-conventional resources is even lower (Seljom *et al.*, 2010; WEO, 2010). Thus, it is not surprising that the fossil-fuel industry, particularly in the case of oil, has seen sharp increases in extraction costs over the past decade, although equipment, raw materials and labour demand have also

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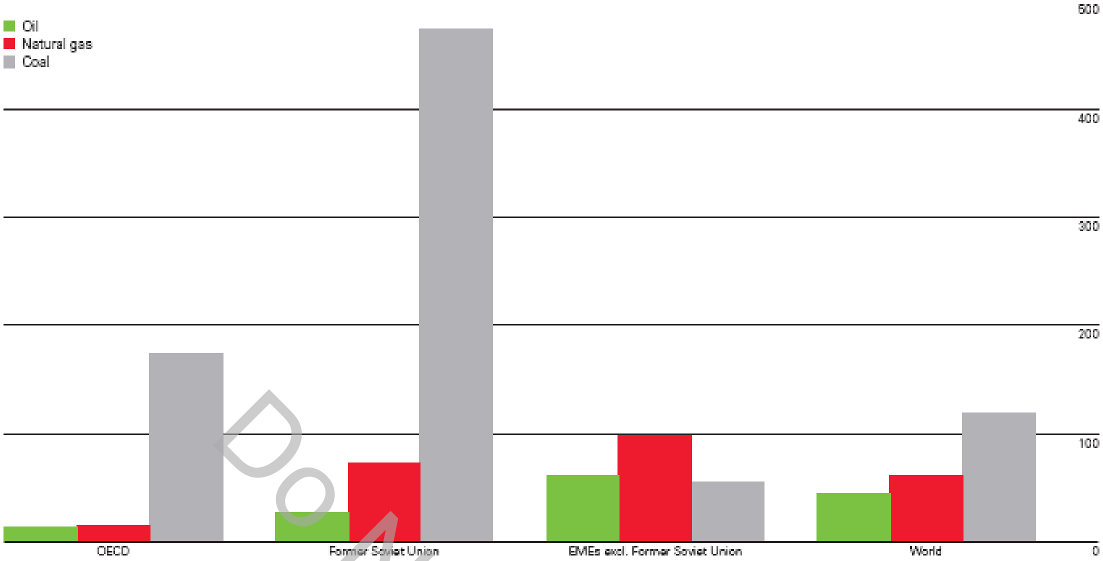
[3] Recent discoveries of shale gas and coal-bed methane and improvements of extraction technologies are expected to result in notable production of natural gas from these non-conventional resources in the near future WEO, 2008: *World Energy Outlook 2008* IEA.

[4] Since 1990, proven conventional reserves of oil and natural gas have moderately grown due to revisions in official statistics, new discoveries, and increased recovery factors. However, new discoveries have lagged behind consumption. Ultimately recoverable reserves (which include reserves that are yet to be discovered) are considerably larger than proven reserves; their actual size crucially depends on future oil prices and development costs Ibid.

played a role (EIA, 2009). Correlated with the increasing amounts of input energy to extract resources are the life-cycle carbon emissions from these resources.



While coal remains the world's most abundant fossil fuel, with an R/P ratio of 119 years, proved reserves of oil and natural gas increased in 2009 and have tended to rise over time. OECD countries account for less than 10% of global proved reserves for oil and natural gas, but 42.6% of proved coal reserves.

Figure 9.3.7 Ratio of proven (conventional) reserves of production for oil, natural gas, and coal (in years) at the end of 2009 for different regions. Source: (BP, 2010).

The spatial distribution of reserves, production, and exports of fossil fuels is very uneven and highly concentrated in a few regions, as can be seen from Figure 9.3.8. Over 60% of coal reserves are located in just three regions (the United States, China and the former Soviet Union; (BP, 2010), and in 2009 China alone accounted for about half of global production of hard coal (WEO, 2010). Over 75% of natural gas reserves are held by OPEC nations and states of the Former Soviet Union, and 80% of the global gas market is supplied by the top ten exporters. This heavy concentration of energy resources, many of which are located in politically unstable countries, creates a dependency for importers and raises the danger of disruptions of energy supply (Gupta, 2008). However, it should be noted that the conventional wisdom that oil-price shocks were responsible for the recessions in the 1970s is not easily supported by econometric evidence (Bohi, 1991; Barsky and Kilian, 2004) unless it is assumed that changes in oil prices have also triggered simultaneous changes in the demand for consumption goods and durables, such as automobiles (Lee and Ni, 2002; Hamilton, 2005).

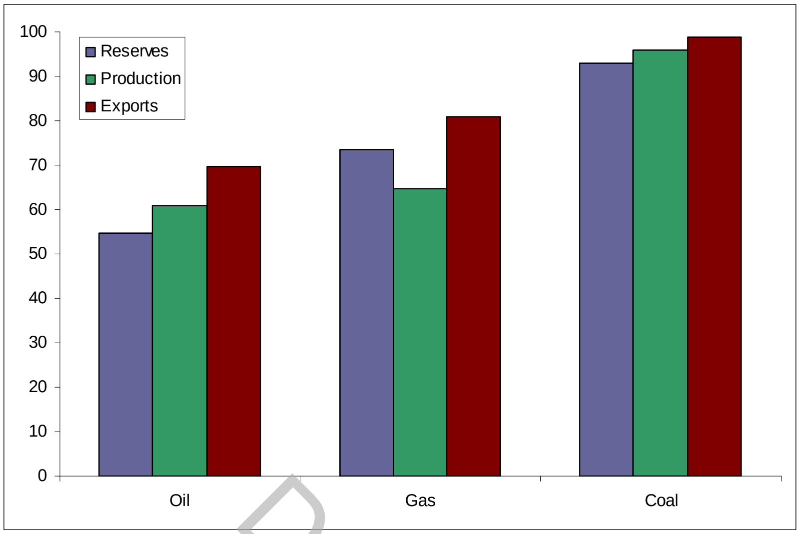


Figure 9.3.8 Concentration of (i) reserves, (ii) production, and (iii) exports of oil, gas, and coal. Concentration is measured by the cumulative share of the top ten resource owners / producers / exporters (in %). Source: Own calculations based on (WEO, 2010) and (BP, 2010).

As there is relatively little overlap between the location of fossil fuel reserves and the place of their consumption, fossil fuels are heavily traded and many countries with relatively scarce endowments rely heavily on imports of energy to meet desired levels of consumption. Due to the fact that a substantial share of global energy trade is channelled through a rather small number of critical geographical areas (so-called ‘chokepoints’), it is highly vulnerable to accidents or terrorist attacks and importers face a considerable risk of supply disruption or price hikes (Gupta, 2008). Figure 9.3.9 shows that currently the Euro area, North America, and East Asia and the Pacific region are such net importers. Traditionally, the Euro area is the region which displays the highest share of imports in total energy use, which amounted to about 63% in 2007. For North America (which enjoys relatively abundant reserves of fossil fuels), dependence on energy imports has increased considerable in the last decades, from less then 10% in 1990 to more than 20% in 2007. The Middle East and North Africa are the most important exporters of fossil fuels (for the region as a whole, exports of oil and gas by far exceeded domestic consumption), and to some lesser extent Russia, Sub-Saharan Africa as well as Latin America and the Caribbean. This particular constellations leads to a situation in which countries that heavily depend on energy imports frequently raise concerns that their energy consumption might be seriously affected by possible disruptions of supply (Sen and Babali, 2007).

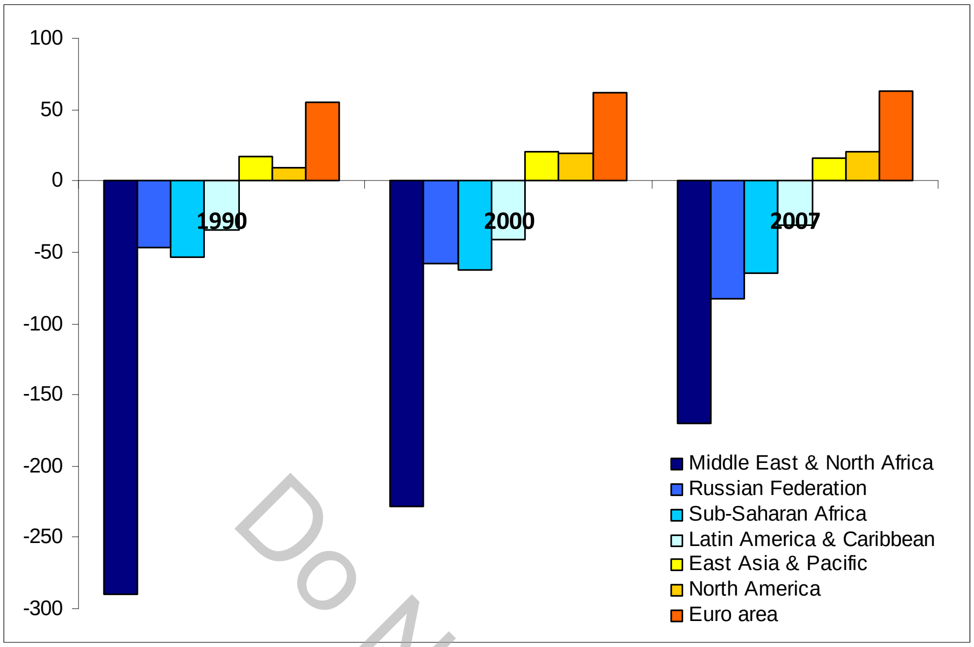


Figure 9.3.9 Energy imports as share of total primary energy consumption (in %). Negative values denote net exporters of energy carriers. Source: Own graph, based on (WDI, 2010).

RE can improve energy security in all the three of the dimensions discussed above. First, increased use of renewables permits countries to substitute away from the use of fossil fuels, such that existing reserves of fossil fuels are depleted less rapidly and the point at which these reserves will eventually be exhausted is shifted farther into the future (Kruyt *et al.*, 2009). Second, to the extent that countries with large reserves increase their own consumption as part of the development process, less will be available for export to other countries, thus leading to potential tensions over access. As many renewables are localized and not internationally tradable, increasing their share in a country's energy portfolio diminishes the dependence on imports (Grubb *et al.*, 2006). The extent to which this diminishes the risk of energy supply disruptions depends, however, on the supply characteristics of the energy sources that substitute the imported energy. Third, RE resources are far more evenly distributed around the globe than fossil resources (WEC, 2007). Therefore, energy systems suitable for RE help to diversify the portfolio of energy sources (Awerbuch, 2006; Bazilian and Roques, 2008), and to reduce the economy's vulnerability to price volatility (Awerbuch and Sauter, 2006). Besides these advantageous properties, renewable energies also possess some drawbacks with their variable availability due to e.g. seasonal variability or changing weather conditions (see also Chapter 8) probably being the most important ones. These problems can be addressed developing and/or deploying appropriate technical solutions such as increased storage and back-up capacity (Azoumah *et al.*, in press) as well as optimized institutional settings for energy markets, e.g. regionally integrated electricity markets in which local fluctuations are smoothed by means of geographic diversification (Roques *et al.*, 2010). These technical solutions and arrangements involve, however, additional costs which have to be taken into account in the comparison to the relative benefits of RE and conventional energy technology projects. More generally, as highlighted in Section 9.3.1.3, evaluating if a certain technology is desirable requires not only the direct costs involved, but also all positive and negative external effects as well as existing subsidies (on RE and fossil fuels) to be included in the analysis.

9.3.3.2 Micro-level

As shown in Section 9.3.1.3, the reduction of import bills for conventional energy is an important motivation for developing countries to promote RE. However, part of diversification may also be to engage more in regional power sector integration and there are emerging regional power collaborations in East, West and Southern Africa, South and Central America, and South East Asia that aim to enhance the reliability of electricity grids and therefore local supply. ESMAP has studied 12 sub-regional integration schemes (ESMAP, 2010) and found that for most schemes energy security has been one of the motivating factors. Larger integrated networks may also provide benefits in terms of cost efficiency, trade and more general economic development.

Many developing countries specifically include providing adequate and affordable access to all part of the population as part of their definition of energy security and in this way links the access and security issues while broadening the concept to include stability and reliability of local supply. While regional interconnections may be an interesting way to ensure better supply security at the national level it does not automatically “trickle down” to the poorer segments of the population in terms of increased access or even stable and affordable supply for those who are connected. GNESD has examined the effects of power sector reforms on access levels and found that only when there was strong political commitment to improve access to electricity by poor households did reforms deliver results (GNESD, 2004). Explicit focus on poor households was found essential along with specific protection of funds for electrification.

While electricity connection is often used as a key indicator for access to modern energy services it is important to underline that household connections have restrictions in terms of capacity, stability and outage problems, as illustrated by the data from the World Bank and IEA and can be seen in Table 9.3.5.

Table 9.3.5 Indicators of the reliability of infrastructure services (IEA, 2010)

	Sub-Saharan Africa	Developing countries
Delay in obtaining electricity connection (days)	79,9	27,5
Electrical outages (days per year)	90,9	28,7
Value of lost output due to electrical outages (per cent of turnover)	6,1	4,4
Firms maintaining own generation equipment (percent of total)	47,5	31,8

Energy security at the micro level in developing countries may therefore have a number of social and economic effects that go beyond direct impacts of any fuel price increases (Jain, 2010). Improving access to affordable and reliable energy supply will therefore not only provide improved energy services, but it will broadly increase productivity, avoid parallel investments in infrastructure from small scale generation equipment to parallel lighting and cooking systems where most household have at least two different options to hedge against unstable supply.

However, decentralized RE is competitive mostly in remote and rural areas, while grid connected supply generally dominates denser areas where the majority of households reside (Deichmann *et al.*, 2010).

9.3.4 Reduced environmental impacts

Sustainable development must ensure environmental quality and prevent undue environmental harm. As no large-scale technology deployment will come without environmental tradeoffs, environmental interventions and impacts of RE technologies should be evaluated and compared to conventional alternatives prior to their concerted deployment. The goal of this section is to evaluate the current evidence along multiple environmental indicators. The complexity of technologies and the environment, knowledge gaps and incommensurate metrics and methods thwart a fully comprehensive and clear-cut assessment. For example, it is not possible to cover all relevant environmental aspects and impact[5] categories of energy chains within the scope of this chapter. Moreover, the large-scale application of new technologies may lead to unanticipated impacts. Nevertheless, conclusions can be drawn in a few areas.

This section concentrates in large parts on electricity generation and transport fuels, as these areas are best covered by the literature. Heating and household energy are discussed only briefly, in particular with regards to air pollution and health. Regarding life-cycle impacts of heating fuels, upstream impacts of fuel extraction and processing are in many cases similar to those of the corresponding transport or electricity generation chains, but some new technologies such as heat pumps or passive solar may exhibit completely different properties. The employment of renewable energy technologies in the passenger transport sector includes liquid or gaseous fuels produced from biomass feedstock in conventional internal combustion engine vehicles; use of renewable electricity generation for charging of electric battery vehicles or hydrogen production with subsequent use of this hydrogen in combustion engine or fuel cell vehicles. As currently only utilization of biofuels can be considered as a mature technology available for large-scale application. Generally, the focus of this subchapter is on current technologies, and only limited discussion of technology integration options can be provided.

Data available for different attributes vary widely regarding number and quality of sources. GHG emissions are generally well covered, and can therefore be compared across technologies. A significant number of studies reports on air pollutant emissions and operational water use, but evidence is scarce for life-cycle emissions to water, and land use, and health impacts other than those linked to air pollution. Impacts on biodiversity and ecosystems are mostly site-specific and difficult to quantify. Therefore, the discussion on biodiversity and ecosystems remains qualitative, in particular as evidence for most technologies is anecdotal. To account for burdens associated with accidents as opposed to normal operation, we conclude with an overview about risks associated with ET in the last section of this subchapter. Omitted from this evaluation is the critical issue of constrained supply of some materials, which could not be addressed for lack of comprehensive and comparable sector-level data for all energy technologies.

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[5] Within this subsection, the terms impact and impact categories are not used in the strict sense of their definition within the field of LCA.

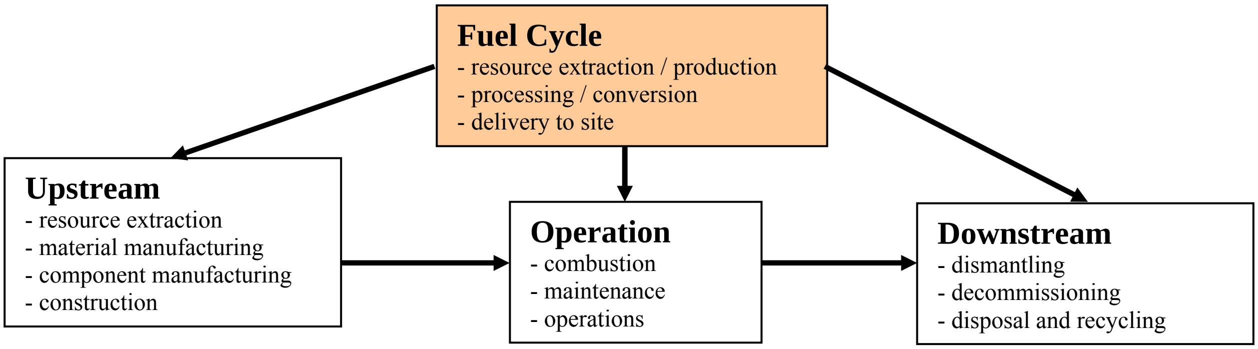

Figure 9.3.10 Schematic of generalized life-cycle stages for an energy technology. Examples of specific stages within the broad categories of upstream, operation, downstream and fuel cycle will differ by energy technology. The fuel cycle as employed in operations is only applicable to fossil-fuel, biopower and nuclear technologies, however, to the extent fuels are used in other life cycle stages (e.g., to power construction equipment or maintenance vehicles) it is applicable to all technologies. For these complexities, this box is distinguished from the others by shading. Background processes, such as electricity supplied by the grid, are not shown in this figure but are relevant to all stages. [TSU: Figure will be redesigned to more clearly depict different stages of Energy LCA]

When accounting for all effects along global supply chains, one particularly useful approach for quantifying and fairly comparing environmental impacts of energy technologies is Life-Cycle Assessment (LCA). LCA systematically quantifies the impacts of a technology (or product or process) across its life cycle (Figure 9.3.10). LCA studies provide a well-established, comprehensive and quantitative basis for comparing RE to conventional energy technologies. Because this section reviews the results of hundreds of LCAs, the methods, advantages and limitations of LCA in the context of energy systems are discussed briefly here. LCA methodologies have been evolving for a few decades and are now supported by international initiatives ((UNEP and SETAC, 2010)) and governed by standards ((ISO, 2006a; ISO, 2006b)). The majority of the available literature on energy systems is based on so-called attributional LCAs, mostly process-based studies. Most published LCAs of energy supply technologies only assemble life cycle inventories, quantifying *emissions* to the environment (or use of resources) rather than *effects* (or impacts) on environmental quality. When relying on LCA data, this section uses a similar approach.

Though LCA is increasingly applied to energy technologies, some methodological challenges persist (Udo de Haes and Heijungs, 2007). These include allocation of multi-process inputs and outputs, potential for multiple-counting when assessing large interconnected energy systems (Lenzen, 2009), and assumptions regarding the background system (Curran et al 2005; Weidema and Ekvall 2009; Brander et al 2008). For process based LCA, lack of completeness owing to the setting of a fixed system boundary has been shown by multi regression analysis (Lenzen and Munksgaard, 2002; Lenzen, 2008).

A key limitation to attributional LCA in the context of energy technology is its lack of consideration of effects in market-related sectors not directly included in the supply chain of the system of interest. An approach to better reflect the dynamic interdependencies within the energy system and between the energy system and other economic sectors is the recently developed consequential LCA, which considers the marginal effects of implementing a technology, *and* displacing and changing the operation of other technologies, as reflected by market dynamic interactions between technologies and industries (Rebitzer et al (2004), Finnveden et al (2009) and Brander et al (2008)).

For electricity generation, this approach is central in two ways. First, attributional LCAs look at the electricity generating facility in isolation, excluding relevant systemic changes that might result from the decision to instal additional renewable capacity. For instance, for variable renewable energy sources such as wind and PV, the variability and limited predictability leads to an increased need for balancing reserves and efficiency penalties for the remaining conventional power plants (Pehnt, Oeser et al. 2008, Gross et al. (2007).

Second, characteristics of the background energy system (e.g., its carbon intensity) particularly affect LCAs of most renewable energy technologies, since their life-cycle impacts stem almost entirely from component manufacturing (e.g. (Lenzen and Wachsmann, 2004).

Variability in published LCA results can be substantial (as seen for example in Figure 9.3.11), partly due to variation in spatial and temporal aspects of the analysed system (e.g. background energy system, the energy resource and geographic context), as well as technology characteristics (e.g., design, capacity factor, variability, service lifetime and vintage). Differences in LCA technique (e.g. process based LCA, or hybrid input-output LCA) and central methods and assumptions (e.g., co-product allocation, avoided emissions, study scope) are also important.

Given these significant caveats, emphasis will be placed on the underlying reasons for uncertainties and variations when describing the results for selected energy technologies.

The discussion presented here cannot take the place of an evaluation of local impacts in the context in which a technology is meant to be deployed. Such evaluations are critical for accomplishing sustainable development with minimal environmental harm. Still the knowledge of aggregate emissions to the environment enables comparison between technologies on a global and generic level, if limitations are transparent and well understood.

Energy payback [TSU: will go into a box]

The role of high quality energy sources for the development of modern civilizations is widely recognized. The energy return on energy invested (EROEI) and similar concepts are used as a measure for the ability of technologies or fuels to supply the energy needs of modern societies. In the following, we characterise the balance between the energy expended for the manufacture, operation and decommissioning of electricity generating plants (the “embodied” energy) and their energy output in terms of an energy payback time (EPT), ie the operational time it would take the technology to recuperate its own embodied energy. For combustion technologies, this includes the energy requirements of fuel extraction and processing, but not the energy content of the fuel itself. The EPT is closely related to other common metrics such as the Energy Ratio (ER), the Energy Payback (EP), or the Energy Return On Energy Investment (EROEI). The latter quantities depend on assumptions about the expected lifetime of a plant, which is also shown below. For some renewable energy technologies, e.g. wind and PV, EPT have been declining rapidly over the last years due to technological advances and economies of scale. Thermal power technologies are characterised by the ongoing energy requirements for fuel extraction and processing, ultimately resulting in higher EPT. This might become of increasing importance with declining qualities of conventional fuel supply, and increasing shares of unconventional fuels (Farrell, 2006) (Gagnon, 2008b), Lenzen 2008.

All values in Table 9.3.6 vary with LCA methodology, scope, plant vintage, and assumed plant lifetime. In addition, the capacity factor has a major bearing on the energy payback time in particular of variable renewable energy technologies. Apart from these common parameters, the ranges in Table 9.3.6 are mainly caused by variations in:

- fuel characteristics (for example coal moisture), cooling method, ambient and cooling water temperatures, and load fluctuations (coal and gas),
- ore grades and enrichment technology (nuclear),
- crystalline or amorphous silicone materials (PV),
- power rating (wind), and
- storage capacity and design (concentrating solar).

Table 9.3.6 Energy payback times and energy ratios of electricity-generating technologies (derived from (Lenzen 1999; Lenzen and Munksgaard 2002; Lenzen, Dey et al. 2006; Gagnon 2008; Lenzen 2008; Kubiszewski, Cleveland et al. 2010)).

Technology	Energy payback time (y)		Assumed	Energy Ratio (kWhel/kWhprim)	
	Low value	High value	lifetime (y)	Low value	High value
Brown coal, new subcritical	1.9	3.7	30	2.0	5.4
Black coal, new subcritical	0.5	3.6	30	2.5	20.0
Black coal, supercritical	1.0	2.6	30	2.9	10.1
Natural gas, open cycle	1.9	3.9	30	1.9	5.6
Natural gas, combined cycle	1.2	3.6	30	2.5	8.6
Heavy water reactors	2.4	2.6	40	2.9	5.6
Light water reactors	0.8	3.0	40	2.5	16.0
Photovoltaics	0.5	11.0	25	1.2	15.0
Concentrating solar	0.7	7.5	25	1.0	10.3
Geothermal	0.6	3.6	30	2.5	14.0
Wind turbines	0.1	1.5	25	5.0	34.0
Hydroelectricity	0.1	3.5	70	6.0	280.0

The low energy density of biomass-based energy has spurred a vivid and controversial dispute about net energy yields from Biomass and its ability to supply a developed economy with sufficient energy (e.g. (Cleveland, 2005),(A. Pradhan, 2008), (Cherubini *et al.*, 2009), (Pimentel *et al.*, 2009), (Farrell *et al.*, 2006) Pimentel and Patzek (2008). Due to this ongoing controversy, including uncertainties about net energy metrics for bioenergy, and the very wide array of resulting estimates, Biopower is not included in the Table 9.3.6.

9.3.4.1 Climate change

Life Cycle GHG Emissions of Electricity Generation Technologies

This section synthesizes literature estimates of life cycle GHG emissions of electricity generation technologies powered by renewable and non-renewable resources, along with the current state of knowledge, and its limitations, regarding specific generation technologies and key drivers of life cycle GHG emissions. Figure 9.3.11 displays variability and central tendency in previously published estimates based on a comprehensive review of primary literature covering all regions of the world; literature collection, screening and analytical procedures are detailed in the Methods Annex as well as citations for all references used in Figure 9.3.11.

Estimates of GHG emissions associated with land use change (LUC) are not included in Figure 9.3.11. LUC-related GHG emissions are especially important for reservoir-based hydropower and biopower technologies, and are areas of active research. Current estimates of LUC-related emissions for biopower systems, mostly utilizing lignocellulosic feedstocks, could increase non-LUC-related life cycle GHG emissions (EPA, 2010). However, relative to typical starch, sugar, and oil crops that are often used to produce biofuels, lignocellulosic feedstocks are likely to have lower or possibly negative (beneficial) LUC impacts (Hoefnagels et al., 2010; Fargione et al. 2010) as they often enhance soil carbon and can have a smaller land displacement effect (US EPA, 2010). Nevertheless, uncertainties in their estimation are high relative to our understanding of emissions associated with the technology itself. For bioenergy systems, a text box in this section briefly summarizes the main issues of LUC, albeit with a biofuels focus; Ch. 2 provides a more detailed discussion on biopower systems. Ch 5 addresses the LUC issue for hydropower. LUC-caused GHG emissions from resource extraction for other electricity generation technologies (e.g., GHG emissions from soils exposed to air after mountaintop-removal coal mining (Fox and Campbell, 2010) or from oil production (Yeh et al., 2010)) are even more uncertain and less frequently studied than for hydropower and bioenergy (Gorissen et al., 2010).

The present review relies on attributional LCAs, whose methodological limitations, as discussed in the introduction to this section, should be kept in mind. In particular, the functional unit typically reported by electricity generation LCAs (unit of electricity generated) does not account for the quality of power produced, e.g., its variability, dispatchability and distance from load. Further, attributional LCAs, which the assessment of this chapter relies on, consider the electricity generation unit (EGU) analyzed in isolation from the system in which it is embedded. Impacts to the electrical system from the decision to add a new EGU can cause additional GHG emissions compared to the system without that unit. For instance, Pehnt et al. (2008) found that 20 to 75 g CO2-e/kWh additional GHG emissions are caused by adding offshore wind to the German electrical system owing to operational impacts of wind energy, including the increased need for balancing reserves and part-load efficiency penalties for the remaining conventional power plants due to the variability and limited predictability of wind energy. A broad review of similar studies confirms the findings of Pehnt et al. (Gross, 2007). Similar impacts could result from the introduction of other variable generation technologies, and additional research on the general issue of systemic impacts could alter our understanding of GHG emissions attributable to electricity generation technologies.

In addition, understanding limitations to the interpretation of the distributions displayed in Figure 9.3.11 is also important. The median value of published estimates does not necessarily reflect the likeliest or typical outcome for a given technology in any specific or set of deployment contexts.

Also, estimates collected from a review of published literature do not represent a statistical sample (of electricity generators, designs, applications, deployment contexts, etc.); therefore, statistical inferences should not be drawn. Finally, despite the depth of previous estimates for many technologies, cases outside the bounds of previous research can exist, so the range defined by the estimates reviewed here does not necessarily define the true minima or maxima for a given technology under all deployment conditions. Nevertheless, given the breadth and number of estimates available for many technologies and the broad agreement found under repeated, independent research, the state of knowledge for some technologies appears reasonably robust.

Based on estimates from existing research (Figure 9.3.11), life cycle GHG emissions normalized per unit of electrical output (g CO2e / kWh) from technologies powered by renewable resources are, in general, considerably less than from those powered by fossil fuel-based resources. Nuclear power exhibits a similar interquartile range (IQR; the range from 75th to 25th percentile values) and median as do technologies powered by renewable resources. The maximum estimate for many renewable energy-powered technologies (CSP, geothermal, hydropower, ocean energy and wind) is less than or equal to 100 g CO2e / kWh, although the number of references examining several of these technologies is small. The upper quartile of the distribution of estimates for photovoltaics and biopower extend 2-3× above the maximum for other RE technologies, as it does for nuclear, owing mainly to differences in system boundaries of the cited studies (nuclear) and cases of poorly performing production processes (PV, biopower).

Cases of post-combustion carbon capture and sequestration (CCS), shown as individual points in Figure 9.3.11, represent the emissions associated with the base technology plus CCS. As expected, their life cycle GHG emissions are considerably lower than the base technology's. Biopower with CCS displays significantly negative GHG emissions. It should be noted that although capture of CO2 is well known and commercial, the geological storage portion has not been deployed at commercial scale. The time horizon considered in each study and assumed leakage rate during that period can influence the reported results and the ultimate magnitude of GHG emission reduction benefit of these technologies.

Variability in estimates of life cycle GHG emissions from the evaluated technologies is caused by both factors related to the literature review method and factors relating to specific technologies. Many studies examined multiple scenarios that yielded a range of estimates depending on, for instance, different methodological choices (e.g., co-product allocation, avoided emissions, system boundary), design permutations, geographic location, background energy system characteristics (e.g., the GHG intensity of grid electricity), technological characteristics, or technological vintage, all of which are considered here even though some could be less likely to occur than others. Both theoretical and empirical studies were included, also increasing methodological variability.

For combustion technologies (fossil fuels and biopower), variability is also caused by the range of real conditions over which these plants are deployed, most prominently the capacity factor, the combustion technology employed, carbon content of the fuel and conditions under which fuel is grown/extracted and transported. Biopower additionally is affected by assumptions regarding the BAU use of the biomass feedstock. Biopower from residues and waste can be considered as avoiding CO2 and methane emissions when compared to, e.g., a BAU case of disposal in a landfill (labelled "with avoided emissions" in Figure 9.3.11). Variability for PV stems from the rapidly evolving and multiple solar cell designs, some of which appear to perform poorly in terms of GHG emissions. For solar, geothermal and wind technologies, the primary energy resource significantly influences power output. Hydropower variability is partially based on differing GHG emission profiles of hydropower technologies (run of river compared to reservoirs).

The key drivers of GHG emissions from technologies powered by renewable and non-renewable resources differ by life cycle stage. For non-renewable technologies except nuclear, the vast majority of GHG emissions are emitted during fuel combustion, and thus are related to the carbon content of the fuel and the efficiency by which fuel energy is converted to electrical energy. For nuclear and RE technologies, the majority of GHG emissions are upstream of operation. Most emissions for nuclear and biopower are generated during feedstock production (biopower) or fuel processing (nuclear) and for other renewable technologies from GHGs emitted during component manufacturing and used in facility construction. The background energy system that, for instance, powers component manufacturing, will evolve over time, so estimates today may not reflect future conditions. Nuclear also has a significant share of GHG emissions associated with decommissioning.

The state of knowledge on life cycle GHG emissions from the evaluated electricity generation technologies was assessed and found to vary. This synopsis was based on an assessment of the number of references and estimates, the density of the distribution of estimates (IQR and range relative to the median), and an understanding of key drivers of life cycle GHG emissions. Life cycle GHG emissions from fossil-fueled technologies and wind appear well understood. Reasonably well known, though with some open questions or need for additional research, are those for biopower, hydropower, nuclear, some PV technologies and CSP. The current state of knowledge of geothermal and ocean energy is not as well understood.

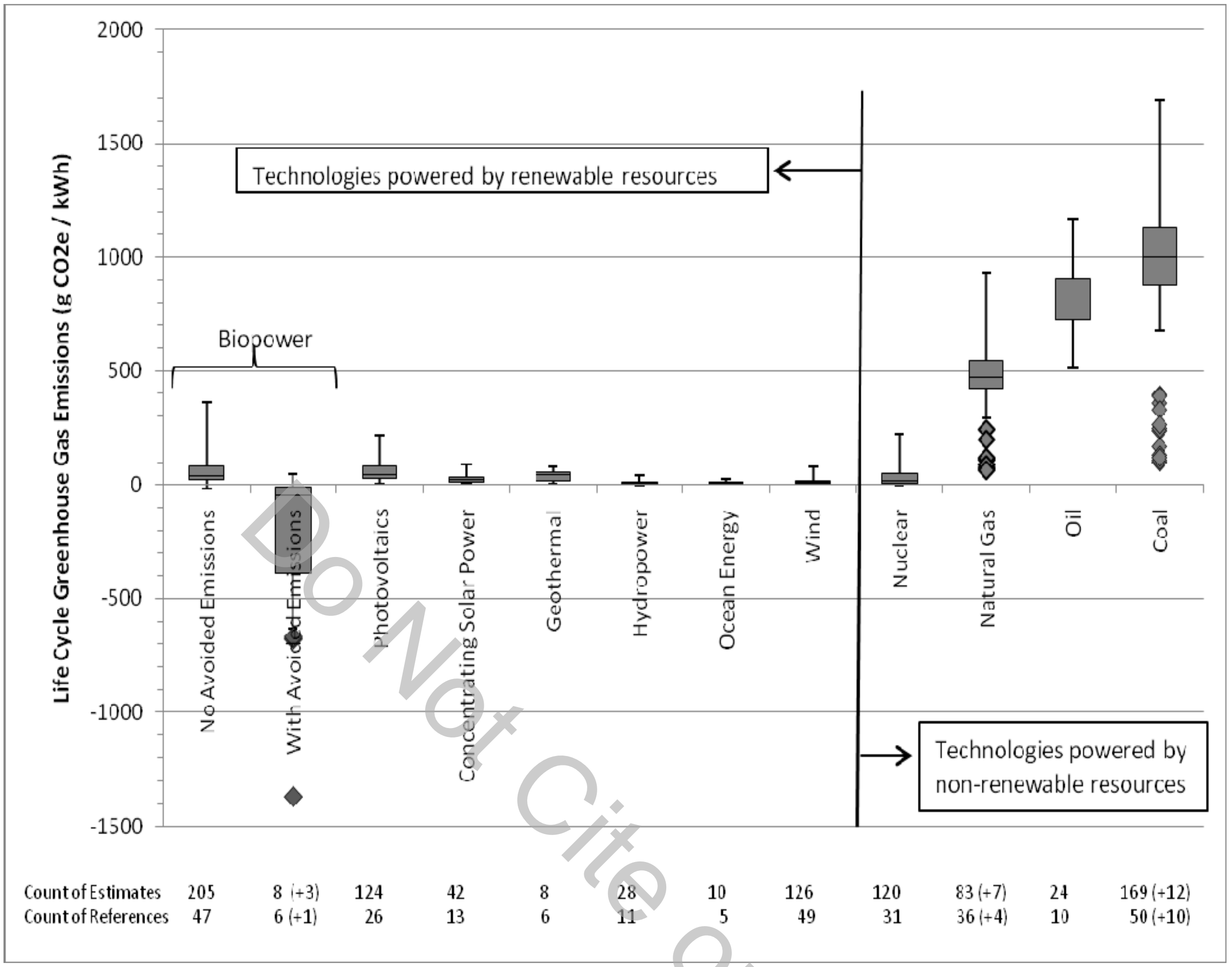

Figure 9.3.11. Estimates of life cycle GHG emissions (g CO2e / kWh) for broad categories of electricity generation technologies, plus some technologies integrated with carbon capture and storage (CCS). All estimates were screened for quality and relevance during a comprehensive literature review. See Methods Annex for details of methods and complete list of references. Count of estimates is greater than the count of references because many studies produced estimates based on multiple scenarios of deployment of the same technology. Counts are reported in parentheses for those technologies evaluated with CCS. Elements of the box and whisker did not consider CCS, and represent, from bottom to top: minimum estimate, 25th percentile, 50th, 75th and maximum. Technologies integrated with CCS are shown as points. [TSU: design will be optimized and harmonized among technology chapters and this chapter]

Life cycle greenhouse gas emissions of selected bio- and petroleum-based transportation fuels

Based on a review of selected life cycle assessment (LCA) meta-analyses and studies, this section presents literature-derived estimates of life cycle (LC) greenhouse gas (GHG) emissions for liquid, road transportation fuels derived from petroleum and biomass. Existing biofuels (e.g., sugar- and starch-based ethanol, and oil seed-based biodiesel and renewable diesel), and selected next-generation biofuels derived from lignocellulosic biomass (e.g., ethanol and Fischer-Tropsch diesel (FTD)) are considered.

LCAs of transportation fuels are generally conducted on a well-to-wheel (WTW) basis, which encompasses two major stages: the activities from feedstock production through processing to fuel delivery to the vehicle are referred to as the well-to-tank (WTT) stage while use of the fuel in the vehicle is referred to as the tank-to-wheel (TTW) stage. Here, only the WTT results are reported because this stage determines the differences between the petroleum fuels and biofuels considered here and because other chapters consider WTW comparisons. Since carbon contained in biofuels originates from CO_2 absorbed from the air through plant's photosynthesis, which is different from the fossil carbon in petroleum fuels, this "biogenic carbon" is counted as a credit in the WTT stage of biofuel production. Biogenic carbon is subsequently emitted during the TTW stage. The TTW GHG emissions are of similar magnitude across petroleum fuels and biofuels on the basis of 1 MJ of fuel combusted (ranging from 72 to 76 g CO_2 eq/MJ for gasoline, diesel, ethanol, biodiesel, renewable diesel and FTD) (CONCAWE, 2008; EPA, 2010). Given that the vehicle fuel efficiency (fuel energy required per unit distance traveled) remains virtually unchanged when biofuels (considered in this section) displace their counterpart petroleum fuels, the functional unit selected for comparative purposes here is 1 MJ of fuel available at the tank. Emissions from land use change are excluded for all fuels. (See Box on Direct and Indirect Land Use Change and Bioenergy in this chapter for a discussion of this topic.) Readers are encouraged to refer to Chapter 8 for a comparison of WTW GHG emissions of various fuels (including hydrogen and electricity) used in different vehicle configurations, and Chapter 2 for a detailed review of biofuel technologies and their LC GHG emissions.

Results from the meta-analyses and studies reviewed here suggest that both existing and next-generation biofuels have lower WTT GHG emissions compared to petroleum-derived gasoline and diesel fuels from a variety of sources (e.g., European, US, Middle Eastern, Nigerian, Venezuelan, and Canadian crude oil) (Figure 9.3.12). The range in WTT GHG emission estimates for petroleum fuels primarily results from variability in crude oil properties (e.g., viscosity, sulfur content) and differing assumptions on oil production and refining processes (NETL, 2008). In comparison, the ranges in GHG emission estimates for biofuel pathways are much wider than those for gasoline and diesel fuels. The wide ranges in GHG emissions cited for biofuels can be attributed to many factors, including the types of feedstocks utilized, land and soil productivity, crop management practices, conversion process employed, source of process energy, and methodological choices in LCAs such as coproduct allocation approaches and definition of system boundaries (Williams *et al.*, 2009; Cherubini and Strømman, 2010; Hoefnagels *et al.*, 2010).

Although there is significant overlap in the ranges of WTT GHG emissions for virtually all biofuels, not all biofuel systems are equally efficient in reducing GHG emissions compared to their petroleum-derived counterparts. For example, Brazilian sugarcane produces more biomass per unit fertilizer and land than European wheat and US corn (von Blottnitz and Curran, 2007; Miller, 2010). Further, processing starch crops into ethanol requires higher energy input per unit output than making ethanol from sugar (Solomon *et al.*, 2007). As a result, ethanol from sugarcane has lower WTT GHG emissions than that produced from wheat and corn.

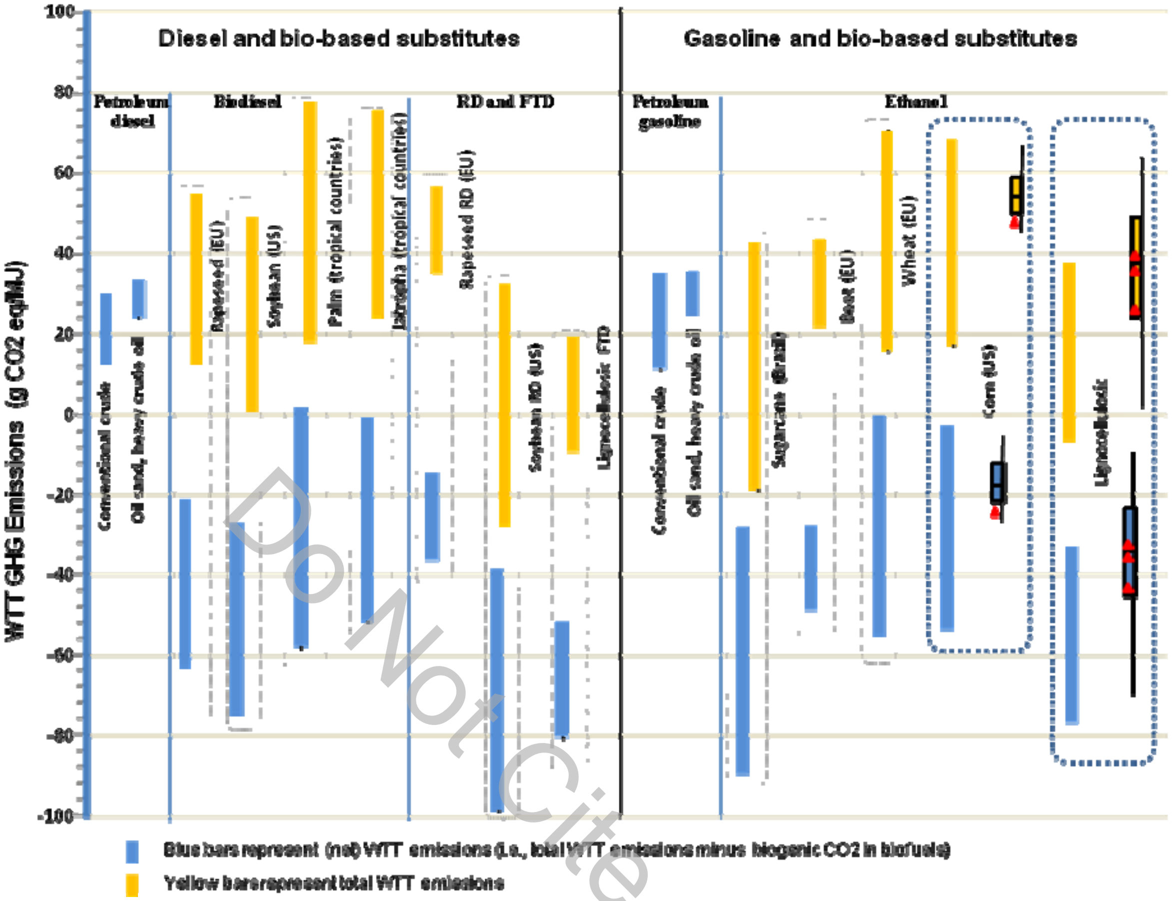

Figure 9.3.12. Ranges in reported WTT GHG emissions (blue bars) of petroleum fuels, existing biofuels and selected advanced biofuels derived from lignocellulosic biomass based on a review of selected literature. Biofuels exhibit lower WTT GHG emissions than petroleum-derived gasoline and diesel fuels based on the studies reviewed (without considering land use change). However, the magnitude of the differences between biofuels and petroleum fuels vary considerably, depending on many factors. [For corn and lignocellulosic ethanol (presented here as a combination of results for three feedstocks), results from Hsu et al. (2010) are presented separately using boxes and whiskers because their uncertainty analysis was more comprehensive than others. (In descending order, percentiles for the box and whisker are 95th, 75th, 50th, 25th and 5th.) The red triangles represent the reference cases examined for corn and three lignocellulosic feedstocks (in descending order of WTT GHG emissions: corn stover, switchgrass, and wheat straw) all with performance projected to year 2022.]
[Sources for estimates plotted: (Wu *et al.*, 2005; Fleming *et al.*, 2006; Hill *et al.*, 2006b; Beer *et al.*, 2007; Wang *et al.*, 2007; CONCAWE, 2008; Macedo and Seabra, 2008; Macedo *et al.*, 2008; NETL, 2008; CARB, 2009; Hill *et al.*, 2009; Huo *et al.*, 2009; NETL, 2009a; NETL, 2009b; Hoefnagels *et al.*, 2010; Hsu *et al.*, 2010; Kaliyan *et al.*, 2010; Larson *et al.*, 2010; Wang, 2010)].
Note: 1) BD = biodiesel; RD = renewable diesel; FTD = Fischer-Tropsch diesel. 2) Ranges in the plot are indicative only, and do not necessarily represent the range of all possible fuel production pathways. The central tendency is not necessarily in the middle of the displayed range.

Estimates are reasonably comparable for biodiesel derived from European rapeseed and US soybean (Hill *et al.*, 2006b; CONCAWE, 2008; Huo *et al.*, 2009; Hoefnagels *et al.*, 2010). Without land use change, biodiesel derived from relatively new feedstocks such as palm oil and jatropha are estimated to have either similar or higher WTT GHG emissions than rapeseed and soybean biodiesel (Beer *et al.*, 2007; CONCAWE, 2008; Hoefnagels *et al.*, 2010; Whitaker and Heath, 2010). Palm oil biodiesel can have higher GHG emissions because organic wastes are traditionally disposed in lagoons where methane is released under the anaerobic decomposition conditions, and because palm requires relatively higher fossil energy input for processing the feedstock (CONCAWE, 2008; Reijnders and Huijbregts, 2008). For Jatropha biodiesel, GHG emissions can be higher than first generation biodiesel feedstocks because seed yield varies considerably under different climate and soil conditions (Achten *et al.*, 2010).

Significant uncertainties exist in modelling GHG emissions from lignocellulosic ethanol due to the lack of commercial production of both the feedstocks and the fuels; this is manifested by the much wider uncertainty range for lignocellulosic ethanol than that for corn ethanol (Figure 9.3.12) (Hsu *et al.*, 2010). The narrower range shown in Figure 9.3.12 for lignocellulosic FTD compared to lignocellulosic ethanol may not reflect a lower level of uncertainty because fewer lignocellulosic FTD studies have comprehensively investigated uncertainty across the entire life cycle (i.e., uncertainty in all activities from feedstock production through fuel production to fuel use).

Box - Direct and Indirect Land Use Change and Bioenergy

Conversion from one land type to another directly and indirectly affects global land system GHG stocks and flows, and has been a significant contributor to global GHG emissions (Watson et al. 1996 (Watson *et al.*, 1996; Le Quere *et al.*, 2009). Agriculture and forestry systems are important drivers of these land use changes (LUC), with energy systems being an additional stressor (Schlamadinger, 1997). While LUC can be caused by other energy systems (e.g., hydropower's water reservoir), focus on bioenergy results from its proposed greatly-expanded use and inherent connection to land use.[6] While quantifying GHG emissions from LUC is difficult, it is important to investigate and account for them. The potential GHG emission reduction benefits from increased use of bioenergy compared to fossil energy sources can be partially or wholly negated when LUC-related GHG emissions are considered along with other life cycle GHG emissions.

Direct LUC (dLUC) occurs when production of bioenergy feedstocks modifies an existing land use type, resulting in a change in above- and below-ground carbon stocks. dLUC-related GHG emissions are dependent on site-specific conditions such as the prior land use, soil type, local climate, crop management practices, and the bioenergy crop to be grown (Intergovernmental Panel on Climate Change (IPCC), 2006; Croezen and Kampman, 2008; Wicke *et al.*, 2008).[7] The conversion of certain land types (e.g., rainforest and peatland) can lead to very large GHG emissions while most others are within ±200 g CO_2e/MJ (±200 t CO_2e/ha) (Figure 9.3.13). In the examples shown in Figure 9.3.13, the original land use is generally a more important factor in determining dLUC-related GHG emissions than the type of bioenergy feedstock planted. Any dLUC-related GHG emissions must be repaid over time before GHG emission reduction benefits

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[6] Replacing dedicated biomass with biomass residues or wastes could avoid LUC, depending on BAU assumptions.

[7] See Chapter 2 for a more detailed discussion of direct and indirect LUC, more detailed review of published estimated of LUC and additional references.

for the use of bioenergy can accrue (Gibbs *et al.*, 2008). Results reported in Figure 9.3.13 are totals averaged over a 30 year time horizon. Not considered in the analyses reviewed here is the time signature of these GHG emissions (an initial pulse followed by a long tail) which are an important determinant of the climate impacts of GHG emissions.

Indirect LUC (iLUC) occurs when a change in the production level of an agricultural product (here, for instance, a reduction in production of food, feed or fiber induced by conversion of agricultural land to production of bioenergy feedstocks) leads to a market-mediated shift in land management activities (i.e., LUC) outside of where the primary driver occurs. iLUC is not directly observable, and is complex to model and attribute to a single cause. Important aspects of this complexity include model geographic resolution, interactions between bioenergy and other agricultural systems, how the systems respond to changes in market and policy, and assumptions about social and environmental responsibility for actions taken by multiple global actors.[2] For example, estimates of iLUC-induced GHG emissions can depend on how land cover is modeled. Models using greater geographic resolution and number of land cover types (e.g., more than pasture and forested land) have tended to produce lower estimates and tighter uncertainty ranges (Nassar *et al.*, 2009; EPA, 2010). Results also depend on the assumed size of the future bioenergy market. Despite similar evaluation methods, Al-Riffai et al. (2010) and Hiederer et al. (2010) report an LUC impact of 25 and 43 g CO_2e/MJ, respectively, for a similar collection of biofuels partly because they evaluated different magnitudes of growth in the biofuels market (0.3 and 0.9 EJ, respectively).

Despite challenges in modeling iLUC attributable to bioenergy systems, improvements in methods and input biophysical data sets have been made. Some illustrative estimates of LUC-related GHG emissions (direct and indirect) induced by several 1st generation biofuel pathways are (reported here as a range in central tendency estimated by several studies plus, in parentheses, an uncertainty range): 14 to 82 g CO2e/MJ (14 to 200) for U.S. maize ethanol; 5 to 28 (-7 to 42) for sugarcane ethanol; 18 to 45 (11 to 68) for European wheat ethanol; 40 to 63 (10 to 102) for soya biodiesel; 35-45 (22 to 67) for rapeseed biodiesel (Searchinger *et al.*, 2008; Al-Riffai *et al.*, 2010; EPA, 2010; Fritsche *et al.*, 2010; Hertel *et al.*, 2010; Tyner *et al.*, 2010).[8]

The wide ranges of even the central estimates reflect the uncertainty remaining in the estimation of LUC-induced GHG emissions from bioenergy systems, but in general point to a non-trivial potential impact of LUC. Thus, it is critical to continue research to improve LUC assessment methods and increase the availability and quality of information on current land use, bioenergy-derived products and other potential LUC drivers. It is also critical to consider ways to mitigate the risk of bioenergy-induced LUC, despite the considerable uncertainty in its quantification (see Chapter 2). For instance, sustainable development of bioenergy can be encouraged and ensured through the use of Agro-Ecologic Zoning systems (EMBRAPA, 2010) coupled with adequate monitoring and enforcement and site-specific evaluation of the carbon footprint of the bioenergy products.

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[8] Estimates reported here combine several different uncertainty calculation and reporting methods and represent neither a comprehensive literature review nor, given literature limitations, an evaluation of all potential real world conditions.

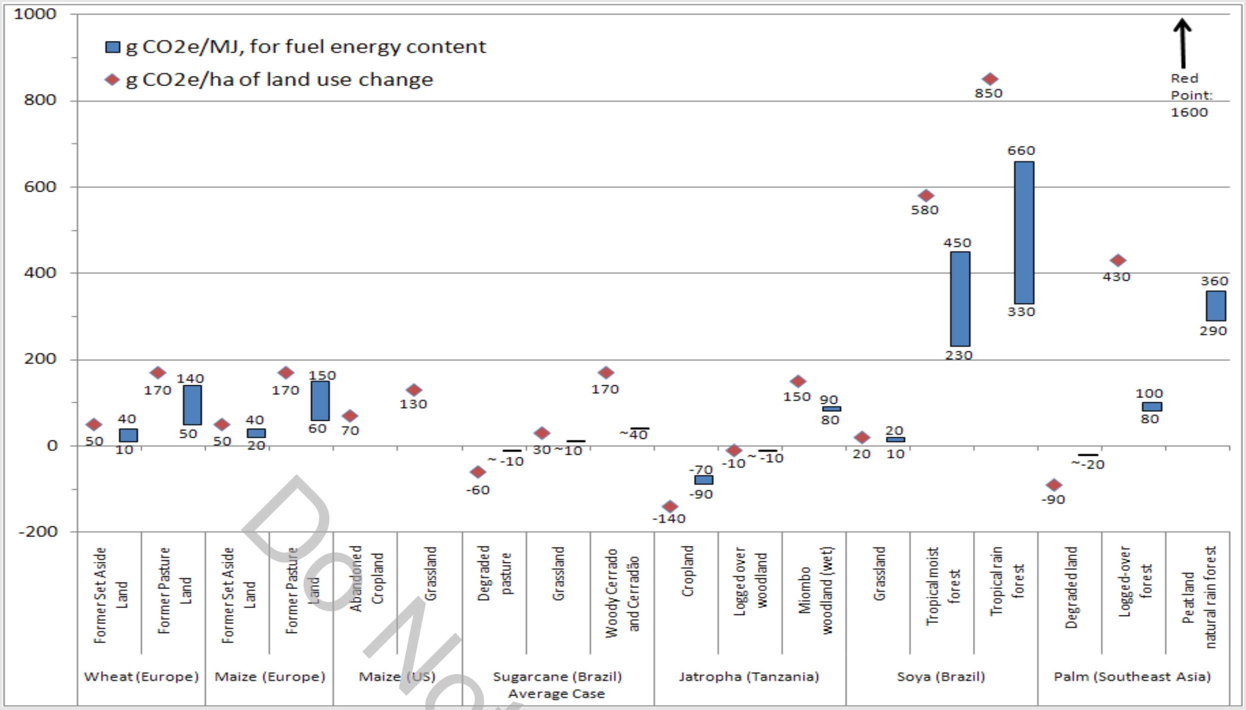


Figure 9.3.13: Illustration of dLUC-related GHG emission estimates from selected land use types and 1st generation biofuel feedstocks. Each estimate indicates the GHG emissions from converting a certain type of land (i.e., vertically-oriented x-axis labels) to one that produces a bioenergy feedstock in a given region or country (i.e., horizontally-oriented x-axis categories). Data, typically reported as t CO2e / ha (shown as single red points), are taken from (Hoefnagels et al., 2010) and (Fargione et al., 2008).Where feasible, conversion to g CO2e/MJ of fuel energy content (i.e. ethanol and biodiesel) (blue bars) is reported to facilitate interpretation of these data alongside other results reported in this chapter. Ranges in the perMJ results are based on different co-product allocation methods (i.e., allocation by mass, energy and market value). The results displayed here were developed using a limited set of methods and data sets not necessarily representative of the potential full range of results under all possible real world conditions. The time frame assumed to calculate the per energy content-based results was 30 years. Results can vary depending on this assumption; see Chapter 2 for more details on this and for additional dLUC estimates.

9.3.4.2 Water

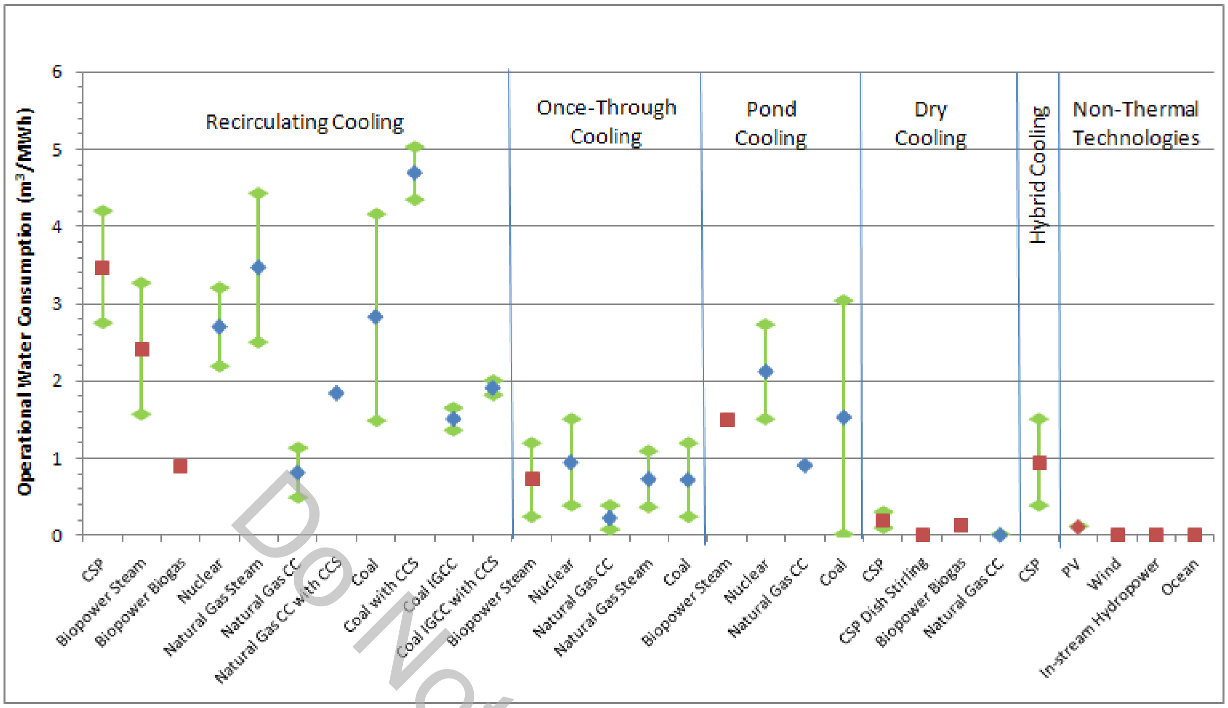
Water is a critical resource with multiple, competing uses, and the implications of RE development on both water quantity and quality should be considered in the context of sustainable development. Compared with literature of other environmental impacts of energy technologies, the amount of literature on water-related impacts is relatively small. While some broad conclusions can be made based on the evidence and first principles, additional research is needed to confirm many of the results presented and fill gaps in knowledge. Impacts on water are discussed in two sections below: first on water quantity (use) and second on quality (pollution).

Water use

Two different metrics are needed to understand impacts of the energy sector on water quantity: withdrawal and consumption. Water withdrawal is the amount of water removed from the ground or diverted from a water source (but which could return to the same or different source), while consumption is the amount of water that is lost to the local water environment through evaporation, transpiration, human consumption, and incorporation into products (Kenny *et al.* 2009). In 2006, the energy and industrial sectors (encompassing electricity generation, mining, refineries, and other industrial activities) accounted for 45% of freshwater withdrawals in Annex I countries and 10% of freshwater withdrawals in non-Annex I countries (Gleick *et al.* 2009).

Figure 9.3.14 depicts the high variability in operational water consumption rates associated with electricity generation units (EGUs), where technologies show greater agreement when organized according to cooling technology than by fuel type. Only operational water consumption of EGUs is considered in Figure 9.3.11 because for most technologies (excluding bioenergy and non-thermal renewables) this life cycle phase has the highest rate of consumption and because consumption data in other life cycle stages are scarce (Fthenakis and Kim 2010). Data are from studies of U.S. systems only, but represent a wide range of technology vintages and climatic conditions, both of which can affect water use rates (Miller *et al.* 1992), and thus their results should apply to other contexts.

Based on this evidence and first principles, non-thermal technologies are found to have the lowest operational consumptive water use. On a life cycle basis, these technologies also have been reported to have the lowest water withdrawals per unit electricity generated (Fthenakis and Kim 2010). Water may be occasionally required for cleaning purposes, but this use is minimal compared to that for cooling requirements in thermal technologies (Fthenakis and Kim 2010, Tsoutsos *et al*., 2005). Water consumption varies widely both within some cooling technology categories, but especially across technology categories. Decisions to use one cooling system instead of another are often site specific and are based on the availability of water, local environmental impacts, water quality impacts, parasitic energy loads, costs, and other considerations (Reynolds 1980). Not shown in Figure 9.3.11 because of their complexity, geothermal water requirements depend on technology types, cooling systems, and whether geothermal steam condensate (process water), freshwater or treated municipal wastewater sources are used for cooling requirements. Geothermal operational water consumption has been estimated to range from 0 to 15 m^3/MWh output (Fthenakis and Kim 2010). While Figure 9.3.14 shows negligible operational water consumption for in-stream hydroelectric facilities, substantial evaporation can occur from hydroelectric power production if reservoirs are used, resulting in evaporative rates estimated to be as high as 208.5 m^3/MWh generated in Southwestern desert regions of the U.S. (Torcellini *et al.* 2003). However, reservoirs often serve other purposes besides power production (e.g., flood control, freshwater supply, and recreation), such that it is challenging to apportion the water evaporated from reservoirs amongst the various uses (Torcellini *et al.* 2003).



n	18	4	1	16	2	7	3	5	4	5	1	1	9	3	3	2	1	7	1	1	11	2	1	2	4	2	2	1	1
Sources	12	3	1	6	1	2	1	4	4	5	1	1	4	3	3	2	1	2	1	1	5	2	1	2	2	2	2	1	1

Figure 9.3.14 Ranges of rates of operational water consumption by thermal and non-thermal electricity generating technologies based on a review of available literature (m^3/MWh). Technologies powered by renewable resources display their midpoint of available estimates (or single estimates) in red squares; those powered by non-renewable resources use blue diamonds. The green endpoints of ranges represent absolute minima and maxima from available literature. Data are reported mainly for technologies deployed in the United States, but are likely applicable to many other locations. "n" represents the number of estimates reported in the number of sources. Methods and references used in this literature review are reported in the Methods Annex. (CSP: concentrated solar power. CCS: carbon capture and storage. IGCC: integrated gasification combined cycle. CC: combined cycle. PV: photovoltaic)

Life cycle assessments of water quality and quantity impacts are complicated by the highly localized nature of water impacts and the different basins from which water is used throughout the life cycle. Biopower is a primary example of this limitation, where more water is generally required for feedstock production than for power generation, though the biopower feedstock and the methods used to produce and process the feedstock differ by location and could change throughout the lifetime of the plant (Stone *et al.* 2010, Berndes 2002, Berndes 2008). In addition, the allocation of water consumed to the portion of biomass used for energy production may vary significantly depending on the allocation methods used (Singh and Kumar 2010). Water consumption for hydropower is another technology where estimates of water consumption vary considerably depending on assumptions about reservoir-specific characteristics and the allocation scheme for multiple use reservoirs (Gleick 1993, Torcellini 2003).

Water will become an increasingly important consideration for renewable and non-renewable energy sources given expected changes in the climate. Climate change may impact freshwater availability for all portions of the life cycle, but thermal-based plants may be especially vulnerable due to their dependence on water resources throughout their operational lifetime (Bates *et al.* 2008; Dai 2010). Reduced levels in bodies of water, or substantial increases in the temperature of these water bodies, may require thermal power plants to run at lower capacities or to shut down completely (Poumadére *et al.* 2005). Additionally, increases in temperatures may lead to reduced plant-level thermal efficiency and cooling system performance, resulting in an increase in water consumption per unit of electricity generated (Miller *et al.* 1992). Turchi et al. (2010) have found that *CSP parabolic troughs* located in hot, dry areas will have water consumption rates 20% higher than similar plants in a cooler area; similar research is necessary on other thermal-based power plants. Water levels in reservoirs and rivers may also be affected by climate change, which could alter the performance capabilities and output of hydropower (Harrison and Whittington 2002).

Water resource vulnerabilities of thermal-based power plants can be reduced by utilizing alternative sources of water, such as municipal wastewater, or by utilizing a dry-cooling system, yet there are cost, performance, and availability tradeoffs and constraints (EPRI 2003; Gadhamshetty *et al.* 2006).

Water is also required for the production of transportation fuels. Comparisons amongst bioenergy systems are complicated by the variety of metrics reported, which imply different system boundaries, and by the use of different functional units, for instance: water volume per energy content of fuel, water volume per energy content of feedstock, water volume per volume fuel, and water volume per vehicle distance travelled. A metric that is helpful in understanding water use impacts of biofuels is the water footprint, defined here as the total volume of freshwater consumed for feedstock production from natural and anthropogenic sources (Gerbens-Leenes *et al.* 2009). The water footprint can also be applied to other life cycle phases and other energy systems and fuels. The water footprint consists of three components: green water (precipitation), blue water (irrigation), and gray water (effluent or the amount of freshwater that must be used to dilute pollutants). Similar to producing energy crops for biopower, the water footprint of growing biofuel crops is highly dependent on the crop, where it is produced, and the production methods utilized (Gerbens-Leenes *et al.* 2009, Harto *et al.* 2009, Wu *et al.* 2009).

Figure 9.3.15 compares the global average water footprint for ten crops providing ethanol and two crops providing oil for biodiesel, weighted by country production masses (Gerbens-Leenes *et al.* 2009). As seen in the figure, the water footprint of biofuels varies considerably by feedstock, with the total water footprint of ethanol produced from sugar beet requiring just 14% of the water of ethanol from sorghum. Also, with the exception of ethanol produced from sorghum, the water footprint of biofuels crops for biodiesel is nearly two to four times greater than the water footprint for ethanol crops. Because Figure 9.3.15 represents the global weighted-average water footprint for various feedstocks, it does not capture the great variability of the water footprint within each feedstock (Gerbens-Leenes *et al.* 2009). The water footprint of any feedstock is dependent on the local climatic conditions of where the feedstock is being produced, farm management practices, and by the crop species chosen for each feedstock, all of which may change from year to year. Thus the water footprint for an individual case may differ substantially from the weighted global average.

One factor not considered in Figure 9.3.15 is the water consumption that occurs during the processing of fuels. By various metrics, water consumption and withdrawal requirements during the fuel processing stage (including exploration and production of crude oil) are equivalent to twice as high for biofuels than for petroleum-based fuels, making the overall life cycle water consumption intensity (i.e. the blue water footprint) of biofuels one to three orders of magnitude greater than the water consumption intensity of the production of petroleum-based fuels (King and Webber 2008, Wu *et al.* 2009, Harto *et al.* 2009). Despite the higher water intensity of fuel processing for biofuels, water consumption during fuel processing represents the majority of water consumption for petroleum-based fuels, yet is generally a negligible component of irrigated biofuel water consumption demands, as these values are generally less than 1 L/MJ (Berndes 2002, King and Webber 2008, Wu *et al.* 2009, Harto *et al.* 2009)

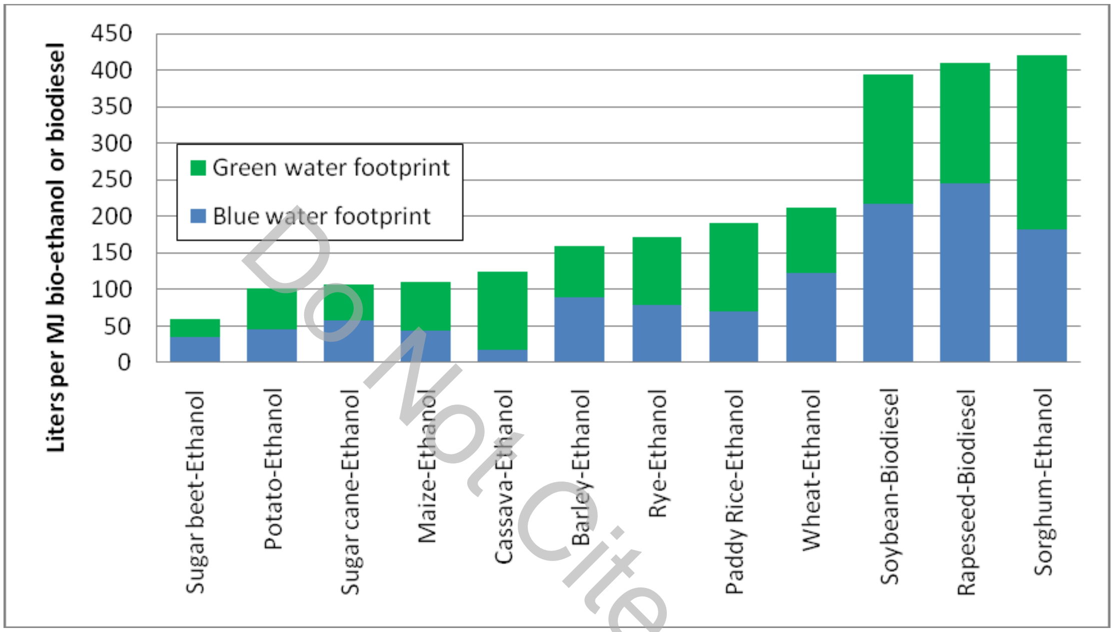


Figure 9.3.15: Water footprint of feedstock production for ten ethanol-producing feedstocks and two biodiesel-producing feedstocks Values represent global averages weighted by production in main producing countries. The irrigation requirement (blue WF) is defined as the crop water requirement minus effective precipitation, assuming that irrigation requirements are actually met. The green WF of a crop (m3/ton) is the total green water use over the length of the growing period (m3/ha) divided by the crop yield (ton/ha). The blue WF (m3/ton) is the total blue water use over the length of the growing period (m3/ha) divided by the crop yield (ton/ha). Energy content of feedstocks, used to convert reported WF (m3/ton) to final units of L / MJ, is taken from Gerbens-Leenes *et al.* 2009. Values represent calculated average yields over 5 production years (1997– 2001) (FAO 2008). Sources: (Gerbens-Leenes *et al.* 2009).

Water withdrawals, consumptive uses, and footprints will have localized impacts, and should be considered on a site-specific basis. Regional water availability conditions will dictate the impact of energy technologies on water resources.

Water Pollution

EGUs can affect water quality through thermal and chemical pollution during normal operation and through accidents. These impacts can occur in many different stages of their life cycle. During normal operation, EGUs utilizing once-through cooling systems can elevate the temperature of water bodies receiving the cooling water discharge, which can negatively affect fresh, coastal, and estuarine ecosystems (Barnthouse 2000, Kelso *et al.* 1979, Poornima *et al.* 2005). EGUs have been estimated to account for 75-80% of thermal water pollution in the U.S. (Laws 2000). Hydroelectric facilities can have impacts on the temperature and dissolved oxygen content of the released water while also altering the flow regime, disturbing ecosystems, and disrupting the sediment distribution process (Cushman 1985, Liu and Yu 1992). Operation of tidal energy facilities located at the mouths of estuaries could impact the hydrology and salinity of estuaries (Pelc and Fujita 2002, Vega 2002). Production of bioenergy crops can have similar water quality impacts as other row crops resulting from fertilizer and pesticide use, yet many energy crops require less water and chemical inputs for production than row crops (Lovett *et al.* 2009, Paine *et al.* 1996, McLaughlin and Walsh 1998). Water pollution may also occur directly at ethanol plants from distillery waste discharges, yet these potential pollutant sources can be mitigated through existing anaerobic digestion technologies (Gaimpietro *et al.* 1997, Wilkie *et al.* 2000).

Geothermal facilities can affect both surface and ground water quality through accidents that result in spills of hazardous substances during exploration or hydraulic stimulation, the spillage of geothermal fluids at the surface during operation, leakage from surface storage impoundments, and through contamination of nearby freshwater wells by intrusion of polluted groundwater (Brophy 1997, Dogdu and Bayari 2005). Ocean thermal energy conversion technologies can alter local water quality through accidental release of toxic chemicals, such as ammonia and chlorine (Pelc and Fujita 2002).

Mining operations, fuel processing, and air pollutant emissions from the combustion of fossil fuels deposited to water bodies can also have considerable impacts on water quality. For instance, effluent from coal mining can degrade local water quality by lowering pH and increasing concentrations of solids and heavy metals; leachate water from overburden dump can also have high metal concentrations (Tiwary 2001). Effluent from uranium mining for nuclear power increase concentrations of uranium, radium, selenium, molybdenum, and nitrate in surrounding surface water and ground water (van Metre and Gray 1992, Kaufmann *et al.* 1976). Radioactive water contamination can also occur from reprocessing of spent nuclear fuel, but releases have been greatly reduced through regulation (CEC 1999). In the North Sea, reprocessing has been estimated to contribute orders of magnitude less to radioactive contamination than from off-shore oil and gas operations and fertilizer production (CEC 1999). Operational oil tanker discharges (i.e., dumping of oil during tanker cleaning operations) account for about 45% of the total oil pollution in the world's oceans, while ship and oil platform accidents contribute 5% and 2%, respectively (ESA, 1998). Air pollutants emitted from coal combustion can lead to acid deposition, a problem especially for countries highly dependent on coal such as China (Larssen *et al.* 2006).

Accidents from non-renewable energy sources can also impact water resources (see also 9.3.4.6). Hydraulic fracturing techniques to extract natural gas may result in local water contamination through accidental spills of fracturing chemicals (Kargbo *et al.* 2010). Spills from the extraction and production of petroleum fuel can also lead to accidents that affect both saline water and freshwater resources (Blumer *et al.* 1970, Kramer 1982).

Most countries have established strict limits and standards on water pollution, yet this does not always prevent accidents.

9.3.4.3 Local and regional air pollution

This section presents data on selected air pollutants with most important impacts on human health – as indicated by the World Health Organization WHO (WHO 2006) – that are emitted by energy technologies, namely particulate matter (PM)[9], NO_x, SO_2 and non-methane volatile organic compounds (NMVOC). Their dispersion in the atmosphere entails significant impacts at the local and regional scale (up to a few thousand km) (e.g. (Hirschberg et al., 2004)). In contrast to GHG emissions, impacts due to these air pollutants are location-specific and depend on their overall concentrations in the atmosphere as well as those of further pollutants acting as reactants, e.g. for formation of secondary particulates (e.g. (Hallquist *et al.*, 2009), (Kalberer *et al.*, 2004), Andreani-Aksoyoglu *et al.*, 2008). Air pollution also varies significantly between urban and rural areas. Therefore, cumulative life cycle inventory results, i.e. quantities of pollutants emitted per unit of energy delivered, must be interpreted with care drawing conclusions on potential impacts on human health and the environment (Torfs *et al.*, 2007). These results can only act as basic data for the estimation of specific impacts (see section 9.3.4.4).

Also indoor air pollution (IAP) through high PM emissions caused by low quality fuels in traditional cook stoves constitutes a health hazard (see section 9.3.4.4). Black carbon, a fraction of total particulate matter emissions, can also have impacts on the global and regional climate (see Box on Black Carbon).

Box – Black Carbon

Black carbon is a short lived air pollutant formed by incomplete combustion of fossil or biogenic fuels. Prime sources of BC are agricultural and forest fires, (diesel) combustion engines, in particular maritime vessels running on heavy oil, and residential use of fuel (Bond *et al.*, 2004), (Lack *et al.*, 2008). BC emissions are particularly high in developing countries. Asia is the global "black carbon" hot spot, with highest total and per/capita residential BC emissions (Bond *et al.*, 2004). BC is emitted together with organic carbon (OC), and other aerosols like sulphates, mostly in the form of soot. BC has detrimental health effects (cp section 9.3.4.5), and can accelerate global warming through both its heat absorbing properties, and by reducing the Albedo of cloud, snow and ice surfaces (Ramanathan and Carmichael, 2008). However, the net warming effect of aerosol emissions from combustion is source and location dependent, and still uncertain (Bond *et al.*, 2004). Recent research suggests that contained combustion of fossil fuels and residential combustion of solid biofuels results in net warming (Hansen *et al.*, 2005), (Jacobson, 2004), (Koch *et al.*, 2007). In contrast, the net effects of open combustion (field fires) of biogenic sources are negative, due to higher ratio of reflective OC to absorptive BC aerosols (ibid.). Both processes play a prominent role in the formation of atmospheric brown clouds, that exhibit strong regional climate impacts (Ramanathan *et al.*, 2005), (Ramanathan *et al.*, 2007), e.g. alteration of the Indian Monsoon (Aufhammer There is evidence that atmospheric heating by BC and dust aerosols over the Indo-Gangetic Plain as well as BC deposition contribute substantially to snow-melt and the accelerated stationary decay of Glaciers on the Himalayan-Tibetean Plateau (Flanner et al., 2009, Ramanathan et al. 2007,(Lau *et al.*, 2010)). Regional effects due to BC and other aerosols also include larger warming in the elevated regions of the tropics (Ramanathan et al. 2005, Lau et al, 2008, Gautam et al, 2009), and changes in location of

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[9] PM emissions are specified as PM_d, where the subscript d indicates the largest diameter (in µm) of the particles that are included. Particles emitted by internal combustion engines are all very small and almost entirely included in the $PM_{2.5}$ measure.

tropical rainfall (Wang, 2004; Robert and Jones, 2004; Ming and Ramaswamy, 2009; Chung and Seinfeld, 2005).

Black Carbon abatement has thus been proposed as a significant means not only for Climate Change Mitigation, but also for addressing additional sustainability concerns such as air pollution, public health and energy services for the poor (Grieshop *et al.*, 2009). Providing alternative energy-efficient and smoke-free cookers and transferring technology for reducing soot emissions from coal combustion in small industries could have major impacts on the radiative forcing due to soot, while at the same time combating indoor air pollution and respiratory deseases in urban centers (Ramanathan et Carmichael, 2008). A switch from diesel to LPG in the public transport system in Delhi has resulted in substantial reductions in CO2(e) mainly by reducing the BC loads (Reynolds and Kandlikar, 2008). There is, however, a fuel penalty on most technologies reducing tail pipe emissions, like flue gas treatment and sulfur scrubbing for coal plants, or particulate traps on diesel engines (Boucher and Reddy, 2008). Removing the „masking" effect of reflective aerosols might accelerate impacts of committed warming (Ramanathan and Feng, 2008), (Carmichael *et al.*, 2009).

Heat and electricity supply

Figs.9.3.16 show cumulative LCI results per kWh of end use energy for space heating and electricity generation systems at the outlet of the boilers and the busbars of the power plants, respectively (ecoinvent 2009; Viebahn *et al.*, 2008; Bauer *et al.*, 2009; Bauer 2008). In case of space heating, minimum and maximum figures represent the best and the worst technology option among the sample of datasets evaluated. Additionally, the type of fuel (e.g. wood logs, chips, or pellets in case of biomass) affects the results. The figures for solar heating are valid for a certain location in Europe, variation in solar irradiation is not considered in the interval shown. In case of fossil electricity generation, the results include country-specific average current technology and fuel supply for all European countries, but also for further selected ones, e.g. the US and China. Minimum and maximum figures therefore mainly represent the country with the best and worst power plant and pollution control technology, respectively. The intervals for PV and wind turbines are due to technology specific variations in the environmental burdens as well as different sites, i.e. different solar irradiation and wind speed, taken into account.

Neither heat and electricity distribution nor backup systems for stochastic electricity sources like wind turbines and photovoltaic modules are considered. Also the potential increase in the overall emissions of the power system due to a more flexible operation of fossil power plants as a response to feed-in of fluctuating renewable electricity is not taken into account.[10]

For electricity production and space heating with fossil fuels and biomass (wood) combustion, the dominant contributor to the LCI results in focus is the combustion stage with typically 70 to almost 100% share in the overall emissions (e.g. (Dones *et al.*, 2007), (Jungbluth 2007), (Bauer 2007)). However, in case of long distance transport of coal, natural gas, and wood fuel, the transport stage might become more important (e.g. (Dones *et al.*, 2007), (Bauer, 2008)). In general, natural gas causes the lowest emissions among fossil fuels with SO_2 and $PM_{2.5}$ emissions in a similar range as the renewables (except of wood combustion) and nuclear. Contributions of different sections of the energy chains as well as total emissions vary within

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[10] The latter effect is discussed in chapter 7, see this section for details.

orders of magnitude with power plant technology, application of pollution control technologies (flue gas desulfurization, particulate filters, etc.) and characteristics of fuel feedstock applied, as indicated by minimum and maximum values in Figs.9.3.16. Emissions on the lower end of the shown intervals can be expected for industrialized countries with modern technologies as opposed to developing economies with older technologies, less pollution control and hence higher emissions. Also lack of environmental regulation in developing countries results in comparatively higher emissions. Molina and Molina (2004) report outdoor urban air pollution in cities from industry, energy and transport that are up to ten or more times higher than in developed nations. However, air pollution abatement has gained importance since the early 1990ies, in particular in China, resulting in a slowdown of Sulfur emissions in Asia ((Carmichael *et al.*, 2002)). The substantial potential of RE to contribute to air pollution abatement has been studied in particular for emerging economies Electricity and transport sector (e.g. (Boudri *et al.*, 2002), (Aunan *et al.*, 2004), Creutzig 2008).

The non-combustion renewable energy technologies and nuclear power cause comparatively minor emissions, only from upstream and downstream processes. Also the variations in the results, depending on both technologies applied and site of power generation (in terms of e.g. solar irradiation (Jungbluth *et al.*, 2009) and wind conditions (EWEA 2004)), are in general much lower for renewables and nuclear than for fossil power and heating systems. The use of biomass via gasification shows clear environmental advantages compared to combustion of solid biomass. Although not considered in these results, the type of electricity used for the operation of the geothermal heat pump has a significant impact on the performance of this technology (Heck 2007).

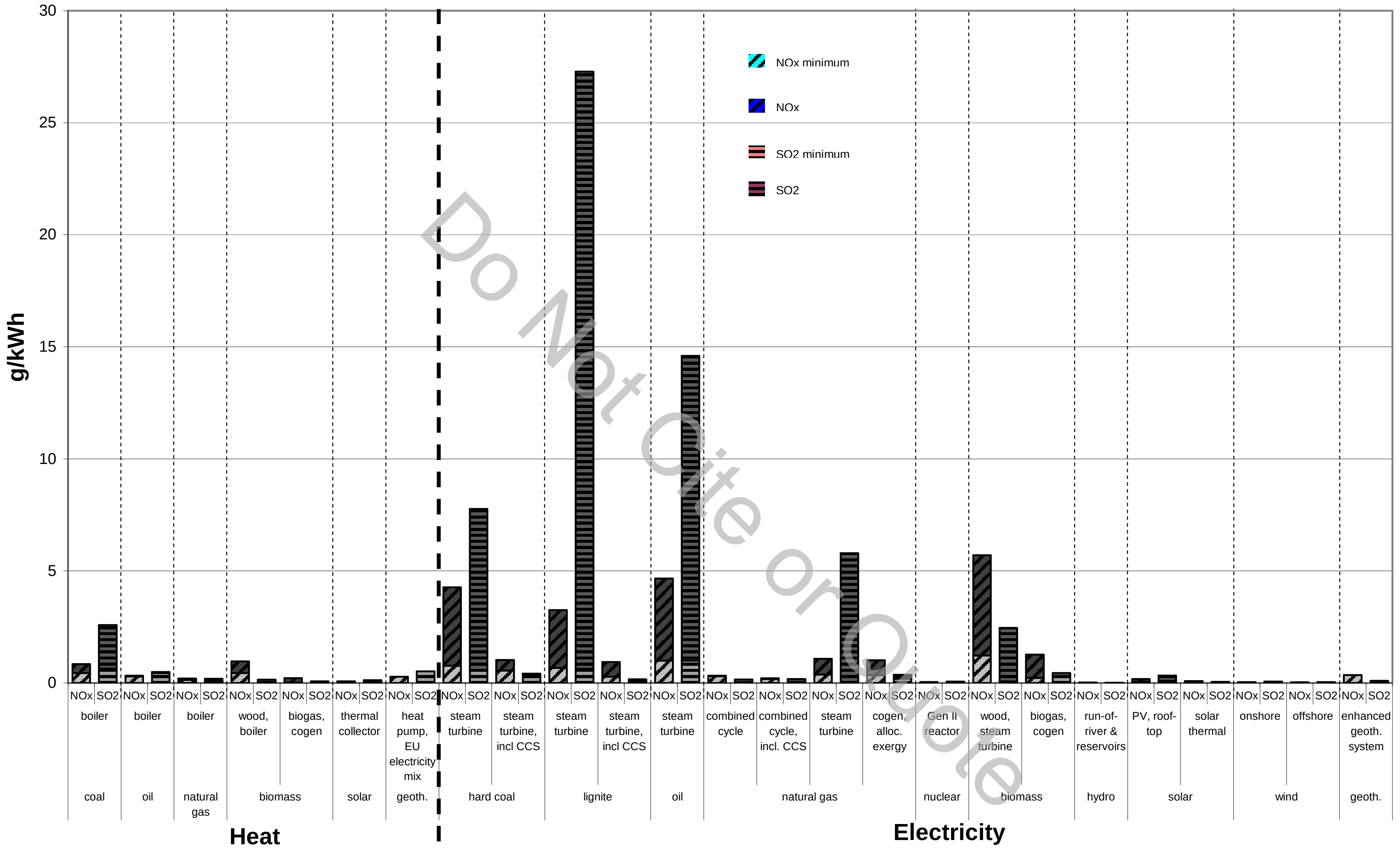


Fig. 9.3.16a. Cumulative life cycle emissions of NO_x and SO_2 for current heat and electricity supply technologies according to (ecoinvent 2009; Viebahn *et al.*, 2008; Bauer 2008). Figures for coal and gas power chains are valid for near future forecasts (Bauer *et al.*, 2009). [TSU: Design will be improved and graphs merged in final edit]

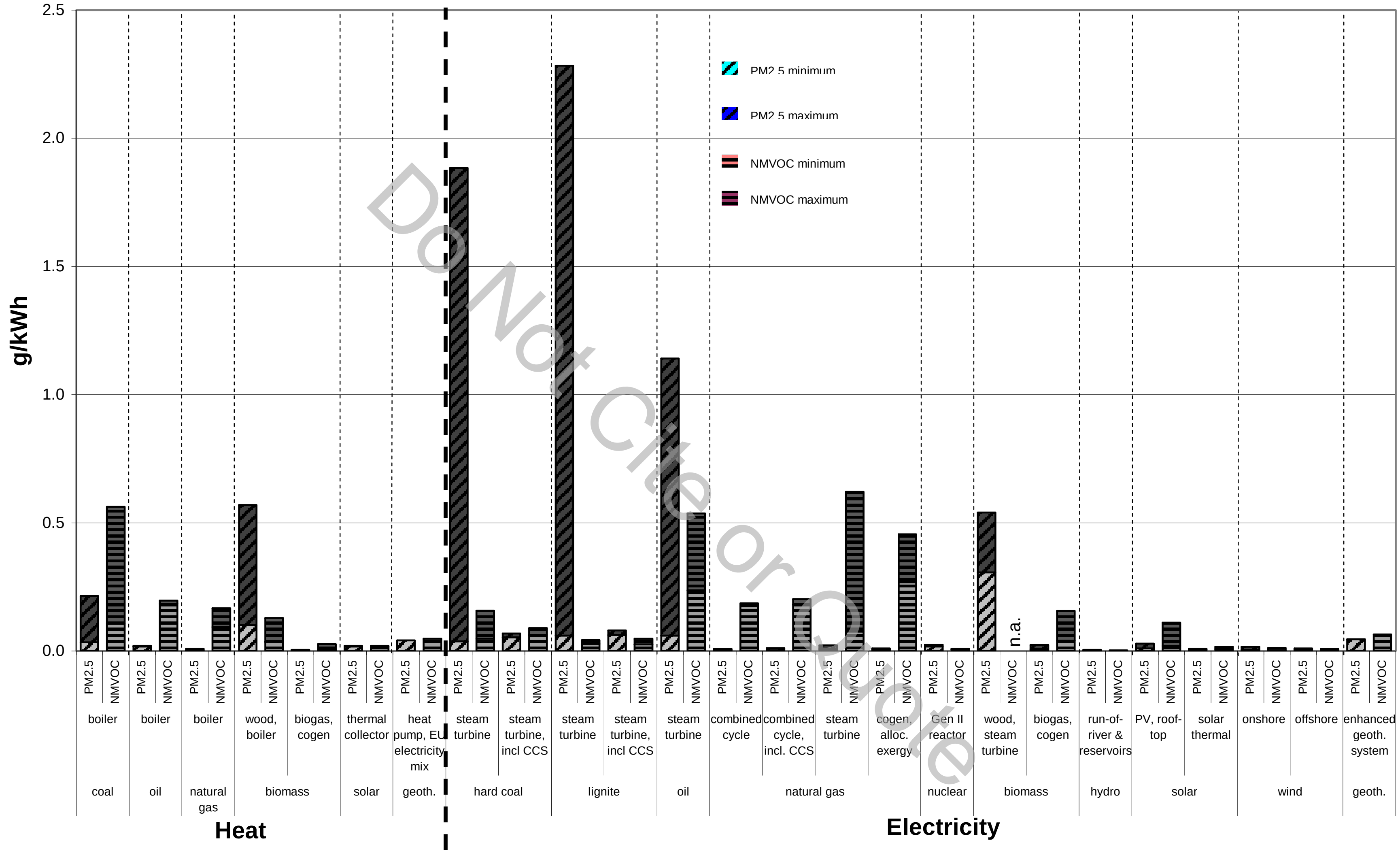


Fig. 9.3.16b. Cumulative life cycle emissions of NMVOC and PM2.5 for current heat and electricity supply technologies according to (ecoinvent 2009; Viebahn et al., 2008; Bauer 2008). Figures for coal and gas power chains are valid for near future forecasts (Bauer et al., 2009). [TSU: Design will be improved and graphs merged in final edit]

Transport fuels

The environmental performance of biofuel based transport services depends to a major extent on the feedstock used and the production route of the biofuel. LCA results indicate that the overall environmental performance of biofuels can be by far better, but also clearly worse than the environmental performance of conventional gasoline and diesel fuels, depending on the certain type of biofuel (e.g. Zah *et al.*, 2008, Huo *et al.*, 2009). This high variability is mainly due to differences in the upstream processes of biofuel production, not in its use, i.e. combustion. In general, using biogenic waste materials like manure, oil residues, or solid biowaste as feedstock results in lower environmental burdens than using crops like corn or rye dedicated for biofuel production. Also the location of biofuel production can play a significant role: while conditions for ethanol production from sugarcane seem to be favourable in Brazil, cultivation of energy crops in the US and Europe shows much less environmental benefits. Use of gaseous fuels – both fossil and biogenic origin – tends to reduce air pollution compared to liquid fuels (Zah *et al.*, 2008).

Effects of bioethanol and ethanol blends on tailpipe emissions have been examined by numerous authors with varying results (Costa and Sodre, 2009; Demirbas, 2009; Graham et al, 2008; Hilton and Duddy, 2009, Liu et al, 2006; Niven, 2005; Pang et al, 2008, Park et al, 2010; Roayaei and Taheri, 2009; Schifter et al, 2010; Yoon et al, 2009; Zhai et al, 2010, Yanowitz and McCormick, 2009). Fuel blends, combustion temperatures and additives play a decisive role for air pollutant formation (Ginnebaugh et al, 2010), (Coelho et al, 2006; Lucon et al, 2005). Ethanol fuel can reduce overall PM fraction, but with elevated amounts of fine particulate matter, that are particularly detrimental for human health (Ferreira da Silva et al, 2010). Biodiesel from certain feedstocks was found to reduce the overall life cycle emissions of PM, CO, SO_2, VOCs and unburned hydrocarbons significantly. However, it increases nitrogen oxide emissions (Fernando et al, 2006), (Coronado et al, 2009), (Pang et al, 2008).

Oxygenates from biofuels blended in conventional motor fuels (bioethanol and biodiesel, respectively in gasoline and diesel) are blamed for increasing evaporative emissions, leading to higher concentrations of tropospheric ozone, a toxic substance. There is a controversy on this matter, since it is possible to reformulate gasoline and diesel, as well as to use more advanced tailpipe exhaust control equipments (Schifter et al, 2004). Second generation and future biofuels are expected to improve performance, when the combustion system is specifically adapted (Pischinger et al, 2008), (Ußner and Müller-Langer, 2009).

Recent research (e.g. Notter *et al.*, 2010, Zackrisson *et al.*, 2010) and the ambivalent LCA results of biofuels suggest that future vehicle designs like battery vehicles or hydrogen based fuel cell cars offer a much higher potential for a clear reduction of air pollution (as well as other environmental burdens) due to passenger transport, if electricity from renewable sources is used as energy carrier.

Box – Air pollutant emissions from ethanol fuel blends in Brazil

Brazil has by far the largest experience on running higher blends and dedicated ethanol vehicles. Pure gasoline was phased-out in the early 1980’s, when sugarcane ethanol replaced toxic lead-based additives (Coelho et al, 2006; Goldemberg et al, 2009). The National Alcohol Program (PROALCOOL), a reaction to the oil shock of the seventies, and the unstable sugar prices, lead massive investments into sugarcane ethanol production and development and manufacturing of pure ethanol cars in Brazil. As a result, the number of vehicles running on gasohol (E22, a blend with 78% pure gasoline and 22% ethanol) and hydrous ethanol (E100) increased steadily (Moreira and Goldemberg, 1999). In 2005, flexible fuel vehicles (FFVs) were commercially introduced, soon dominating the market and discontinuing the production of dedicated ethanol (E100) cars.

The use of ethanol fuels had positive impacts on urban air quality. Due to the ethanol blend, lead ambient concentrations in Sao Paulo Metropolitan Region dropped from 1.4 mg/m3 in 1978 to less than 0.10 mg/m3 in 1991, far below the air quality standard (Goldemberg *et al.*, 2008)). Reductions in total carbon monoxide (CO), hydrocarbons and sulfur emissions were significant, and ethanol hydrocarbon exhaust emissions are less toxic than those of gasoline, since they present lower atmospheric reactivity (ibid.). Reductions occurred also in PM and Volatile Organic Compounds (CETESB, 2010), (Goldemberg *et al.*, 2008). In some cases, ethanol fuel use entails more emissions of ozone precursors like NOx, and concerns have been raised by higher aldehyde emissions (Graham *et al.*, 2008) (Goldemberg *et al.*, 2008). However, while mass emissions are higher, Acetaldehydes formed by ethanol are less toxic than formaldehydes from fossil fuels (Coelho et al, 2006).

9.3.4.4 Health Impacts

Energy generation impacts human health mainly due to **air pollutant emissions** caused by fossil fuel and biomass combustion (cf 9.3.4.3). A consensus has been emerging among public health experts that air pollution, even at current ambient levels, aggravates morbidity (especially respiratory and cardiovascular diseases) and leads to premature mortality (Wilson & Spengler 1996, WHO 2003, Holland et al 2005a). The largest contribution to the impacts comes from mortality due to particulate matter (PM). Another important contribution arises from chronic bronchitis due to particles (Abbey et al 1995).

Significant reduction of mass emission of pollutants by deployment of RE should yield increased health benefits (though the relationship is complex).

Exposure to **indoor air pollution** (IAP) from the combustion of solid household fuels (coal and traditional biomass) is an important cause of morbidity and mortality in developing countries (Ezzati and Kammen, 2002). A recently published World Health Organization (WHO) risk assessment shows that more than 1.6 million deaths and over 38.5 million of disability-adjusted life-years (DALYs) were attributable to indoor smoke from solid fuels in 2000 (WHO, 2002; Smith et al., 2004; Smith and Mehta, 2003). The WHO estimates did not include deaths from the cardiovascular diseases as a result of ambient air pollution due to lack of epidemiologic studies. There are also robust findings that tie cataract to IAP (Pokhrel *et al.*, 2005).

Regarding contaminant concentrations, traditional biomass based fuels yield worse result compared to charcoal or coal for simple cookstoves ((Zhang and Smith, 2007), Bailis *et al.* (2005), (Oanh *et al.*, 1999). The overall impacts of improved technology and ventilation is dominant for mitigating effects especially on children across all fuel types (Palanivelraja and Manirathinem, 2009), (Bruce *et al.*, 2004), (Smith *et al.*, 2000). Modern biomass technologies (improved cookstoves, biogas) can yield health benefits without fuel switch.

Other health impacts [references partly missing from Ref list]

Health impacts of *hydropower* reservoirs are well researched (cf Chapter 5). Major health impacts are spread of vector borne diseases associated with the reservoirs itself and irrigation projects (Yewhalaw et al., 2009; Keiser et al., 2005). High concentration of populations and working migrants during construction phases have also raised concerns about for large infrastructure projects (ref WCD ch 5) Emissions of hydrogen sulphide emissions from geothermal plants can occur and and cause nuisance and health impairments ((Anspaugh and Hahn, 1979). Nuisance from noise has been an issue for *Wind* turbines. The frequency and volume of this noise can be controlled, but not eliminated by wind turbine design, and impacts mitigated by proper siting (Leventhall, 2006; Rogers et al., 2006).

Health impacts from radioactive pollution might occur for the nuclear chain, and also by radioactive releases (NORMS = normally occurring radioactive materials) from off-shore oil and gas operations and fertilizer production, but has so far been neither quantified nor compared for different pathways (ref.) Radon in high concentrations has long been recognized as a correlative of lung cancer, and poses a significant risk to workers in uranium mines (Ramsay, 1977), (Al-Zoughool M, 2009). Increased cancer risk of residencts, particularly children, near Nuclear Power Plants, has been studied but to date remains an open question (Ghirga, 2010). Possible association between exposure to pesticides and adverse human health effects through numerous pathways is increasingly studied (e.g. (Faria, 2007),(Ritter L, 2006), (Colborn, 2006). Groundwater pollution by agrochemicals can also result in adverse health impacts, in particular for children. Concerns have been raised for Bio Energy feedstock production (Tomei and Upham, 2009), (Hill *et al.*, 2006a).

9.3.4.5 Land use

High land requirements are often cited as an important issue for renewable energy technologies, in particular for comparably diffuse resources like solar, wind and biomass (Denholm and Margolis, 2008), (Fthenakis and Kim, 2009). Depending on degree of disturbance and local conditions, human land use can entail substantial impacts, particularly life support functions of soils and Biodiversity (Dubreuil *et al.*, 2007).

A variety of metrics has been used in the literature to describe land use efficiency by renewable sources in terms of energy output per area occupied by the generating facility, or cultivated for Biomass feedstock, e.g. area occupied (m^2/kW) and % effective land use (Rovere et al. 2010), land footprint (m^2/cap) (Denholm and Margolis, 2008), land use efficiency (Trieb, 2009) and land requirements (m^2/cap*year) (Nonhebel, 2005).

LCA literature on life-cycle land use per energy output is very scarce. The impact category **land use** in LCA groups all intentional activities necessary to make land usable as a resource in economic sectors, distinguishing between initial land transformation (m^2) and the following land occupation (m^2yr), and including indirect land use of up- and downstream processes (Scholz, 2007). Figure 9.3.17 shows life cycle land use (dividing total land area by lifetime) for selected technologies generating electricity, based on a recent paper by (Fthenakis and Kim, 2009).

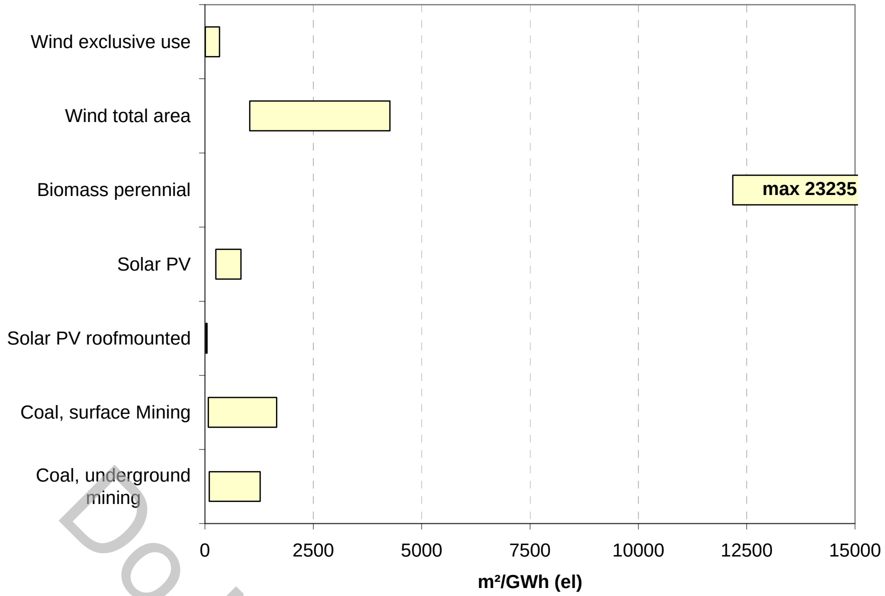


Figure 9.3.17 Life-cycle land use (direct and indirect transformation) for Electricity generation technologies, on 30-years timeframe, square meters per GWh; Data from USA, Germany, Denmark, based on (Fthenakis and Kim, 2009) TSU: graph will be redesigned

Due to the high continuous requirement of arable or forestry land for feedstock production results, land intensity of Bio-Energy is significantly higher than for any other ET (Keoleian, 2005). Variations are substantial for different feedstocks and climatic zones.

For wind, wave and tidal energy, spacing between the facilities is needed because of energy dissipation, as for solar PV to a minor extent due to shading. Thus the direct land or ocean area transformed is quite large, but secondary uses, such as farming, fishing and recreation activities are feasible (Jacobson, 2009). As the land cover change due to roads and turbine foundations affects max 10% of the total wind park area, impacts are not proportional (Denholm *et al.*, 2009).

Solar PV can be roof-mounted, resulting in negligible land use during operation, while for central PV plants and solar thermal installations design considerations can influence extent and exclusiveness of the land use (Denholm and Margolis, 2008).

Geothermal generation has a very low above ground direct land use, which increases considerably if the geothermal field is included for risk of land subsidence (Evans *et al.*, 2009). Run of River Hydropower has the lowest land use impact of all technologies, while the values for reservoir hydro differ greatly depending on the physical conditions of the site. (Gagnon *et al.*, 2002) reports values up to 200.000 m²/GWh [TSU: number under review] found in the literature. The impoundment and presence of a reservoir stands out as the most significant source of impacts (Egré and Milewski, 2002), with social issues such as involuntary people displacement or the destruction of cultural heritage adding a critical dimension in particular for very large developments. However, attributional issues most be reflected in the many cases of multipurpose reservoir use (see Chapter 5.6 for details).

For conventional energy technologies, land use is dominated by upstream processes, depending on type of mining operations or extraction (in-situ, leaching, surface or underground mining), quality of mineral deposits and fuel, and supply infrastructure (Fthenakis and Kim, 2009), (Jordaan, 2009). For coal and solid biomass power plants, handling and transport of large volumes results in significant land requirements. In the case of coal, waste disposal sites must be accounted for (NRC, 2010), (Hirschberg *et al.*, 2006).

Total land use of nuclear power is dominated by the metrics applied to waste-disposal sites. Above ground land transformation results in lower ranges than fossil fuel operations, dominated by higher space requirements during operation because of security cordons. However, the necessity to maintain depositories for nuclear waste shielded from access for a very long timespan (10.000 – 100.000 years) can increase the occupational land use of nuclear facilities substantially (Gagnon *et al.*, 2002), (Fthenakis and Kim, 2009).

The land requirements needed for establishment and upgrade of distribution and supply networks may vary with technology choice and is substantial, but not covered in the literature.

The assessment of impacts of land use is even more complex, with many methodological challenges yet to be solved (Scholz, 2007), (Dubreuil *et al.*, 2007). Categories and indicators discussed include landscape fragmentation (Jordaan, 2009), impacts on life support functions and ecosystems services, impacts on naturalness of areas, including the time necessary for regeneration after different types of use and impacts on biodiversity (Lindeijer, 2000), (Scholz, 2007), (Schmidt, 2008).

9.3.4.6 Impacts on Ecosystems and Biodiversity

Energy technologies impact ecosystems and biodiversity through various pathways, most evidently through (large scale) direct physical alteration of habitats in the case of Reservoir creation and alteration of rivers, surface mining, tidal barrages, waste deposits and land use changes associated with Biomass feedstock production and unsustainable harvesting.

The deterioration of habitats due to air and water pollution is largely associated with fossil energy technologies and mining (cf. (Jacobson, 2009). Thermal pollution is a serious concern for all thermal technologies, affecting aquatic life. Potential impacts of severe accidents in the extraction stage of fossil fuels are relevant (cf 9.3.4.5).

Scientific evidence for renewable energies impacts on biodiversity is varying: Effects of reservoir Hydropower developments have been studied extensively (Rosenberg et al., 1997; IUCN, 2001; Fearnside, 2001; Craig, 2001; Rancourt and Parent, 1994, Coleman, 1996), and impacts are well understood (cp Chapter 5). In addition to habitat change due to reservoir creation, most prominent impacts are interference with fish migratory routes, changes in water temperature, variations in flow and chemical composition of the river, extirpation of native species through alteration of physical habitat or introduction of exotic species. Effects of Land use Change due to Biomass feedstock production have been documented and are severest in case of conversion of high quality natural habitats to productive sites (Searchinger et al 2008, (Dauber *et al.*, 2010), (Firbank, 2008). Also, introduction of invasive species has been reported (Barney and DiTomaso, 2008), (Low and Booth (2007), Randall 2004), Sala et al., 2009. Intensification of agricultural production has severe effects on agrobiodiversity and wildlife (Geiger, 2010). Biomass production exhibit similar properties, depending on type of feedstock and intensity of production, with perennial plants faring better than annual crops (Baum et al., 2009; Schulz et al., 2009, (Fletcher *et al.*, 2010). Bioenergy is also driving introduction and spreading of genetically modified species [ref. missing TSU].

For large scale *concentrating solar* power developments, concerns over impacts on fragile desert ecosystems have been raised, whereas for PV shading could potentially allow enhancement of biodiversity (Tsoutsos *et al.*, 2005).

Tidal barrages are potentially harmful to marine and coastal ecosystems. The change in water level and possible flooding would affect the vegetation on the coastline. The quality of the water in the basin or estuary can also be affected; with sediment levels changing the turbidity of the water, which can affect fish and birds (Mettam, 2005). Brackish waste water and polluted polyethylene membranes from salinity gradient energy (SGE) sites can adversely impact the local marine and river environment. For ocean thermal energy conversion (OTEC) technology, impcts of the up-welling effect of bringing nutrient-rich deep water to the surface on aquatic life needs further research (Vega, 2002).

For *wind* energy production, concerns over fatalities of (migratory) birds and bats have been reported in many regions of the world. However, the majority of studies have recorded relatively low mortalities (Masden et al., 1996, (Desholm and Kahlert, 2005), and siting considerations account for migration routes (see also Chapter 7.6.2). For off-shore wind power farms, negative effects on marine mammals due to sound waves during construction are prevailing, while and positive effects were found in some areas has increased due to artificial reefs appearance (Köller *et al.*, 2006; Wilhelmsson *et al.*, 2006).

9.3.4.7 Hazards and Risks

A large variety of definitions of the term risk exists, depending on the field of application and the object under study (Haimes, 2009). In engineering and natural sciences, risk is frequently defined in a quantitative way: risk (R) = probability (p) × consequence (C). This definition does not include subjective factors of risk perception and aversion, which can also influence the decision-making process, that is, stakeholders may make trade-offs between quantitative and qualitative risk factors (Gregory and Lichtenstein, 1994; Stirling, 1999). Risk assessment and evaluation is further complicated when certain risks significantly transcend everyday levels; their handling posing a challenge for society (WBGU, 2000). For example Renn et al. (2001) assigned risks into three categories or areas, namely (1) the normal area manageable by routine operations and existing laws and regulations, (2) the intermediate area, and (3) the intolerable area (area of permission). Kristensen *et a.l* (2006) proposed a modified classification scheme to further improve the characterization of risk. Recently, additional aspects such as critical infrastructure protection, complex inter-related systems and “unknown unknowns” have become a major focus (Samson *et al.*, 2009; Elahi, 2010; Aven and Zio, 2011).

The energy sector is both a critical infrastructure and key resource for today’s society and economy. Its complex and interdependent technical systems and facilities make the energy sector an absolutely necessary element for the functioning of our information society (Rinaldi *et al.*, 2001; Zio, 2007; Kröger, 2008). Thus, the comparative assessment of accident risks is a pivotal aspect in a comprehensive evaluation of energy security aspects and sustainability performance associated with our current and future energy system. 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 and Hirschberg, 2008), purposed malicious action (e.g., Giroux, 2008), and human errors (e.g., Meshakti, 2007; Ale *et al.*, 2008). This contribution primarily compares risks from accidental events of different energy technologies on the basis of objective information focusing on societal risk measures (e.g., Jonkman *et al.*, 2003), whereas impacts from normal operation, intentional actions, violations of ethical standards, as well as voluntary vs. involuntary risks and aspects of risk internalization in occupational safety are not covered. Additional risk aspects that can potentially lead to accidents or pose a risk to the deployment of a technology are also discussed.

The risks of various energy technologies to society and the environment occur not only during the actual energy generation, but at all stages of energy chains (Hirschberg *et al.*, 1998; Burgherr and Hirschberg, 2008). It has already been recognized in the early 1990s that accidents in the energy sector form the second largest group of all man-made accidents worldwide, however in terms of completeness and data quality their treatment was not satisfactory (Fritzsche, 1992). In response to this the database ENSAD (Energy-Related Severe Accident Database) has been developed, established and continuously updated by the Paul Scherrer Institute (PSI) (e.g., Hirschberg *et al.*, 1998; Hirschberg *et al.*, 2003; Burgherr and Hirschberg, 2008). The results here are focused on so-called severe accidents because they are most controversial in public perception and energy politics. A detailed description of the methodological approach is given in the Appendix.

First, two complementary, fatality-based risk indicators are evaluated for large centralized and decentralized technologies to provide a comprehensive overview. Fatalities were chosen because (1) fatality data is typically most reliable, accurate and complete (Burgherr and Hirschberg, 2008), (2) reducing risks to acceptable levels often includes fatalities since they are amenable to monetization (Viscusi, 2010), and (3) actual or precursor events can provide an estimate for the maximum fatality potential of a technology (Vinnem, 2010). The fatality rate is based on the expected number of fatalities normalized to the unit of electricity production, which occur in severe (≥ 5 fatalities) accidents. The maximum consequences are based on the maximum number of fatalities that are reasonably credible for a single accident of a specific energy technology.

Figure 9.3.18 shows risk assessment results of 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 in non-OECD. Among fossil chains, natural gas performs best with respect to both indicators. The fatality rate for coal China (1994-1999) is distinctly higher than for the rest of non-OECD (Hirschberg *et al.*, 2003; Burgherr and Hirschberg, 2007), however, data for 2000-2009 suggest that China slowly approaches the rest of non-OECD (see Appendix). Among large centralized technologies, western style nuclear and hydro power plants have the lowest fatality rates, but at the same time the consequences of extreme accidents can be very large. Experience with hydro in OECD countries points to very low fatality rates, comparable to the representative PSA-based results obtained for nuclear power plants, whereas in non-OECD dam failures can claim large numbers of victims. For nuclear energy latent fatalities dominate total fatalities (Hirschberg *et al.*, 1998). New Generation III reactors are expected to have significantly lower fatality rates than currently operating power plants, but maximum consequences could increase (see Appendix). Finally, the Chernobyl accident is neither representative for operating plants in OECD using other and safer technologies, nor today's situation in non-OECD countries (Hirschberg *et al.*, 2004; Burgherr and Hirschberg, 2008). In contrast, decentralized renewable technologies exhibit distinctly lower fatality rates than fossil chains, and are fully comparable to hydro and nuclear in highly developed countries. Concerning maximum consequences, new renewables clearly outperform all other technologies because their decentralized nature strongly limits their catastrophic potential. However, it is important to assess additional risk factors of renewables that are currently difficult to fully quantify, but could potentially impede their large scale deployment.

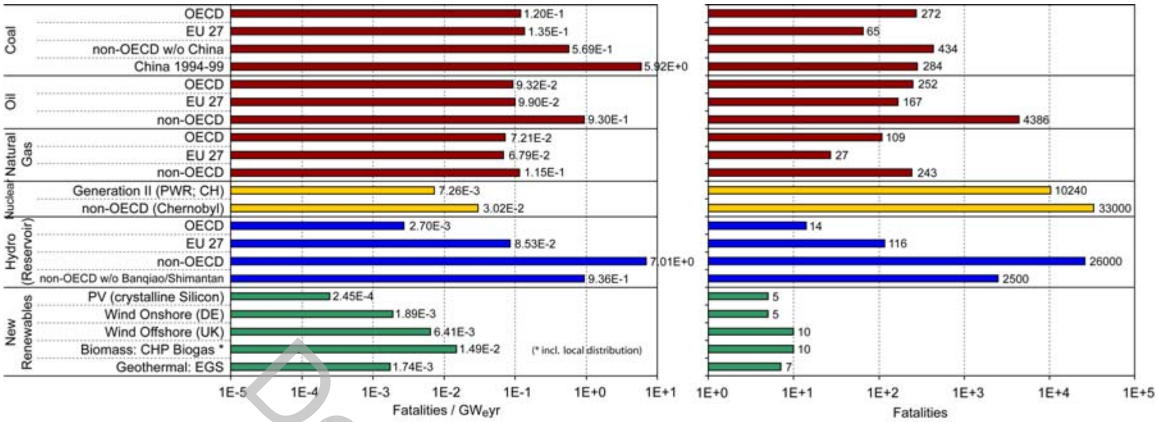


Figure 9.3.18 Comparison of fatality rates and maximum consequences of currently operating large centralized and decentralized energy technologies. Fossil and hydropower is based on the ENSAD database (period 1970-2008); for nuclear PSA is applied; and for new renewables a combination of available data, literature survey and expert judgment is used. See Appendix for methodological details.

Accidents can also result in the contamination of large land and water areas. Accidental land contamination due to the release of radioactive isotopes is only relevant for nuclear technologies (Burgherr *et al.*, 2008). Regarding accidental releases of crude oil and its refined products into the maritime environment, substantial improvements were achieved since the 1970s due to technical measures, but also international conventions, national legislations and increased financial liabilities (Burgherr, 2007; Knapp and Franses, 2009; Kontovas *et al.*, 2010). Nevertheless, very disastrous events like the one of the drilling platform Deepwater Horizon (Gulf of Mexico; 2010; 670’000 t spill; (NIC, 2010)) cannot be excluded in future. Furthermore, increased extraction of deep offshore resources (e.g. Gulf of Mexico, Brazil) as well as in extreme environments (e.g. Arctic) provides an additional threat for accidents with potentially high environmental and economic impacts.

Table 9.3.7 summarizes a variety of risk aspects that are not amenable to full quantification yet because only limited data and experience are available or they cannot be fully covered by traditional risk indicators focusing mainly on consequences.

Table 9.3.7 Overview of selected additional risk aspects for various energy technologies.

Risk aspect	Affected technologies & references
Induced seismicity, subsidence	Oil and gas production, coal mining (Klose, 2007; Suckale, 2009; Klose, 2010b); hydropower reservoirs (Kangi and Heidari, ; Gupta, 2002; Klose, 2010a; Lei, 2010); geothermal (Bommer *et al.*, 2006; Majer *et al.*, 2007; Dannwolf and Ulmer, 2009); Carbon Capture and Sequestration - CCS (Benson, 2006; Holloway *et al.*, 2007; Bachu, 2008; Ayash *et al.*, 2009).
Resource competition	Biofuels (Koh and Ghazoul, 2008; Ajanovic, 2010; Bartle and Abadi, 2010) Reservoir Hydro (Wolf, 1998; Sternberg, 2008; McNally *et al.*, 2009)
Hazardous substances	Relevance for PV requires sector downscaling to allocate appropriate share of consequences (see Appendix) (Coburn and Cohen, 2004; Bernatik *et al.*, 2008)
Proliferation	Nuclear (Toth and Rogner, 2006; Yim, 2006)
Geopolitics, terrorist threat	Security and energy geopolitics of hydrocarbons and renewables (e.g. solarthermal) (Le Coq and Paltseva, 2009; Giroux, 2010; Toft *et al.*, 2010; Lacher and Kumetat, Article In Press) Pirate attacks on oil / gas tankers (Hastings, 2009; Hong and Ng, 2010)

Induced seismicity has already been the cause of delays, and two major EGS projects in the USA (California) and Switzerland (Basel) were even permanently abandoned (Majer *et al.*, 2007; Dannwolf and Ulmer, 2009; Oppenheimer, 2010). With the accelerating expansion of offshore wind parks, the risk analysis of ship collisions with offshore wind turbines and the subsequent implementation of risk reducing measures becomes an import aspect; although the frequency of occurrence is low, the consequences could be large (Christensen *et al.*, 2001; Biehl and Lehmann, 2006). Threats to renewable energy infrastructure and supply could become an issue if large capacities would be installed in geopolitically less stable regions (Lacher and Kumetat, Article In Press). Key issues for biofuels include potential competition with food production and use of water resources (e.g., Koh and Ghazoul, 2008).

In conclusion, accident risks of renewable technologies are not negligible, but their decentralized structure strongly limits the potential for disastrous consequences. However, numerous additional risks should also be considered because they may play an important role in public debate (e.g. risk aversion) and decision-making (e.g. policies).

9.4 Implications of sustainable development pathways for renewable energy

In contrast to the foregoing section that focused on the impacts of current and developing RE systems on SD criteria, this section addresses the implications of possible future renewable energy deployment pathways with sustainable development. Hence, this section will incorporate the intertemporal concerns of sustainable development (see section 9.2). Since SD pathways and their interaction with renewable energy cannot be anticipated by relying on a partial analysis of individual energy technologies or particular regions, the discussion in this section will be based on results from the scenario literature that typically treats the portfolio of technological alternatives in the framework of a global energy system.

Two issues are essential for understanding the state of scenario modelling today. First, the global integrated assessment models in existence today were generated around a relatively specific set of tasks relating to understanding the effects of policy or economics on (1) the energy portfolios of fairly large world regions and (2) the emissions trajectories implied by changes in those energy portfolios over time. As expanding the models beyond these tasks can be challenging there is room for improving treatment of sustainability in the future.

A second and less tractable question regards the ability of the models accurately to model cultural dimensions of energy use and the impact of non-price policies on behaviour and investment. For example, van Ruijven et al (2008) argue that the some assumptions about energy transitions – such as a gradual increase and then a decrease in environmental pollution as incomes rise – are embedded in the current generation of models but could be avoided via technological leapfrogging.

This section will be structured along the lines of the four criteria laid out in section 9.2, i.e. sustainable social and economic development, increased energy access, enhanced energy security and reduced environmental impacts. The section will give an overview of what we can learn from the IAM literature with respect to the interrelation between sustainable development pathways and renewable energies. The aim of this section is twofold – first, to assess what model based analyses currently have to say with respect to sustainability pathways and the role of renewables; and second, to evaluate how model based analyses can be improved to provide a better understanding of sustainability issues in the future.

9.4.1 Sustainable social and economic development

This section discusses research results relevant to understanding the relationship between renewable energy deployment and economic development. The models used in this chapter generally focus on a strong macro-perspective and therefore ignore aspects like life-expectancy or leisure time that would be relevant for alternative welfare indicators compared to GDP, as for example the HDI. Therefore, this section will focus strongly on economic growth. In general, economic growth as such is an insufficient measure of sustainability, as it neither includes defensive cost, nor natural capital, nor does it specify intertemporal concerns (see section 9.2). Most IAMs that are covered in chapter 10 and thus also implicitly or explicitly relevant for the analysis presented here include a tentative strong sustainability constraint by putting an upper limit on future GHG emissions. More generally, however, the non-linear nature of low-likelihood high-risk impacts (related to strong sustainability) is insufficiently reflected. However, economic growth can be used as an indicative measure for future consumption path effects of deployment of renewable energies.

9.4.1.1 Sustainable social and economic development in scenarios of the future

There has been an enormous amount of analysis over the past two decades on the costs of reducing Greenhouse Gas Emissions (see for example, IPCC WG3 1996, 2001 and 2007). These analyses are typically based on a variety of socioeconomic, technological, and geopolitical assumptions extending over periods of decades to a century or more. When a constraint is imposed on GHG emissions, welfare losses are incurred. These are usually measured in terms of GDP or consumption (a major component of GDP) foregone. Other concepts of welfare as discussed in foregoing sections of this chapter are usually not considered. Thus, at the heart of such calculations are assumptions about the availability, costs, and GHG emissions generated by those technologies used to satisfy energy demands – with and without a GHG constraint.

Unfortunately, until recently, such analyses have tended to pay insufficient attention to renewable energy technologies. This was understandable for analyses of the short-term where the options are limited primarily to fuel switching among fossil fuels, and conservation. But, even analyses with a longer-time horizon seemed to pay short shrift to renewables in their portfolio of energy technologies. As a result we know a lot less about the potential role of renewables than about more conventional alternatives such as nuclear, IGCC with carbon capture and storage (CCS), and nonconventional sources of oil and gas.

Although we still have much to learn, the analyses reviewed in Chapter 10 contain many useful insights and provide a good point of departure for further analysis. The chapter provides a synthesis of results from 15 energy-economy models used to examine a broad range of scenarios about the future evolution of the energy system. The models are initially calibrated to a set of "standard" assumptions regarding the characterization of three broad categories of technologies: 1) renewables; 2) nuclear and carbon emitting technologies with CCS; and 3) freely emitting fossil fuels. Sensitivity analysis entails excursions from these "standard" assumptions.

Before turning to specific results several caveats are in order. Although there has been some attempt at standardization among models, these are by no means "controlled experiments". For example, the models produce very different business as usual projections based upon non standardized assumptions about a variety of critical factors, such as how each model responds to changes in energy prices. This can have a profound effect on the energy system and welfare losses in mitigation scenarios. Even parameters that tend to be the focus of the analyses often differ across models such as constraints on nuclear and CCS. Moreover some but not all models use "Learning Curves". That is, renewable technology costs are assumed to decline as capacity grows. Additionally, some models allow for biomass plus CCS. As this technology option generates negative emissions it can ease the transformation process and thus can lead to systematically underestimated cost of mitigation (Tavoni and Tol, 2010). All of this leads to considerable variation among models. Importantly however, the models basically agree on the fundamental insights.

The model comparison in Chapter 10 gives an impression of possible welfare implications of renewable energies. First note that, not surprisingly, there are GDP reductions associated with a GHG constraint, independent from a particular technology portfolio. Second, as the options available for constraining GHG's are limited, GDP losses are increased. In general, it can thus be claimed that the losses increase with tighter constraints.

Some analyses determine the specific welfare implications of constraining renewable energy (Luderer et al. 2009, Edenhofer et al. 2010) for different levels of GHG stabilization. First, the wide availability of all kinds of renewable energy technologies is essential to reach low-stabilization targets. Models used by Edenhofer et al. (2010) calculating a low-stabilization target (400 ppm CO2-eq) do not find a feasible solution when constraining renewable energies to their baseline levels. Second, when relaxing the stabilization target to 550 ppm CO2-eq, models involved in the study find a solution but show a significant increase of welfare losses compared to a scenario where renewable energies are fully available. A similar result is derived by a comparable study by Luderer et al. (2009), using different models. Third, four of six models analyzed in both analyses also show that constraining renewable energy has the highest welfare implications in comparison to other low-carbon energies, including nuclear energy, CCS and biomass (see Figure 10.2.12 in Chapter 10).

When other technologies are constrained, not surprisingly, the share of primary energy provided by renewable energies increases (see also analysis provided in chapter 10). With fewer competing options, renewable energy increases its share. At the same time, higher mitigation costs result in decreasing overall energy consumption.

The scenario literature provides little information about the role of different end use sectors. Luderer et al. (2009) for example find that the electricity sector can be decarbonized relatively fast (until the year 2050) due to the fact that many low carbon options are available, including renewable energies, nuclear energy and CCS. The result even proves to be robust when different low carbon technologies are constrained as well as for developed and developing countries. The transportation sector proves to be more difficult to decarbonize and shows a significant share of fossil fuels in all models in the long term up to 2100. This can be explained by a lack of cost-effective alternatives to oil (see also section on energy security) and limitations to the wide availability of biofuels (mainly due to land-use contraints). The electrification of the transport sector might be one alternative (see e.g. Turton and Moura 2007), which was however not explicitly covered in the analysis. Therefore the assessed role of renewable energies in the sector is limited.

Figure 9.4.1 shows the share of non-Annex I countries in global renewable energy deployment for different renewable energy carriers building upon the analysis rolled out in Chapter 10. As pointed out by Krey and Clarke (2011) in a separate review of this analysis, "much of the expansion of renewable energy production will take place in the developing world". The fact that renewable energies are in large scale deployed in developing countries is particularly important because these countries have yet to go through their industrialization process. Even with huge advances in energy efficiency, their development process is likely to still involve substantial growth in energy consumption. The challenge of introducing a carbon-free energy system in developing countries is thus to make renewable energies (and other low carbon technologies) cost-competitive compared to conventional fuels. This could lead to leap-frogging the emission-intensive developing paths that developed countries have taken so far.

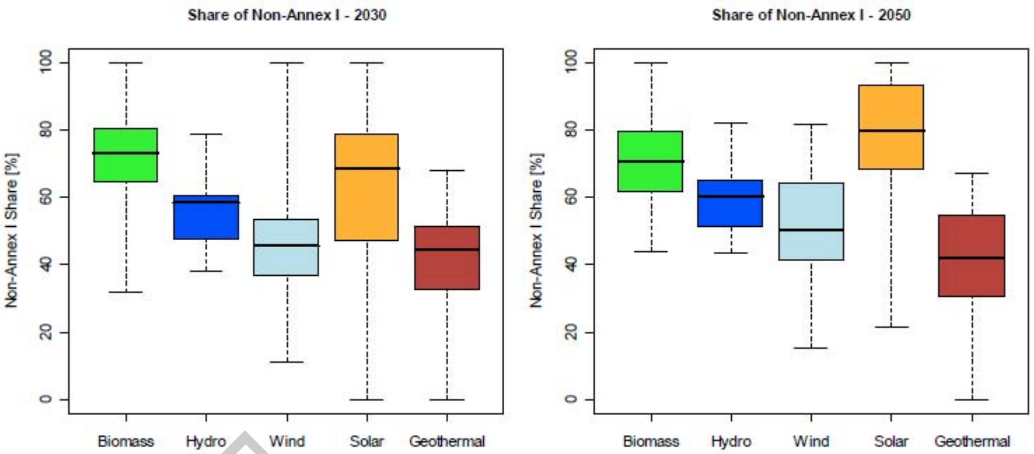


Figure 9.4.1. Share of Non-Annex I countries in the global deployment of different renewable sources in the long-term scenarios by 2030 and 2050. The thick black line corresponds to the median, the colored box corresponds to the interquartile range (25th-75th percentile) and the whiskers correspond to the total range across all reviewed scenarios (Krey and Clarke 2011).

Although global average indicators of welfare are valuable for exploring the general relationship between renewable energy, climate mitigation, and sustained economic growth, a great deal of interest centers not on global totals, but on the relative performance of developing and emerging economies. How might mitigation, and renewable energy in specific as part of a mitigation portfolio, influence sustained economic growth in these economies?

Mitigation scenarios do provide some insights into this issue at a general level. In general, scenarios indicate that the developing countries will need to take on an increasingly large and dominant share of climate mitigation over time, and that renewable energy deployment levels in these countries will, in general, be larger than in developed regions. In general, the same fundamental lessons about renewable energy, mitigation, and sustained economic growth at a global level are found in developing countries, only the forces are generally larger in non-Annex I countries than in the Annex I countries due to more rapid assumed economic growth and the consequent larger mitigation burden over time.

The underlying assumptions of models with respect to a global burden sharing scheme are however crucial for the regional mitigation costs. In general, global mitigation costs do not depend on the allocation of permits but there are significant regional differences depending on the allocation scheme. Whether developing countries gain or lose from mitigation thus depends crucially on how permits are allocated initially. This may also have an effect on convergence/divergence of developing and developed regions.

9.4.1.2 Research Gaps

It should be stressed that the models used for the analyses mentioned above generally provide an incomplete measure of welfare losses because they focus on either GDP or consumption losses. As noted in 9.2, GDP is considered by most economists as a rather poor measure of welfare. However, the use of other welfare indicators proves to be difficult in IAMs as accounting for life expectancy or leisure time would in most cases require a significant higher macro- and micro-economic detail of models. Also, losses are measured at the economy wide level, which although correlated with per capita GDP losses can be misleading. Finally, the models do not give an indication of the distribution of wealth across the population. Is it concentrated among “a few” or distributed more evenly across “the many”?

Beyond the general insights presented in the foregoing section, scenarios do not generally provide strong assessments of many of the forces that might make developing countries behave differently than developed countries; for example, differences in physical and institutional infrastructure and the efficiency and effectiveness of economic markets. The modeling structures used to generate long-term global scenarios generally assume perfectly functioning economic markets and institutional infrastructures across all regions of the globe, discounting the special circumstances that prevail in all countries, and particularly developing countries where these assumptions are particularly tenuous. These sorts of differences and the influence they might have on sustainable social and economic development among countries should be an area of active future research.

9.4.2 Increased energy access

One of the fundamental bases of sustainable development is the expansion of energy services, produced more cleanly, to those people who have only limited access to these services today (Goldemberg et al 1985). While sustainable energy development entails a number of dimensions (see Table 9.4.1), this section focuses particularly on what we might learn from different energy scenarios about the future availability of energy services to different populations. Such services include basic household level tasks (e.g., food preparation, lighting, water heating, water collection, space heating, cooling, refrigeration); transportation (personal and freight); and energy for commerce, manufacturing, and agriculture.

Table 9.4.1. Dimensions of Sustainability in Energy Scenario Modeling. Modified from Nakicenovic et al 2000.

Dimensions of Sustainability in Energy Scenario Modeling			
Modified from Nakicenovic et al 2000			
	Dimension of Impact		
Measurable Category	Access	Environmental	Technology
Reducing relative income gaps	x		
Providing universal access to energy	x		
Increasing affordability of energy	x		
Reducing adverse health impacts		x	
Reducing air pollution		x	
Limiting long-lived radionuclides		x	
Limiting toxic materials		x	
Limiting GHG emissions		x	
Raising domestic energy use			x
Improving supply efficiency			x
Increasing end-use efficiency			x
Accelerating technology diffusion			x

9.4.2.1 Energy access issues in scenarios of the future

Energy models have been used to evaluate and explore possible future energy systems for over three decades, but it is only in the last decade that analyses of energy access have been implemented in these models. Most energy models developed in the past are based on the information and experiences of industrialized countries; energy systems of developing countries were simply assumed to behave likewise (Shukla, 1995). In addition, for energy modelling the data of industrialized countries were historically extrapolated to low-income countries, with no change in the underlying assumptions, to assess scenarios for developing countries. However, there are fundamental differences between the energy systems of developing countries and those of industrialized countries. As such, models grounded in developed country experience, and using developed country data, often fail to capture important and determinative dynamics in, for example, the choices to use traditional fuels, informal access to the electricity grid, informal economies, and structural changes in domestic economies, all of which exert a demonstrably large effect on access in many parts of the world (van Ruijven et al., 2008).

Although these factors are important to analyse both the energy systems of developing countries and the dynamics of energy access, only a handful of energy models explicitly account for them. A comparison study of 12 well-known energy models by Urban et al. (2007) shows that there has been a progress in addressing these issues for application in developing country contexts. All models covered electrification (though not all explicitly), and most models had implemented use of traditional biomass and urban/rural dynamics. However, many of the models still lacked important factors such as potential supply shortages, informal economies, and investment decisionmaking. Some of these issues are being implemented into models. For example, to understand how to avoid supply shortage during the peak hours, a higher time resolution and daily load curves to allow dynamic pricing of electricity were added to a MARKAL energy model of South Africa (Howells et al., 2007). Similarly, to reflect an aspect of the informal economy in fuel choices, a non-commercial “inconvenience cost,” related to using fuels, was added to MESSAGE (Ekholm et al., 2010). Several groups have attempted to increase the distributional resolution, and thereby to capture behavioural heterogeneity, by dividing populations into rural and urban categories, as well as diverse income groups (van Ruijven, 2008, Ekholm et al., 2010). Nevertheless, much more work remains ahead as access models are typically limited to cover only a region or country due to lack of information, or they only cover a part of the energy access issue, electrification or cooking fuel.

While models use such approaches to capture energy access implications, rural populations in developing countries will likely continue to rely on traditional fuel to satisfy their energy needs in the future. Income growth is expected to alleviate some of the access issues, but linking this growth with fuel transitions carries much uncertainty. A scenario analysis of India’s energy system in 2050 showed more than 10% difference in the future electrification rate depending on whether the GINI coefficients approaches the level of present day Italy or China (van Ruijven, 2008). It is vital to have effective policies and major investments in order to achieve high a penetration of modern energy.

Electrification, grid extension or off-grid, is capital intensive and requires large investment. IEA estimates that investment of $756 billion from 2010 to 2030 is needed for universal modern energy access by 2030, of which $700 billion, or $33 billion per year on average, is to accomplish universal electricity access (IEA 2010). If developing countries are not able to secure finance for electrification, the number of people without electricity is going to stay around the level of today. The combination of the availability of the low cost traditional biomass and high initial investment cost for LPG will continue to make fuelwood the main source of energy for cooking. A subsidy will allow higher penetration, but it is more effective when it's coupled with financing. A scenario analysis on cooking fuel in India by Ekholm et al. (2010) show that without financing 50% subsidy on LPG is required for a full penetration by 2020, but only 20% subsidy is needed if improved finance is also offered.

Having access to modern energy is not a guarantee to the path of sustainable development. A shift to modern energy is sometimes a shift to fossil fuel, which is not sustainable in a long run. However, relying on traditional biomass such as fuelwood or charcoal could also lead to environmental problems of deforestation and forest degradation, depending on the source of biomass. To expand access to energy services in a trajectory of sustainable development would likely experience concomitant shifts toward energy supply technologies that produce less unwanted byproducts—carbon or other greenhouse gases, regional pollutants, toxins in manufacture or generation, and radionuclides. One aspect of such a shift would be an increasing fraction of energy supplied by renewable energy technologies, both on-grid and decentralized. In addition, there is a social aspect of energy use, which can lead to an unsustainable use of energy. To secure a sustainable use of energy, measures to alleviate environmental burden in addition to access to modern energy are essential. In an analysis by Howells et al. (2007) on the future rural household energy consumption in South Africa, a shift to electricity outside lighting and entertainment services only occurred in the scenario which puts cost on health or other externalities from local combustion emissions.

9.4.2.2 Research Gaps

From a development perspective, any sustainable energy expansion should increase availability of energy services to groups that currently tend to have less access to them: the poor (measured by wealth, income, or more integrative indicators), those in rural areas, those without connections to the grid, and women, for example (Reddy et al 2000). From this perspective, the distribution in the use and availability of energy technologies, and how they might change over time, is of fundamental importance in evaluating the potential for improvement in access (Baer 2008). Since expanding access requires changes in technology across all values of a variable (e.g., income), understanding the starting distribution as well as the changes over time is necessary to evaluate the potential increase in access in one scenario relative to another. A second confounding factor in using model output to evaluate changes in access is the inability of many models to capture social phenomena and structural changes that underlie peoples' utilization of energy technologies.

These two aspects – lack of distributional resolution and structural rigidity – present particular challenges for energy models. Models have historically focused much more on the technological and macroeconomic aspects of energy transitions, and in the process have produced largely aggregated measures of technological penetration or energy generated by particular sources of supply (Parson et al 2007). Such measures can, of course, be useful for making broad comparisons, such as the relative share of low-carbon energy across countries. However, an explicit representation of the energy consequences for the poorest, women, specific ethnic groups within countries, or those in specific geographical areas, tends to be outside the range of current global model output.

Future modelling efforts could potentially address some of the problems highlighted in this section. Currently, access can be only estimated via proxies to aggregate statistics. However, the relationships between these aggregate statistics and access are clearly not consistent across countries and could change over time. Therefore, if access is a concern, then energy models should incorporate the elements most likely to illuminate changes in energy access. Explicit representation of traditional fuels, modes of electrification, and income distribution could add some resolutions to this process. More fundamentally, linking these to representation of alternate development pathways could provide a more comprehensive view of the possible range of options to provide access. For example, a dramatic expansion of distributed off-grid electricity generation coupled with efficient devices raises the possibility that large grid connectivity may not remain as fundamental a driver of access as it has been in the past. RET, which is valuable in remote places due to conversion of natural energy source on-site, could play a major role in such scenarios.

9.4.3 Enhanced energy security

As noted in Section 9.3.3, energy security (ES), like sustainable development, suffers from a lack of either a well formed quantifiable or qualitative definition. ES is often taken to be synonymous with oil imports. The focus on oil can be traced to the facts that not only are many countries potentially vulnerable to supply disruptions, but in addition, many developed countries experienced an oil supply disruption during the OPEC oil embargo of the mid 1970's. But, the real concern is not necessarily about oil, so much as, vulnerability to sudden disruption in energy supply.

All other things being equal, the more reliant an energy system is on a single energy source, the more susceptible the energy system is to serious disruptions. At the same time, it is important to note that diversity of supply is only beneficial to the extent that the risks of disruptions are equal across sources. To the extent that risks are not equal, it is generally beneficial to rely more heavily on those sources with the lowest and most uncorrelated risks.

There are two avenues by which renewable energy can affect ES: 1. Diversity of energy supply and thereby in energy suppliers' market power, and 2. Reliability of resources.

We begin by focusing on the oil market and then consider issues associated with variability in energy supply associated with RE.

9.4.3.1 Energy security in scenarios of the future

Renewable energy, oil markets and energy security

The role of renewable energy in reducing energy supply disruptions will vary with the energy form. Solar, wind and geothermal (SWG) energy is closely associated with electric power production. Reducing oil demand by increasing SWG energy supplies hinges on the ability of electricity to supplant oil. This happens in greenhouse gas emissions scenarios in the buildings and industrial sectors as a result of increasingly favorable relative electricity prices (as compared with dun-use fossil fuel forms) in end use sectors. But, the demand for liquid fuels in the transport sector is highly inelastic and relatively little substitution of electricity for oil occurs without a technology breakthrough that makes electric power options competitive with liquid fuel transport options.

Bioenergy is another matter. Bioenergy is a versatile renewable energy form that can be transformed into liquids fuels that compete directly with fossil fuel liquids. In reference scenarios, liquids derived from biomass garner market share. The interaction between bioenergy and oil consumption is highly sensitive to both policy and technology. In the presence of a carbon price, bioenergy's completive advantage increases. However the utilization of bioenergy depends strongly on whether or not CO_2 capture and storage (CCS) technology is available. Luckow, et al. (2010) demonstrated the sensitivity of bioenergy utilization to the availability of CCS technology. Figure 9.4.2 shows two scenarios in which the concentration of atmospheric CO_2 is stabilized at 450 ppm. In the left figure CCS technology is available, while in the right figure it is not. If CCS is unavailable bioenergy is eventually all transformed into liquid fuels for use as a substitute for fossil fuel derived liquids. When CCS is available, most bioenergy is utilized in solid form by power generation with CCS – resulting in negative net carbon emissions for the system. Bioenergy transformation to liquid form is thus reduced by the presence of CCS technology and liquid fuel production is generally associated with the use of CCS in the refining process to deliver net negative system emissions.

As was previously discussed in earlier sections and chapters of this report, bioenergy is subject to indirect land-use emissions. There is a substantial literature on this point including Calvin et al., 2010, Wise et al., 2009, Searchinger et al. 2008; Tilman, Hill, and Lehman, 2006; Edmonds et al., 2003; McCarl and Schneider, 2001; Yamamoto, et al., 2001). Others have critically assessed the interaction between bioenergy production and food prices (Wise, et al., 2010, Runge and Senauer, 2007; Gurgel, Reilly, and Paltsev, 2008; Gillingham et al., 2008; Edmonds, et al., 2003). Calvin et al., (2010) and Wise, et al. (2009) showed the importance of the policy environment and in particular the valuation of terrestrial carbon stocks. Burney, et al. (2010) and Wise, et al. (2009) both show the importance of traditional crop productivity in reducing greenhouse gas emissions. Wise, et al. (2010) also show that absent continued improvements in agricultural crop yields, bioenergy production never becomes a significant source of renewable energy.

a) Biomass consumption by use (with CCS)

b) Biomass consumption by use (w/o CCS)

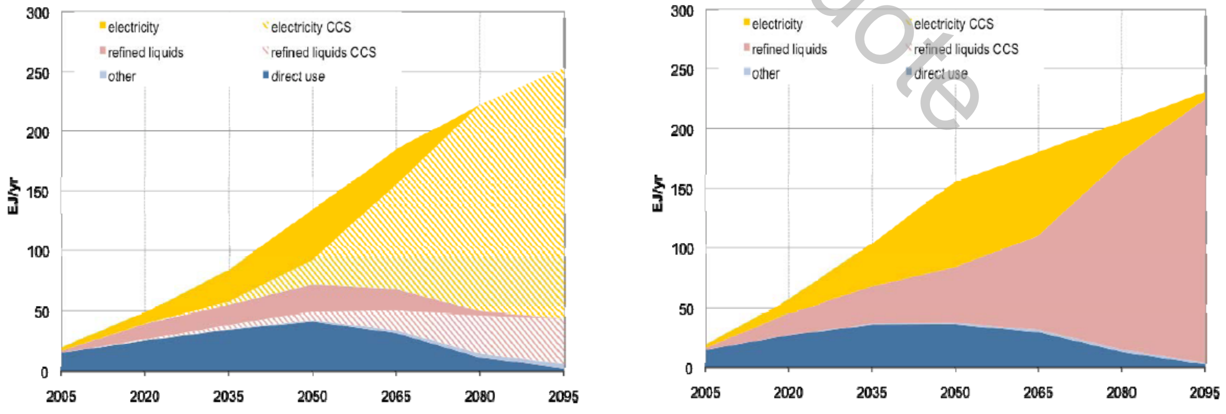
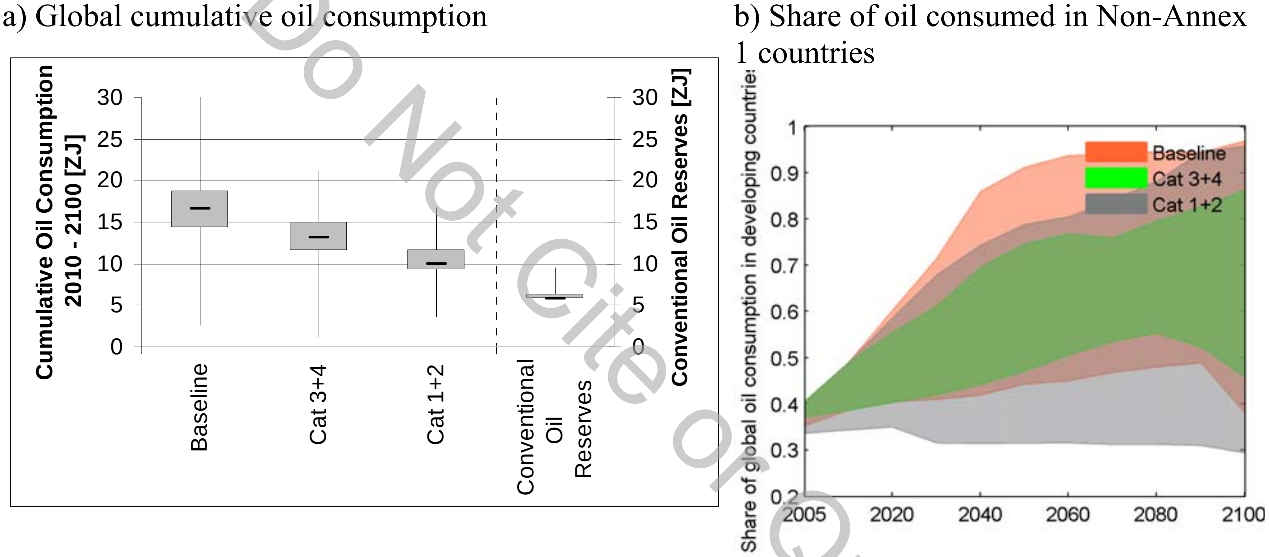


Figure 9.4.2. Biomass consumption by use with (a) and without (b) CCS for a 450 ppm climate stabilization scenario using GCAM. Source: Luckow, et al. (2010).

While we generally think that the emergence of bioenergy as a major energy form would take place in a market characterized by a large number of sellers with relatively little market power, that is by no means certain. If the bioenergy market were characterized by a small number of sellers, then buyers would be exposed to the same type of risk as characterize the global oil market. This sort of risk to portfolio linkage is simply not explored by existing mitigation scenarios.

In the scenarios calculated for the SRREN, the consumption and the price of oil decrease in mitigation scenarios not as significantly as, for example, the consumption of coal. This is because oil is majorly consumed in the transportation sector, and as electrification of the transportation sector is not an option in most models, alternatives for crude oil, such as biofuels, are a) difficult to generate and b) expensive (see Chapter 2). These scenarios therefore do not see dramatic differences between the baseline and policy scenarios with respect to cumulative oil consumption (see.Figure 9.4.3a).


a) Global cumulative oil consumption

b) Share of oil consumed in Non-Annex 1 countries

Figure 9.4.3.a) Conventional oil reserves compared to cumulative oil consumption in SRREN scenarios (see also Chapter 10 for a more detailed discussion of scenarios) from 2010 to 2100 in ZJ for different scenario categories, i.e. baseline scenarios, category 3 and 4 scenarios and low stabilization (category 1+2) scenarios. The thick black line corresponds to the median, the grey box corresponds to the interquartile range (25th – 75th percentile) and the whiskers correspond to the total range across all reviewed scenarios. The last column shows the range of proven recoverable conventional oil reserves (grey box) and estimated additional reserves (whiskers) (Rogner 1997)[11] b) Range of share of global oil consumed in non-Annex 1 countries for different scenario categories over time.

Compared to the SRREN baseline scenarios the median of cumulative consumption decreases by 20% in category 3+4 scenarios and by 40% in low stabilization scenarios. To the extent that imports also decline, countries would be less vulnerable to oil supply disruptions than in a

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[11] According to Rogner (1997) proved recoverable reserves are between 5.7 to 6.3 ZJ. In addition to that estimated additional reserves range between 2.6 and 3.2 ZJ. The total consumption of oil goes far beyond that in most scenarios accessed for the SRREN, which directly imply the use of unconventional reserves as well as coal to liquid technologies.

reference scenario. However, oil still plays a major role in the mitigation scenarios. Based on the SRREN scenarios, ES discussions concerning oil supply disruptions that have been raised in the past will thus remain relevant in the future. For developing countries the issue will become even more relevant, as their share in global total oil consumption will increase in all scenarios, independent from the climate target (Figure 9.4.3b).

Furthermore, in scenarios that stabilize CO_2 concentrations, carbon prices generally rise to the point where unconventional oil supplies, such as coal-to-liquids and oil shales, which enter the market in reference scenarios (see, e.g., Figure 9.4.3 a), are dramatically limited in supply. On the one hand, this effect would limit the environmental concerns (such as water pollution) that are generally associated with unconventional oil production. On the other hand, depending on a country's domestic resource base, this could increase (decrease) energy supply vulnerability for countries with (without) endowments of coal and unconventional liquids.

The effect of a GHG emissions constraint with respect to conventional oil is also interesting in terms of consumption timing. Because conventional oil is relatively inexpensive to produce, the immediate suppression in demand, imports and the oil price to suppliers (consumer prices rise), is offset by an increase in oil use in later years. In other words, the effect of the cap in a CO_2 concentration stabilization scenario is to lower the peak in oil production and shift it further into the future. This has the effect of reducing near-term oil imports and increasing oil consumption in later years. As the allowable long-term CO_2 concentration declines, this effect is overwhelmed by declining cumulative allowable emissions. See for example, Bollen, et al. (2010).

The effect of ES policies on renewable energy and greenhouse emissions is also interesting. For example, based on a static general equilibrium model for the European Union to analyze trade flows to and from the former Soviet Union, Kuik (2003) showed that policies to subsidize the domestic production of bioenergy, simultaneously reduced fossil fuel CO_2 emissions and oil imports. However, Kuik concludes that the policy is not cost-effective in achieving climate goals.

Renewable energy and energy system reliability

Another source of energy supply vulnerability is exposure to unpredictable disruptive natural events. For example, wind power is vulnerable to periods of low wind. Of course, wind is not uniquely exposed to this class of vulnerability. Other energy forms such as solar power or bioenergy are also exposed to unusual weather episodes.

An important method for addressing energy supply stochasticity is holding stocks, which act to buffer the system (see section 9.2.2 for the example of oil reserves in the amount of 90 days of net imports that member countries of the IEA have to hold as stocks). An increase in the role of bioenergy would likely lead to the creation of bioenergy stocks – either in the form of stocks of solid fuel or bioenergy liquids – as a hedge against uncertainty of supply.

Renewable energy forms such as wind, solar and wave energy, which produce electricity, are generally not easily stored in their native forms. Energy supply variability can be reduced by increasing the geospatial diversity of supply. However, even distribution over very large areas such as the 48 contiguous United States does not guaranteed reliability. The system can also be buffered by a variety of storage methods ranging from hydro pump storage, compressed air storage, to battery storage.

The need to hold buffering stocks grows as the RE form garners increased market share. In all instances the need for storage introduces increased costs, which in turn dampens that energy form's competitive position in the market.

Future emissions mitigation scenarios are generally characterized by increased energy supply diversity, if for no other reason than mitigation generally decreases the contribution of fossil fuels, which continue to dominate the energy system absent climate mitigation. See for example, Clarke, et al. (2009) or Grubb, et al. (2006). This would be particularly beneficial for regions with fossil fuel demand that can only be met by domestic or external monopolistic suppliers.[12] Yet, market power in resource markets is typically not represented by global IAMs.

Since renewable energy deployment levels generally increase with mitigation in IAMs, there is a sense that the emergence of a relatively small share of many individual renewable energy technologies can be part of a more broadly diversified energy portfolio at the same time that mitigation is undertaken, an ES benefit.

It is important to apply the caveat that it is not necessarily clear that mitigation will increase the diversification of supply. For example, if the deployment of particular options is largely constrained or society chooses to focus most heavily on one option, such as nuclear power, then mitigation may not lead to substantial increases in supply diversity.

9.4.3.2 Research gaps

The relationship between renewable energy and ES is characterized by numerous research gaps ranging from the lack of a clear quantifiable definition of ES to the existence of a focused literature on the relationship between RE and ES. Consideration of ES commonly focuses on the most prominent of ES issues in recent memory, for example, disruptions to the global oil supply and security issues surrounding nuclear energy production. However, ES issues go well beyond these issues. For example, the supply of rare Earth metals and other critical inputs could constrain the production of many (renewable) energy technologies. These broader concerns are largely absent from future scenarios of mitigation and renewable energy.

Generally missing from the literature is a focus on the relationship between ES and system reliability. An important aspect of deploying renewable energy sources at large scale is their integration into the existing supply structures. Systems integration is most challenging for the intermittent electricity generation technologies such as wind power, solar PV and wave energy. A first order proxy for the challenges related to systems integration is therefore the share of different intermittent renewable energy sources, mostly wind power and solar PV, at the global level (see also Figure 10.2.9). Again, those scenarios with high proportions of wind and solar PV on the grid implicitly assume that any barriers to grid management in this context are largely overcome, for example, through electricity storage technologies, demand-side management options, and advances in grid management more generally (see Chapter 8). This is a strong assumption and managing storage, back-up capacity, grid improvement and demand-side innovation costs will be essential to balancing variable renewable generation and ensuring grid reliability.

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[12] The concentration of energy supplies in the hands of a small number of sellers means that that a small group has the potential to control access. Diversification of the set of suppliers is one potential response to reduce the potential for energy supply disruptions.

9.4.4 Assessment of environmental impacts

In addition to evaluating alternate scenarios with respect to the potential contribution to energy access and energy security, any assessment of energy futures under sustainable development criteria must include a comparison of the environmental impacts of energy services. At a fundamental level, reductions in environmental impacts derive from increases in the efficiency of providing services or shifting to lower-impact sources of supply.

9.4.4.1 Environmental impacts issues in scenarios of the future

As existing models include explicit representation of energy efficiency and energy supply mix, the scenarios they produce provide information on both of these dimensions of sustainability. In addition, several models have included explicit representation of factors that are linked to environmental or health impacts. For example, combustion of sulfur-containing coal without control technology can generate pollutants that are important at local and regional levels (e.g. SO_x). This raises the possibility that a move away from sources of combustion would generate benefits not via reductions in greenhouse gas emissions but also via reductions in local air pollution. Several models include sulfate pollution and therefore provide the basis for some estimation of the health or ecosystem consequences of this combustion byproduct (van Ruijven et al 2008). In standard scenarios, however, the link between SO_x emissions and consequences is not explicit. Bollen et al (2009) addressed this question by performing a cost-benefit analysis (using the MERGE model) that included both greenhouse gas and SO_x reductions. They found that climate policy can help drive improvements in local air pollution but that air pollution reduction policies do not necessarily drive reductions in greenhouse gas emissions. Shrestha and Pradhan (2010) performed a broader co-benefits analysis within a specific country case, linking the MARKAL model to a model of Thailand’s energy system. They found similarly that climate policy would lower the impacts from coal combustion.

Another implication of some potential energy trajectories is possible diversion of land to support biofuel production. While this has been a topic of intense discussion, many models have until recently not supported explicit links between energy supply options and land use. Early attempts to address the links were focused on trade-offs across energy supply and food production (Yamamoto et al 2001) or used existing scenarios as a basis for estimating future bioenergy use (Hoogwijk and Faaij 2005). Subsequently these approaches were combined by embedding bioenergy modules directly into integrated assessment models (Gillingham et al 2008). Wise et al (2009) incorporated a geographically explicit land-use component into the MiniCAM integrated assessment model. They found that, absent a carbon price on terrestrial carbon, climate policy could drive widespread deforestation as land was shifted to bioenergy crops. Melillo et al (2009) incorporated indirect land-use change as well as agricultural inputs such as fertilizer into MIT’s EPPA model. They found similarly that biofuels policy executed poorly would drive widespread emissions from land conversion, both direct and indirect, and also could result in substantial N_2O emissions derived from improper fertilizer application. In both investigations, what might ostensibly have been seen as a “sustainable” energy scenario (i.e., the increasing use of biofuels) was shown to have potential consequences that contravened the principles of sustainable development.

Model scenarios therefore can be useful in demonstrating scenarios of potentially unanticipated (or at least unquantified) environmental benefits as well as scenarios of unanticipated or unquantified environmental costs. Other aggregate measures that could be amenable to analysis under current scenarios include, for example, water use intensity of energy (m^3/MWh) and land use (hectares/MWh). These could be linked to other dimensions of sustainability, such as loss of biodiversity or changes in food security, though the appropriate treatment of this link is not defined.

9.4.4.2 Research gaps

Unfortunately, aside from the two linkages discussed above (land use and sulfur dioxide emissions), the existing scenario literature does not give explicit treatment to the many non-emissions related elements of sustainable energy development as, for example, water use, or the impacts of energy choices on household-level services or indoor air quality. These environmental aspects of sustainability depend to a much greater degree on the distribution of energy use and how each energy technology is used in practice. Analysing this with the existing models might be difficult since models have been designed to look at fairly large world regions without looking at income or geographic distribution. Existing scenarios rather enable users to compare the outcomes of different possible "futures" (O'Neill and Nakicenovic 2008) by allowing easy comparisons for aggregate measurements of sustainability – for example, national or sectoral greenhouse gas emissions. Although some models have also begun to allow for comparison across smaller geographic scales of impact, such as for regional air pollution and land use change, some environmental impacts remain opaque in the scenarios produced to date: the distribution of the use of traditional fuels, for example, can matter significantly for the health of billions of people (Bailis et al 2005). What these impacts are, whether and how to compare them across categories, and whether they might be incorporated into future scenarios would constitute useful areas for future research.

9.5 Barriers and opportunities for renewable energies in the context of sustainable development

Pursuing a renewable energy deployment strategy is faced by the callenge to take all environmental, social and economic effects explicitly into account. Clear and integrated policy implementation and planning processes can support this by anticipating and overcoming potential barriers to and building on opportunities of RE deployment. In the context of sustainable development, there are socio-cultural barriers with respect to environmental concerns and social acceptance; information and awareness barriers, including capacity building; and market failures and economic barriers. Following the discussion of these barriers in section 9.5.1, section 9.5.2 focuses on how integrative approaches from the international to the local level can overcome such barriers to arrive at opportunities for renewable energy deployment that could entail a multi-dimensional progress for sustainable development.

9.5.1 Barriers

Not withstanding the strong linkages and consequent beneficial synergies between RE and SD, criteria for the latter may put additional constraints on the deployment of the first. In order to reap all sustainability benefits RE policy-making and deployment need to be embedded in a clear and consistent framework of sustainability strategies. This means that links to the three pillars of sustainable development have to be taken into account, so that RE policies as well as project planning, construction and operation are rooted in the specific social, economic and environmental context of a given country. They should also remain aligned with multilateral environmental agreements (MEAs). Barriers identified in the following section have been grouped according to the overall structure, laid out in Chapter 1, and provide – sometimes overlapping – links to possible environmental, social or economic constraints or concerns that have been partly addressed in the report and should be taken into account during RE policy-making and deployment.

9.5.1.1 Socio-cultural barriers

Environmental concerns with respect to the deployment of RE have many different origins. Measuring and calibrating the necessary level of sustainability requisites is a difficult task, which can be supported by tools such as life cycle analyses, environmental impact assessments, strategic socioeconomic and environmental planning, land use zonings, certification schemes or overall environmental management systems. Perception and acceptance of impacts vary considerably with source, type of stakeholders or policies in place. One of the most commonly discussed impacts – but not necessarily addressed at local implementation level – are greenhouse gas emissions. For example, in the case of biofuels, life cycle GHG emissions should be at least lower than a fossil fuel baseline and should contribute to the minimization of overall GHG emissions. This is not always what occurs at the local level, as shown by the following examples: (i) land use clearing (deforestation or peatland conversion) to grow palm trees for biodiesel; (ii) fossil fuel intensive life cycles of some types of ethanol and biodiesel, due to local weather conditions and crop mechanization. (see also 9.3.4).

Carbon leakage and *indirect land use change* are complex and at the same time important topics to be considered. Discussions on indirect land use change are found in sections 2.4.4.2 (sustainability frameworks and standards addressing unwanted land use change), 2.5.3 (challenges related to estimating and modeling direct and indirect land use change from modern bioenergy); discussions on carbon leakage are found in sections 8.3.3.2 (the problem of energy-intensive industries moving to developing countries through green-field investments and the possible solutions brought about by sectoral approaches in international climate policy, reducing leakage risks and facilitating technology transfer, as well as financing of mitigation measures), 11.6.7 (integration of RE-climate policies to reduce leakage risks). *Energy payback times* (section 9.3.4) reflect the input-output matrix of a given fuel, which can be affected by long distance transport, mechanization or production processes. *Waste products*, including local and regional air pollutants, are another topic worth of investigation (see section 9.3.4 on vehicle emissions). *Biodiversity impacts* associated with crop production are difficult to assess and may either represent a limitation (especially when there are pathologic case studies associated) or an impulse (when compared to conventional energy sources) to the deployment of some types of renewables (see section 2.5.3.3). The precautionary principle is applicable to assess the level of impacts on rare, vulnerable or threatened species, maximizing habitat restoration and protecting high quality habitats. Other criteria include the *extent of land, aquatic or marine area affected* (environmental footprint) and associated aquatic and terrestrial ecological impacts (soil, water, natural resource depletion). Concerns regarding the negative effects to ecology and landscape, for example, led to the failure or revision of several planned biomass energy developments in the UK (Upreti, 2004). Additional factors are *chronic effects* to human health (e.g. from toxic air pollutants, pesticides, genetically modified organisms, dioxins and furans, radioactive wastes) and the avoidance of exceptional natural and human heritage sites. This has proved particularly important in the context of wind farm deployments, where the main concerns relate to the scenic impact and landscapes expected for the proposed sites (Wolsink, 2000; Wolsink, 2007b). Disregarding such concerns during the planning process can ultimately lead to the failure of projects (Upreti, 2004; Jobert *et al.*, 2007; Wolsink, 2010). Finally, but not exhausting the list, criteria for sustainability include respect for *land and land use rights*, and prior formal and customary *water rights*. Attitudes towards offshore wind farms, for example, depend on the type and frequency of beach use with regular visitors perceiving coastal landscapes as more pristine resources and thus less suited for industrial usage (Ladenburg, 2010). However, reasons for local opposition to renewable energy projects can vary significantly and may also depend on the methods used during the opinion elicitation process (van der Horst, 2007).

Social concerns include project acceptance and ensuring effective public participation. Similarly to environmental concerns, social concerns can constrain the deployment of renewables in different ways. *Displacement* issues, for example, are common in land-use intensive projects, such as large scale hydropower (Water Alternatives, 2010) and commercial scale energy crops (IIED, 2009). Other types of displacement are more related to nuisances, as is the case of noise from windpower turbines, or to changes in resource use and biodiversity in the area of the proposed project and the impacts this may have on the local community (Bosley and Bosley, 1988). Economic compensation for displaced people may not be sufficient to cover housing replacement costs – and much less externalities such as losses in cultural heritage (Cernea, 1997; World Commission on Dams, 2000).

There are other types of displacement, such as that caused by environmental accidents, both in renewables (crop fires, dam bursts) and non-renewables (LNG plant explosions, oil spills, nuclear plant disasters). *Risks* differ from process to process – as well as its perceptions. Large scale, concentrated incidents and accidents, are usually more visible to the public awareness, and possibly also lead to displacement, than diffuse ones (e.g. several minor spills or other technical incidents) (see section 9.3.4.5 for a more detailed discussion). *Hazards* occur also at occupational level, affecting human and labour rights, e.g. in field crop work (ILO, 2010). Food security is another important issue (see section 2.5.7.4). The *competition among food-feed-fuel* is closely related to land use change issues (section 9.3) to which certification schemes are paying increased attention (see Chapter 2).

Most renewable energy applications have traditionally been perceived as environmentally friendly by the general public, with exceptions for some large hydropower and bioenergy projects. However, with up-scaling and the development of new installations being driven by more commercial stakeholders, typically utilities or private power companies, it is not evident that the positive public perception is immediately maintained. Increased public resistance to new large installations have been experienced in many countries, often beyond the more narrow "not in my backyard" type concerns (Wolsink, 2007b). Public awareness and acceptance is therefore an important element in the climate mitigation driven need to rapidly and significantly scale-up the adoption and deployment of RE technologies. Evidently, such large scale implementation can only successfully be undertaken with the understanding and support from the public. This will require dedicated awareness raising on the achievements of existing RE options and the opportunities, prospects, and potentials associated with wider scale applications (Barry *et al.*, 2008). At the same time, however, public participation in planning decisions as well as fairness and equity considerations play an equally important role (Wolsink, 2007b; Malesios and Arabatzis, 2010).

9.5.1.2 Information and awareness barriers

An often used argument for the promotion of renewable energy projects is their contribution to *poverty reduction*, with local communities benefiting via employment, skills development, investment opportunities and technology transfer. However, should these benefits not be perceived by the local community, acceptance of projects may be problematic (Upreti, 2004; see box in section 11.6.5). In developing countries the limited technological and business knowledge and skill base are particularly apparent in the energy sector where awareness, among potential renewable consumers, of alternative sources of energy is a key determinant in terms of uptake and market creation. This gap in awareness (and lack of market drivers) is often perceived as the single biggest factor affecting the development of both the uptake of renewable and energy SMEs and their ability to contribute to economic growth. The neglect of social aspects of decentralized units can thus often result in abandoned and dysfunctional systems (Werner, Schaefer, 2007).

In cases where the proprietary ownership of RE technologies is mostly in the hands of private sector companies and the diffusion of technologies also typically occurs through markets in which companies are key actors (Wilkins, 2002), there is a need to focus on the capacity of these actors to develop, implement and deploy RE technologies in various countries. Therefore, the importance of increasing technological capability – as a part of *capacity building* (Box) – at the micro or firm–level needs to be addressed (Lall, 2002; Figueiredo, 2003).

Box – Capacity Building

As recognized by several Multilateral Environmental Agreements (MEAs), e.g. the WSSD Plan of Implementation or the UNFCCC Bali Roadmap, lack of *capacity building* is a key barrier to the rapid transfer of technologies to and within developing countries. Lack of capacity to set RE policies and to design and implement programs delays and sometimes negates implementation of renewable technologies. There are many different types of constraints to an enabling environment for innovation, revised technical regulations, international support for technology transfer, microfinance, technical training and liberalization of energy industries (see Chapter 11.6). This need for capacity development for making appropriate planning efforts on RE is most urgent in developing countries, however, the capacity of many industrialized countries to develop and implement RE policies and technologies is still limited (Assmann *et al.*, 2006). This often constitutes a significant and real barrier to increased utilization and deployment of RE technologies (Painuly, 2001). Capacity building is needed at the technological level as well as the institution level. At the *technological level* it includes, *inter alia*: (i) research, development, and demonstration to increase technological skills; (ii) developing capacity within the field of testing and licensing of renewable energy technologies; (iii) developing international resource and technology data on renewable energy sources in order to supplement existing measures. At the *institutional level* could be cited: (i) enhancing capacity of energy planners and analysts to e.g. include full costs, include externalities when comparing different technological options; (ii) supporting governments to formulate, implement and enforce renewable energy policy programmes; (iii) increasing awareness among policy makers to better understand energy market distortions, their consequences and the opportunities of renewable energy technologies; (iv) increasing awareness and skills of international and national financial institutions, including enabling them to exploit the opportunities of carbon financing (using the international mechanisms JI, CDM and emissions trading), information and education on all educational levels (basic school, high school, more advanced studies etc.) on national level or through international programmes, in-service training of officials at local as well as national level, provision of incentives for the general population (and particularly farmers and villagers) to take advantage of renewable energy deployment (e.g. tax deduction incentives etc.), twinning between authorities and third sector organizations from countries with different experience, international education programmes and international in-service training programmes (Kofoed-Wiuff *et al.*, 2006). For example, there have been mixed experiences with PV technology in terms of project design and implementation and the involvement of various players like users, implementation agents, policy makers and financiers. Inadequate local support structures have also greatly hampered success rates of PV applications (Zhou, CILSS Report).

9.5.1.3 Market failures and economic barriers

The economics of renewable energy technologies are discussed in nearly all chapters of this report, e.g., when discussing cost of technologies (Chapters 2-7), externalities (Chapter 10), policies (Chapter 11) and various case studies. The three pillar concept of sustainable development, and the paradigms of weak and strong sustainability require specific cost-effectiveness assessments, considering among others (i) the economic viability and planned monitoring of economic performance and (ii) the availability and cost of resources over the projected life of the facility; furthermore, (iii) regulatory compliance, (iv) the geographic, cultural, and socio-economic appropriateness of the technology, levels of efficiency and service required and distributional aspects such as (v) additional or multiple use benefits and (vi) the distribution and sustainability of economic benefits.

There are still many pilot projetcs of renewables in developing countries that give an anecdotal account and do not illustrate the real prospects that renewables can offer to a growing energy poor community (Karekezi and Kithyoma, 2003). In addition, investing in an enabling policy and entrepreneurial support is needed in order to achieve economic growth, stimulate sustainable development and dynamise rural and peri-urban cash economies (Davidson et al., 2003). In many energy poor African societies, emissions reduction is not a key imperative, but focussing on development and economic growth can also lead to a mitigation pathway.

Funding imperatives have also meant that ownership at local level has been quite reduced as most projects run the risk of making only peripheral progress as given the finite life cycles of such projects as donors pull out. This project-based approach has several limitations as it reduces the scope for sustainability. Consequently, a new set of thinking is gradually emerging which treats RE as an integral component of a market-based energy economy. An essential premise here is that for RETs to contribute to job creation and poverty reduction, their dissemination and uptake needs to strongly involve the private sector (GNESD, 2009).

The low economic base of some rural and urban communities is also an inhibiting factor, especially for people in the rural areas. The nature of the cash economy is such that the uptake of renewable energy technologies will remain slow due to the low and seasonal nature of cash inflows. In Zambia, the uptake of Solar Home Systems has for example been slow in rural areas partly because it was based on monthly payments where people do not have a culture of taking things on credit and often do not understand why they have to pay for it (AREED Study- 2006).

Central and local governments in many countries have enacted laws and regulations to promote renewable energy as a basis to encourage sustainable technologies. For economic incentives, a frequent difficulty is defining in policy terms what is eligible as "sustainable" – some cases of "sustainable energy" pre-defined by policies include small hydro plants and bioenergy (Frey and Linke, 2002). In particular for biomass, the concept of "sustainable energy" must be carefully established (Goldemberg and Coelho, 2004).

Economic sustainability decisions should be based on a comprehensive evaluation of resources affected and project costs and benefits, some of which will be difficult to quantify in precise terms. However, the application of a framework that provides for procedural and distributive justice is key to the perceived outcome of a project (Gross, 2007).

Renewable energy deployment depends on geographical specific evaluation and needs to follow quantifiable criteria, such as cost effectiveness, regional appropriateness and distributional consequences (Creutzig and Kammen, 2009). For this process to remain aligned with economic sustainability requirements, the costs of RE options need to be compared to other sources of energy, including fossil fuels. However, only a level playing field of costs of energy carriers can support rational investment decisions, and depends on the removal of subsidies and the introduction of carbon prices to internalize social costs. Decision making on energy deployment is bound by path dependencies (see also Chapter 11), as existing grid networks and engineering capacities will, for example, advantage some sorts of energy over others. Path dependencies may lock-in societies into energy carriers or infrastructures that may in the long-term be inferior in terms of cost efficiency or accumulated social costs (Unruh, 2000). In some but not all cases, developing countries can take advantage of not being bound to the same infrastructures as OECD countries, allowing for double benefits in cost effectiveness and environmental benefits delivered by regionally appropriate technologies. Appropriateness requires that geographical constraints (e.g. latitude, biomass availability, and wind quality) and demographic and societal circumstances (e.g., population density in certain areas) are accounted for. In addition, evaluating the distributional consequences is a crucial precondition of energy deployment. For example, water dams have regularly been criticized for forcing resettlement of rural population while serving the increasing energy demands of urban populations (World Commission on Dams, 2000).

9.5.2 Opportunities

Economic growth, considered as the notion of progress, is not only correlated with extensive nature exploitation but also with the intensification of energy use. Energy sources become, then, a strategic variable for economic development, in some cases disregarding other SD dimensions when characterized by isolated initiatives and programs (Paz et al, 2007).

The need for cross-sectoral SD strategy frameworks has therefore long been noticed and was articulated at the multilateral level and in its precursory form in the report from the Founex seminar held outside Geneva, Switzerland, in 1971 as part of the preparatory process for the 1972 Stockholm Conference on the Human Environment. The report highlighted that environmental problems pose a threat to human well-being and society should consequently seek a development path which takes into account environmental, social and economic aspects in an integrative manner (Founex Committee, 1971; Engfeldt, 2009). The realisation that current decision-making systems still lacke the necessary level of integration led the authors of Agenda 21 to reinforce this concern by urging for the consideration of environment and development aspects at the policy, planning and management level (UNCED, 1992). The adoption of National Sustainable Development Strategies (NSDS) could help to harmonise these processes, by steering them towards holistic approaches that integrate SD objectives in key economic development decisions in order to avoid disjointed and incremental policy-making. SD strategies may thus provide a coherent, systematic and (possibly normative) sense of direction regarding both the substance and the process of policy-making (Steurer and Martinuzzi, 2007).

In the formulation of SD strategies, countries have usually prioritised specific sectors for which national circumstances and international commitments required swift action, such as transport, agriculture and energy (OECD, 2002). Energy with its implications for all three pillars of sustainable development has played an integral part, contributing to productivity, income growth, health and education, gender equality, social impacts of energy extraction, human development, and macroeconomic stability and governance (Energy and Mining Sector Board, 2001). Renewable energy technologies, in particular, can add additional benefits by mitigating climate change and its related impacts, driving innovation, strengthening the development of local markets and creating employment opportunities, diversifying energy supplies, improving energy security and energy access, and impacting positively on health and gender aspects (see section 9.3) (Goldemberg, 2004). In addition, integrating renewable energy policy into national sustainable development strategies provides a framework for countries to select specific policy instruments, to incorporate concerns of other countries into their own and to align with international policy measures. Hence, RE policies in developed countries have often been explicitly integrated within NSDS (OECD, 2002). Some authors (Birda *et al.*, 2005; Dubash and Bradley, 2005) have reported integrated resource planning approaches, assessing the full life cycle costs of alternatives, including end-use efficiency.

A further example for such integrative approaches is represented by the ‘sustainable development policies and measures’ (SD PAMs) as initially proposed by (Winkler *et al.*, 2002). SD PAMs aim to link specific development needs as prioritised by developing countries with climate mitigation and adaptation plans. With key development objectives typically including *inter alia* poverty eradication, job creation, access to modern energy services and transport (Winkler *et al.*, 2002), the possible promotion of renewable energy within the SD PAMs approach is evident (Ellis *et al.*, 2007). Modeling and case studies investigating the potential and actual co-benefits of SD PAMs in Brazil (Moreira *et al.*, 2005) and India (Dubash and Bradley, 2005) document the large role of renewable energies in these approaches. In addition to avoided GHG emissions, co-benefits from RE deployment include reduced import bills, household energy bill savings, reduced indoor air pollution, and rural job creation. However, before SD PAMs may be included in the concept of ‘nationally appropriate mitigation actions’ (NAMAs) for developing countries (UNFCCC, 2008; van Asselt *et al.*, 2010), questions regarding their environmental effectiveness and the available methodologies for the quantification of benefits need to answered (Bradley and Pershing, 2005; Winkler *et al.*, 2008).

Shifting to a sustainable energy system based on efficiency and renewable energy requires replacing a complex and entrenched energy system, as well political will and strong, sustained policies (Sawin and Moomaw, 2010). Also barriers, such as those identified in the previous section, will need to be addressed. In order to account for such SD concerns, industry associations of RE technologies with high maturity levels have drawn up so called guidance and good practice documents. These provide detailed advice and checklists, how planners, developers and producers should proceed in order to ensure greater consideration of sustainability aspects during the assessment of new projects or the operation of existing facilities (WWEA, 2005). For hydropower, the most mature RE technology, a well structured framework for sustainability assessments exist (World Commission on Dams, 2000; IHA, 2004). Taken together all of these official standards, recommendations and guidelines describe sets of criteria that should be considered to ensure beneficial and broadly sustainable outcomes of RE projects. These criteria are described in the following sections where they have been grouped according to the level where (policy) action is required, addressing necessary measures from the national and international to the local level.

9.5.2.1 National and international SD strategies

At the national level, a number of market mechanisms exist that help to overcome barriers for the implementation of SD strategies and as such RETs. The three basic approaches include: (i) removal of existing financial mechanisms that work against sustainable development; (ii) adaption of existing market mechanisms and (iii) introduction of new financial mechanisms that internalize environmental or social externalities in order to provide a level playing field for the different mitigation options.

Numerous studies and events over the past several years have stressed the importance of eliminating barriers to trade in renewable forms of energy and the technologies used to exploit them, as part of a broader strategy to reduce dependence on more-polluting and less secure energy sources. This is the case for, among others, charcoal, PV, wind turbines and biofuels (Steenblik, 2005, OECD, 2006, Lucon and Rei, 2006). As outlined in section 2.4.5, barriers for the market penetration and international trade of bioenergy include tariff barriers, technical standards, sustainability criteria and certification systems for biomass and biofuels, logistical barriers, sanitary and phyto-sanitary measures.

Box - RE and Sustainable international trade

Many RE deployment initiatives involve energy trading, such as biofuels as commodities or interconnected international electricity grids. In this context, there may be economic measures taken by nations that could be considered as market distortions, like import quotas, technical barriers or local subsidies considered contrary to trade liberalization. Precise implications of the overlaps between the UNFCCC’s Kyoto Protocol and the WTO’s Doha round negotiations are still uncertain. Interactions that are the most problematic include the potential use of border measures to offset cross-national differences in the energy costs of goods – or, more generally, an interest in finding trade-related ways to impose costs for free riding. Less problematic but nevertheless warranting further attention include CDM and JI projects in relation to the WTO subsidies agreement, efficiency standards in relationship to the WTO technical barriers agreement and carbon sequestration in relationship to the WTO agriculture agreement. As parties to the Protocol develop and implement their own individual policies and measures to achieve emissions targets, compatibility with WTO rules could become a recurrent issue. More generally, the nexus of investment rules inside and outside the WTO with the climate regime needs further attention (Brewer, 2004). With the mission of liberalizing international trade, the WTO allows trade restrictions for environmental reasons, but only under certain specific conditions. Sustainable development and the protection and preservation of the environment are recognized as fundamental goals of the organization. Although WTO members have flexibility to pursue environmental and health objectives, a distinction is necessary between trade measures with a genuine environmental goal and measures that are intended as disguised restrictions and are applied in an unjustifiable, arbitrary or discriminatory manner. There is a wider range of WTO rules relevant to climate change, but no rules specific to it. Trade opening has much to contribute to the fight against climate change by improving production methods, making environmentally friendly products more accessible at lower costs, allowing for a more efficient allocation of resources, raising standards of living leading populations to demand a cleaner environment and by spreading environmentally friendly technologies. Trade can also help countries to adapt to climate change. When countries are faced with food shortages brought about by climate change, trade can play the role of a transmission belt between supply and demand (thus reducing the bioenergy relevant food-fuel conflict). The Organization recognized that the elimination or reduction of barriers to trade will facilitate access to renewable energy and other environmental goods that can contribute to climate change mitigation, fostering a better dissemination of technologies at lower costs. Elimination of both tariffs and non-tariff barriers to clean technologies could result in a 14% increase in trade in these products (WTO, 2010).

Subsidies are one of many policy instruments used by governments to attain economic, social and environmental objectives. Energy subsidies, in particular, are often used to alleviate energy poverty and promote economic development by enabling access to affordable modern energy services. However, poorly implemented energy subsidies for fossil energy sources are economically costly to taxpayers and can damage the environment through increased emissions of greenhouse gas and other air pollutants. For example, multilateral development banks invest 3-4 times as much into fossil than in green energies (Hicks *et al.*, 2008). Carbon disinvestment in cases where fossil fuels carry high social costs - e.g. by introducing mandatory shadow price internal accounting in MDBs - may significantly reduce competitiveness of fossil fuels (Wheeler, 2008). In many but not all cases, renewable energies will appear as the more cost effective options. Nonetheless, some subsidies related to fossil fuels can improve the environment or the welfare of the poor if they encourage reduced reliance on traditional biomass in areas at risk of deforestation, and fund research into ways to sequester carbon emissions from combustion (IEA, OPEC, OECD, World Bank, 2010).

Costs borne by governments, including fossil fuel related direct subsidies, tax concessions, indirect energy industry subsidies (e.g. the cost of fuel supply security) and support of research and development costs are not externalities. They do, however, distort markets in a similar way to negative externalities, leading to increased consumption and hence increased environmental degradation (Owen, 2006). The use of subsidies to promote the development of renewable energies worldwide includes the gradual phase out of considered harmful subsidies and instead increasing the provision of subsidies to more sustainable renewable energy production and use.

Also very important is the *adaption of existing market mechanisms*. The importance of the financial viability of new SD policies was realized by most governments about 5 years after the Rio Summit (Dalal-Clayton and Bass, 2002), when the World Bank released a report, highlighting the need to remove perverse subsidies, to impose environmental taxes and to apply more adequate user charges as policy instruments (World Bank, 1997). When RE deployment is well integrated within cross-sectoral SD strategy, there are better possibilities to arrive at multi-benefit results. A good benchmark is the experience with Kyoto Protocol's Clean Development Mechanism projects that are submitted to sustainability screening and approval at national level by the Designated National Authority (see Box).

Box – National SD Screening of KP-CDM projects

Renewable energy replacing fossil fuels constitute a significant contribution under the Clean Development Mechanism (CDM), a project-based emissions trading mechanism that the Kyoto Protocol has established and which enables cooperation between industrialized and developing countries. CDM has the twin objective to achieve sustainable development (SD) in host countries and assist Annex-1 countries in achieving their emission reduction targets in a cost-efficient manner. However, trade-offs between the two objectives exist in favor of cost-efficient emission reductions, leading to a series of ad-hoc projects, rather than serving the overall host countries' sustainable development needs and priorities. Moreover, the considered slow implementation of incentives for industrialized country companies to embark on CDM projects and low carbon prices led to a preference for just buying Certified Emission Reductions (CERs) instead of investing in projects (Michaelowa, 2007). Additional to definitions established at host country level by Designated National Authorities (DNAs), there is no international standard for sustainability assessment to counter weaknesses in the existing system of sustainability approval. Thus, DNAs have an important role in meeting the countries' sustainable development priorities – as well as to attract investment (Winkler et al, 2005). Literature review has identified assessments of transferring and implementing potentials in Chile, China, Israel, Kenya, Thailand, Yemen, Egypt, India, South Africa and Uruguay (Karakosta and Psarras, 2009; Sieghart, 2009; Shao-jun, 2009; Ganapati and Liu, 2009; Ganapati and Liu, 2008; Nhamo, 2006; Heuberger et al, 2007) and proposed methodologies for verifying potential SD benefits, such as a multi criteria decision making method (Karakosta et al, 2008; Heuberger et al, 2007) weighting values and a taxonomy for sustainability assessment based on analysis of 744 project design documents (Brent et al, 2005; Olsen and Fenhann, 2008). More than a question of definition and establishment of priorities, SD screening depends on many aspects, such as the institutions of CDM management and implementation, CDM project assessment standards, admission regulations for developer institutions, as well as the study and training on CDM knowledge (Shao-jun, 2009).

Finally, there is a constant need for the introduction of *new financial mechanisms that internalize environmental or social externalities*. Diffusion of renewable energy technologies are driven by policies and incentives due to their inherent characteristics such as high upfront costs, lack of level playing field but distinct advantages from energy security, environmental and social considerations (Rao and Kishore, 2010). However, when external costs (more in Section 10.6) are included, the relative advantage of renewable energies is highlighted – especially regarding GHG emissions. Incorporating external costs requires good indicators. A methodological limitation found in studies for different energy production systems is their utilization of relatively few comparable sustainability indicators, drawing conclusions of which would be the "most sustainable energy source" simply based on highest ranked ones (Onat and Bayar, 2010, Varun et al, 2010, Doukas et al, 2010, Xydis et al, 2010 , Philips, 2010, Bagliani et al, 2010, Brent and Rogers, 2010, Hoffmann, 2010, Mikkila et al, 2009, Kowalski et al, 2009, Rule et al, 2009, Doukas et al, 2009, Brent and Kruger, 2009, Eason et al, 2009). Although multicriteria approaches contribute significantly, it is recognized that appraising the renewable energy options' contribution to sustainable development is a complex task, considering the different aspects of SD, the imprecision and uncertainty of the related information as well as the qualitative aspects embodied, that cannot be represented solely by numerical values (Doukas et al, 2010, Donat Castello, 2010, Cavallaro, 2009, Michalena et al, 2009). Within the current debate about responses to climate change, the idea that developing countries might be able to follow more sustainable, low carbon development pathways is particularly attractive. Such decision towards a more sustainable pathway is both political and societal, but depends intrinsically of the understanding of the leapfrogging concept (Box).

Box – Leapfrogging

‘Environmental leapfrogging’, basically skipping of pollution intensive stages of development, would prevent latecomer countries from going through the same pollution intensive stages of industrial development as industrialised countries have experienced in the past. Three different types of ‘environmental leapfrogging’ are distinguished: leapfrogging within overall development pathways, leapfrogging within industrial development, and leapfrogging in the adoption and use of technologies. A sufficient level of absorptive capacity – i.e. the ability to adopt new technologies – is a core condition for successful leapfrogging. This capacity includes technological capabilities, knowledge and skills as well as supportive institutions. There are a range of policies that can be implemented to develop this capacity. The evidence suggests that a mix of generic functional policies (e.g. to strengthen levels of education) and more specific policies (e.g. to stimulate innovation in a particular sector) are required. Any leapfrogging strategy involves risks. Latecomer countries can, however, benefit if initial risks of developing new products and establishing markets have been borne in ‘frontrunner’ countries. Once a market is established, developing countries can catch up through rapid adoption of new technologies and/or the development of manufacturing capacity. For a sustainable growth strategy within developing countries, such manufacturing capacity needs to be complemented by investments in domestic technological capabilities to develop imported products further. More radical innovation – due to a shift in technological paradigms – can provide additional ‘windows of opportunity’ for developing countries. Different factors have been identified for the success of this process. In the case of developing countries that have partly skipped landline phone systems in favour of mobile phone systems, early adoption in industrialised countries enabled leapfrogging. Developing countries had access to a competitive international technology market which had already reduced costs. They could also adopt recognised standards and a proven technology. The success of the Indian and Chinese wind industries illustrates the benefits of incentives for the deployment of wind technology. This market creation was allied with the development of domestic wind manufacturing industries. This, in turn, was enabled by access to external knowledge and the creation of knowledge networks. Key factors for success in leapfrogging are different in each case. It is therefore not possible to generalise to a large degree. This echoes the result of earlier studies of the ‘Asian tiger’ economies which concluded that there is no standard model of development or catching-up. Instead a country’s distinctive resources need to be taken into consideration, and trial-and-error learning needs to be accepted as part of leapfrogging strategies (Sauter and Watson, 2008).

Technological leapfrogging in renewable energy has emerged as an opportunity for developing countries, as reported by several studies (Saygin and A‡etin, 2010, Tarik-ul-Islam and Ferdousi, 2007, Reiche, 2010). Leapfrogging may not necessarily start in more developed countries, as developing ones start first recasting their development strategies around the prospects for sustainable renewable energies and biofuels – the case of Brazil (Mathews, 2007). Not only developing, but developed nations may have barriers against leapfrogging, from non-technical challenges – the case of expansion of use of imported biofuels in Europe (McCormick, Kuberger, 2007).

International technology transfer can allow countries to move quickly to environmentally sound and sustainable practices, institutions and technologies, avoiding past unsustainable practices and being locked into old, less sustainable technologies (Karakosta et al, 2010). Information exchange networks assist in sharing the best available knowledge (Moreno et al, 2007). Regional coordination is needed not only to provide economic growth but also environmental integrity, as shows a case described in the Caribbean (Singh, 2007). Public-private partnerships, known as "civic markets" can create and provide "funds" such as public bonds along with private sector innovation and markets on the regional, state and national levels (Clark, 2007).

9.5.2.2 Local SD strategies

The facilitation of environmentally benign outcomes of RE deployment at the local level begins with the planning, construction and operation of projects in accordance with the recommendations and established codes of good practice set up by the different RE associations (IHA, 2004; WWEA, 2005; RSB, 2009). These require, amongst others, a careful assessment of related net GHG emissions, impacts on biodiversity and alterations to the physical environment (see Chapter 9.3.4 for related discussion on impacts of RE deployment). For bioenergy in particular, a large array of certification schemes is being developed that aims to assist the progress of sustainable production (Chapter 2.4.4).

In addition to focusing on environmental principles, socio-economic impacts need to be considered alongside. Disregarding local interests during the initial consultation stages can have considerable consequences for the success of RE projects. To begin with, the actual project management and the interaction of developers with local actors play an important part. Case studies evaluating the success of wind energy projects in France and Germany found that the familiarity of the developer with local circumstances and concerns was a major determinant for the project’s success. Developers can be perceived as outsiders, interested only in profits and not in the region’s development and “stealing” a landscape that is seen as a common good (Jobert *et al.*, 2007). Also, transparency, the provision of information, and participation of the local population in the planning process from the early stages on are crucial for public acceptance (Wolsink, 2007a). In the context of developing countries, this also includes the empowerment of rural women in order to seek the best solutions for community energy needs (Oikonomou, 2010, Omer, 2003, Singh, 2009).

Positive impacts on the local economy, through the distribution of benefits or community ownership schemes, further improve public attitudes towards RE developments (Jobert *et al.*, 2007; Maruyama *et al.*, 2007; Warren and McFadyen, 2010). However, there is a need for institutionalised guidelines to provide greater clarity and give developers greater confidence to discuss the community benefits package in the early planning stages (Aitken, 2010).

With the three aspects of environment, economics and social commitment being thus factored into a single project, RE deployments can offer various and mutually complementary incentives for different actors. In the short term, these may include environmental motivation, the aspect of participation in a community activity and the motivation to stimulate the local economy. In the middle and long term, the aspect of economic viability of the project, and as such the contribution to sustainability, was found to act as an incentive (Maruyama *et al.*, 2007). The successful diffusion of diffuse and locally considered sustainable energy technologies thus depends on an upgrading of the 'potential adopters' to 'techno-entrepreneurs', by supporting a private sector driven 'business model' approach (Balachandra et al, 2010, Karakosta and Psarras, 2009).

Moreover, acceptance of renewable energy technology involves environmental psychological aspects of the change of energy demand and supply. (Schweizer-Ries, 2008). Matching demand can provide the necessary appeal – for example, to make ends meet for the poorer, instead of saving fuel or achieving a cleaner environment (Alam et al, 2003). A more detailed discussion of pro-active, positive, place - and scale-sensitive planning and permitting approaches is provided in Box 11.X in section 11.2.5.11.

As a consequence, there is a need on the local level to build stronger partnerships between governments, regional authorities and municipalities, energy producers and consumers, market intermediaries, non governmental organizations (NGOs) and financial institutions in order to facilitate a common understanding of the issues, challenges and constraints related to renewable energy development, and to pave the way for greater cooperation among all groups in society (Slavov, 2000) (see Chapter 11.6 for a discussion of the enabling environment). Strategic planning is considered as a combination of an integrated governance framework, fostering and improving the implementation base, developing a national settlement scheme, and providing active citizen programs (Taylor, 2004).

9.6 Synthesis

The renewable energy technologies discussed in this Special Report will play an increasingly important role in the world energy system over the next several decades. Mitigation of climate change caused by the combustion of fossil fuels provides one key motivation for a drastic transformation of the world energy system. Additional factors pointing toward the desirability of increasing reliance on renewable energy include concerns about uneven distribution and future supply scarcity of fossil-fuel resources. Given the heavy reliance of modern societies on fossil fuels, any proposed transformation pathway must be carefully analyzed for feasibility. The aim of this Special Report is to assess the technical literature on renewable energy technology and the prerequisites and consequences of such a transformation.

This implies that technical feasibility or potential resource size alone are not sufficient to determine a pathway leading from the current energy system to a low-carbon-emission future energy system. To aid in the evaluation of transition possibilities, climate target scenarios can be used with integrated assessment models to provide economic cost estimates with respect to non-policy, or “business-as-usual” scenarios. As a complement to technological feasibility assessments, economic assessments are also critically important for understanding which pathways toward a desired climate goal can be achieved in the most efficient way.

Both the technological and the economic analyses of renewable energy (RE) need to be embedded in the broader context of sustainable development and Chapter 9 extends to include the latter in its assessments. It is acknowledged at the outset that the exact nature of sustainable development (SD) is subject to a plethora of definitions and perspectives. Sustainable development is often considered from the point of view of three pillars: Economy, Society and Environment (See Fig. 9.2.1). Within this three-pillar framework there are (at least) two philosophies of sustainability, often referred to as weak and strong sustainability. Weak sustainability allows for substitution between capital created in the economic and societal spheres, on the one hand, and natural capital from the environmental sphere. Strong sustainability essentially makes the assertion that the potential for substitution from the environment is limited, and in fact, presents a fundamental, biophysical boundary condition for growth of the societal and economic spheres.

To better organize this assessment of the literature on sustainable development and make a solid connection to the role of renewable energy in sustainable development, basic goals of a future energy system are used as guidelines. The four criteria used in this Chapter are i) sustainable social and economic development; ii) increased energy access; iii) enhanced energy security; and iv) reduced environmental impacts.

One of the key points that emerges from the literature is that the evaluation of energy system impacts (beyond greenhouse gas emissions), climate mitigation scenarios and sustainable development goals have for the most part proceeded in parallel without much interaction. Effective, economically efficient and socially acceptable transformations of the energy system will require a much closer integration of insights from all three of these research areas. An initial assessment of indicative information available from current IAMs in Section 9.4 generates important insights but also discloses some shortcomings and highlights the need for the inclusion of additional boundaries (e.g. environmental) and more complex energy system models that can represent specific local conditions and variability.

In any case an assessment of sustainable development must evaluate distributional questions. How the poor – on the national or the international level – will be affected by particular measures to promote renewable energy is an important indicator for sustainable development. For integrated assessment modelling this indicates the need to include a high regional resolution, a differentiation of different income groups and a strong micro perspective to name just a few of the relevant issues. However, IAMs were originally designed to assess energy portfolios of fairly large world regions and emissions trajectories implied by changes in those energy portfolios over time. Distributional questions were not the focus of the assessment but have gained more attention just recently. This chapter provides some interesting initial insights with respect to economic and social development. To begin with, energy-economy models clearly show that mitigation of GHG emissions is connected to reductions in GDP; generally, the tighter the constraint, the higher the losses (see also Chapter 10). When assessing the losses in GDP, however, it must be acknowledged that damages from climate change have usually not been included in the analyses that have been used for this report. One result that can be derived from modelling exercises is that renewable energy contributes significantly to cost-efficient mitigation. Constraining the implementation of renewable energy increases mitigation costs considerably, thus leading to lower GDP levels in the future. Also, model results highlight the importance of renewable energy technologies to achieve low stabilization targets. It is important to understand that IAMs in general have not originally been designed to assess sustainability and there is room for improvement in the future. Many of the forces that might make developing countries behave differently than developed countries, e.g. differences in physical and institutional infrastructure are currently not covered in models. With respect to distribution on the international level, the role of different allocation schemes is found to be critical for the regional distribution of mitigation costs. Within regions or countries, the IAMs provide little insights about distributional issues. However, from historical analysis we know that renewable energy can particularly benefit to a basic level of access to modern and reliable energy in rural areas, which is widely recognized to as a critical foundation for promotion of sustainable development.

Furthermore, to measure human development, multidimensional metrics that go beyond GDP are needed, with some alternatives having been proposed. One example that has been used in this chapter is the Human Development Index (HDI), which is composed of data on life expectancy, education and per-capita GDP (i.e. purchasing power parity (PPP)-adjusted income). In this chapter HDI was used as a measure to emphasise the importance of access to non-traditional energy supplies for improving the quality of life. Also, it is used to assess comparative levels of development in countries. Access to clean and reliable energy, which can be promoted by renewable energies, is an important precondition for the fundamental determinants of human development, including health, education, gender equality and environmental safety. However, current scenarios of future energy system developments only contain little information with respect to most of these aspects.

Historically, the development of countries has gone hand in hand with increasing energy use and thus emissions. Therefore, another important question relates to the issue of leap-frogging and how the exchange of renewable energy technologies between developed and developing countries impacts mitigation costs. Even though the aspect is hardly dealt with in any model, results indicate that renewables play a more important role in developing than in developed countries, an aspect that hints to a particular role for leapfrogging.

Second, these aspects are directly linked to the question of energy access. Models, often with a strong bias towards developed countries, often fail to take into account the most important criteria for energy access in developing countries, as for example the choices to use traditional fuels, informal access to the electricity grid, informal economies, and structural changes in domestic economies. Even though there has been some progress recently in the models, most multi-regional models still face major drawbacks in this respect, particularly when it comes to the role of renewable energy and particularly the role of renewable energy in rural areas, where it particularly could benefit the poor. If these aspects are not considered, it can be stated that the increase of energy access is usually capital intensive (thinking of the extension of grids) and will need targeted support by governments in order to achieve universal electricity access. In general, models do not give a clear answer whether or not renewable energies might play a central role for the electrification of poor, rural areas with respect to off-grid facilities. However, if developing countries are not able to secure finance for electrification, reducing the number of people without electricity seems unlikely , despite the fact that universal access to clean, reliable and affordable energy sources is as a key part of enhancing sustainable development.

Third, for many developing countries, the definition of energy security specifically includes the provision of adequate and affordable access to all parts of the population and thus exhibits strong links to energy access aspects. Hence, the definition of energy security is broadened to address the stability and reliability of local energy supply. With respect to modelling activities, this again raises the question for the need of more complex energy system models with a better representation of technical integration, cost-efficiency and urban versus rural energy access, which often shows dramatic differences in developing countries.

Currently, beyond the rather trivial statement that a growing share of domestically produced renewable energy will often increase the diversity of supply and decrease the share of other (often imported) energy sources, the models are often not able to address the interaction between energy security and renewable energy (e.g. variability issues). Some results can however be condensed: First, the role of the transportation sector will remain crucial for energy security in the future. As long as there is no electrification of the sector, which might allow a larger role for all kinds of low carbon technologies, the demand for transportation fuels (both conventional and renewable) remains inelastic. Oil, which has caused energy security concerns in the past as it is provided by comparably few suppliers, remains an important energy carrier in all scenarios, independent from the climate target. For biomass, being an important alternative, it is far from clear that supply will be provided by perfectly efficient markets in the future. Additionally it also raises important concerns with respect to land-use emissions. Also, the future role of biomass in the transportation sector is determined by the availability of CCS, which in combination with biomass can produce negative emissions in other sectors that might generally ease the transformation costs. Second, models assume that variability issues of renewable energy will eventually be solved. Thus results that favour renewable energy deployment might be misleading, emphasizing that the question how electricity from renewable energy can be stored in the future is pivotal.

Fourth, concerning environmental impacts, IAMs might well be suited to include some of the most important indicators in addition to GHG emissions (e.g. local air pollution, water use etc.), but available literature is scarce. Apart from the land use constraints on bioenergy deployment due to terrestrial carbon and N_2O emissions, no renewable energy implications can yet be clearly spelled out.

Expanding existing IAMs today to incorporate more SD indicators is a big challenge since these models were generated around a relatively specific set of tasks which did not include consideration of sustainable development criteria. To derive more valid conclusions about the interaction of renewable energy deployment and sustainable development pathways in a global context, the scenario literature will have to take into account some of the research gaps that are elaborated on in the next section. One area that is conceptually straightforward is to include results from LCA of material, energy and water consumption for various technologies to get a better picture regarding their longer-term environmental impacts.

For example, results from LCAs show that RE, with some exceptions, transmit lower impacts across the categories assessed in this chapter (see section 9.3.4) than fossil fuel based technologies, but some fundamental differences between different RE technologies are evident. In particular, bioenergy has a special role, as it exhibits many properties similar to fossil fuels (combustion leading to air pollution and need for cooling water, energy and water required for fuel processing and transport), and requires very large exclusive land use with all associated challenges, but provides the only opportunity for net GHG sequestration when used in certain circumstances. Overall, the emission reduction potential of all RE power generation technologies is significant, and remains higher than for fossil plus CCS.

However, it is important to note that all energy technologies, especially when deployed at large scale, will create environmental impacts, determined in large measure by the design and integration into local contexts. This is particularly applicable with respect to very localised impacts such as on biodiversity. Hence, integrated assessments at the global and generic level cannot be a substitute for local evaluations and considerations and the evaluation of trade-offs.

In addition to the more economic and technical assessments of the observed and possible long-term impacts of RE, this chapter also evaluates the SD potential of RE in a more policy orientated context. Section 9.5 discusses the barriers and opportunities for RE with respect to environmental, social, economic and governance-institutional considerations and concerns and looks at the required SD policies and instruments to better deploy RE on the global, regional and local levels. Important barriers to the deployment of RE are, among others, environmental concerns and social acceptance, lack of capacity building, cost-effectiveness and appropriateness of the technology, as well as distributional aspects with respect to shared benefits. RE-proactive political willingness, subsidies and other uneven economic incentives to conventional energy and barriers to international trade of environmental goods include further important barriers. Opportunities highlight in particular the possibility of leapfrogging, but also address education, public participation, and the strengthening of cross-sectoral institutional cooperation. In particular, it is shown how well integrated RE policies and deployment can contribute to positive and multi-dimensional progress for sustainable development.

Environmental constraints have many different origins and metrics. Calibrating the necessary level of sustainability requisites is a difficult task, which can be supported by different tools. Perception and acceptance of impacts vary considerably from source, type of stakeholders or ongoing policies. Some indicators of sustainability are relatively straightforward (e.g. energy payback times, waste products, emissions), while other are more difficult to quantify (biodiversity impacts, chronic effects to human health, carbon leakage and indirect land use change) or represent other kinds of complexity (land and land use rights, water rights, displacement issues).

Most renewable energy applications have traditionally been perceived as environmental friendly by the general public, but with up-scaling and development of new installations driven by external stakeholders, such perceptions can potentially change, as symbolized by “not in my backyard” concerns. The neglect of *social* aspects of decentralized units can also result in abandoned and dysfunctional systems. Public awareness and acceptance will be a very important part of successful climate mitigation policies, with rapid and significant increases in the adoption and deployment of RE technologies. Large scale implementation will require dedicated awareness-raising about the achievements of existing RE options and the opportunities, prospects, and potentials associated with wider-scale applications. Capacity-building is also a key driver to technological leapfrogging. Transparency, access to information and participation of the local population in the planning process from the early stages are all crucial for public acceptance.

To conclude, integrating renewable energy policy into national sustainable development strategies provides a framework for countries to select specific policy instruments, to incorporate experience from other countries into their own and to align with international policy measures. Shifting to a sustainable energy system based on efficiency and renewable energy requires replacing a complex and entrenched energy system, which implies the need for thorough analysis of all available options, with careful consideration given to the multiple dimensions of technology, economy, society and environment. In this context, it is important to note that countries at different levels of development have different incentives to advance RE: providing access to energy, creating employment opportunities in the formal economy, reducing costs of energy imports, reducing carbon emissions to mitigate climate change, enhancing energy security and actively promoting structural change in the economy. To identify the right mix of measures for the specific national and regional circumstances requires the cooperation of decision makers, stakeholders and scientists, underlining the need to transgress the traditional boundaries between the natural sciences to social sciences and humanities.

9.7 Knowledge gaps and future research needs

This chapter has described part of the interactions between sustainable development and renewable energy and focused on criteria such as sustainable social and economic development, increased energy access, enhanced energy security and reduced environmental impacts. An assessment of indictors related to these criteria has revealed several gaps in knowledge.

Beginning with the more conceptual discussion of SD, there is a tremendous gap between intertemporal measures of human well-being (sustainability) and measurable sub-indicators that needs to be narrowed. In addition, possibilities to relate the two opposite paradigms of sustainability, weak and strong sustainability, need to be explored. One possibility would be to allow for non-linearities, tipping points, and uncertainty on non-linearities in intertemporal measures, or providing formal guidelines for consideration of the precautionary principle. In the context of this report on renewable energy, this also entails that specific indicators of weak sustainability like genuine savings, ISEW or GPI, but also those of strong sustainability (e.g. land use boundaries) need to be statistically and logically related to renewable energy indicators.

Apart from the definitions, data that are necessary to access sustainability and renewable energy are insufficiently available. There is a clear need for better information and data on energy supply and consumption for non electrified households but also low end electricity consumers. Furthermore, there is a need for analysis of RE based mini-grid experiences for improving access as there is for the analysis of energy security implications of regional power integration.

Many aspects of the assessment of environmental impacts of energy technologies require additional research to resolve key scientific questions, or provide confirmatory research for less contentious but also less studied aspects. Two key issues regarding GHG emissions caused by energy technologies are direct and indirect land use change. For RE technologies, these issues mainly concern the production of biomass for bioenergy systems and hydropower impoundments, but land use change associated with some non-RE technologies deserve investigation as well (e.g., carbon emission from soils exposed by mountaintop removal coal mining). Several energy technologies are lacking substantial or any studies of life cycle GHG emissions: geothermal, ocean energy, and some types of PV cells. Water use has not been consistently or robustly evaluated for any energy technology across their life cycles. The state of knowledge of land use, especially when considered on a life cycle basis, is in similar condition as water. For both, metrics to quantify water and land use need consensus as well as substantial additional study using those metrics. More is known about air pollutants, at least during operation of combustion systems, but this knowledge has not been well augmented on a life cycle basis, and the interpretation of air pollutant emissions on a life cycle basis needs to be enhanced since the important effects of pollutants should not be summarized by summing masses over time and space. For LCAs as a whole, heterogeneity of methods and assumptions thwarts fair comparison and pooling of estimates from different studies. Ex post facto harmonization of the methods of previous research (and meta-analysis) and perhaps stronger standards guiding the conduct of new LCAs is critical to clarifying results and producing robust estimates.

Assessments of the scenario literature have given only little insights on how sustainable development pathways will interact with renewable energy and vice versa. In the past, models have focused on the technological and macro-economic aspects of energy transitions. Therefore the evaluation of sustainable development pathways mostly needs to rely on proxies that are not always informative. One major difficulty is the models' macro perspective, while some issues for sustainable development are relevant on a micro and regional level. Thus, when looking more specifically on different SD criteria, major drawbacks can be found for all of them. (i) With respect to sustainable social and economic development, the scenario literature has a strong focus on consumption and GDP. Even though models address multiple criteria of welfare, they are generally not sufficiently specific to inform largely about distributional issues. Differentiations between income groups, urban and rural population and so on are difficult to make. (ii) Also, the distribution and availability of energy services, and how they change over time are aspects that are not broadly included in most energy-economy models so far, which makes the evaluation of energy access challenging. (iii) Regarding energy security the current representation of the grid structure in most of the models does not allow for a thorough analysis of possible difficulties of large scale integration of renewable energy. Possible barriers are mostly assumed to be overcome without difficulties, particularly when thinking of storage and variability issues that might occur. Possible co-benefits of renewables, such as growing diversity of supply and possibilities to electrify rural areas, are also poorly covered in the literature as, e.g., fuel supply risks are usually not taken into account in the models. (iv) The existing scenario literature does not give an explicit treatment to many non-emissions related aspects of sustainable energy development, as for example water use, biodiversity impacts, or the impacts of energy choices on household-level services or indoor air quality. In addition to that, when regarding section 9.3.4 of this chapter, emissions are generally not treated over the life-cycles of technology choices, which might be an interesting aspect of future research.

We can conclude that our knowledge regarding the interrelations between sustainable development and renewable energy in particular is still very limited. Finding answers to the question of effective, economically efficient and socially acceptable transformations of the energy system will require a much closer integration of insights from social, natural and economic sciences in order to reflect the different dimensions of sustainability. So far, what we now is often limited to very narrow views from specific branches of research, which do not fully account for the complexity of the issue.

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