Appendix A: Definition of GEA Regions

Table 17.A1

11 MESSAGE regions	26 IMAGE regions	Definition (list of countries)
NAM	Canada and USA	North America (Canada, Guam, Puerto Rico, United States of America)
WEU	Western Europe and Turkey	Western Europe (Austria, Belgium, Cyprus, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom)
PAO	Japan and Oceania	Pacific OECD (Australia, Japan, New Zealand)
EEU	Central Europe	Central and Eastern Europe (Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Serbia, Slovak Republic, Slovenia, The former Yugoslav Rep. of Macedonia)
FSU	Russia, Ukraine and Stan Asia	Former Soviet Union (Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan)
CPA	China	Centrally Planned Asia and China (Cambodia, China, China Hong Kong SAR, China Macao SAR, Korea (DPR), Laos (PDR), Mongolia, Viet Nam)
SAS	India and Rest of South Asia	South Asia (Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka)
PAS	Korean, Indonesia and South East Asia	Other Pacific Asia (Brunei Darussalam, East Timor, Fiji, French Polynesia, Indonesia, Malaysia, Myanmar, New Caledonia, Papua, New Guinea, Philippines, Republic of Korea, Samoa, Singapore, Solomon Islands, Taiwan (China), Thailand, Vanuatu)
MEA	Middle East and North Africa	Middle East and North Africa (Algeria, Bahrain, Egypt (Arab Republic), Iran (Islamic Republic), Iraq, Israel, Jordan, Kuwait, Lebanon, Libya/SPLAJ, Morocco, Occupied Palestinian Territory, Oman, Qatar, Saudi Arabia, Sudan, Syria (Arab Republic), Tunisia, United Arab Emirates, Western Sahara, Yemen)
LAC	Brazil, Mexico, Rest of South America and Rest of Central America	Latin America and the Caribbean (Argentina, Bahamas, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, Uruguay, Venezuela)
AFR	South Africa, East Africa, West Africa and Rest of South Africa	Sub-Saharan Africa (Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo (Rep), Congo (Dem. Rep.), Côte d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Réunion, Senegal, Sierra Leone, Somalia, South Africa, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe)

Table 17.A2

5 Regions	List of regions
OECD90	NAM, WEU and PAO
REF	EEU and FSU
ASIA	SAS, PAS and CPA
MAF	AFR and MEA
LAC	LAC
2 Regions	**List of regions**
Industrialized	NAN, WEU, PAO, EEU and FSU
Developing	SAS, PAS, CAP, AFR, MEA and LAC

17.1 Appendix B: Efficiency Improvements in the Main Industrial Sectors

Five main sub-sectors account for about two thirds of industrial energy use: iron and steel making, chemicals and petrochemicals, cement making, pulp and paper, and aluminum. The potential for efficiency improvements in these sectors will be discussed briefly in turn; for further details, see also Chapter 8.

Iron and Steel Making

New smelting reduction processes can enhance the energy efficiency of iron making by about 20%, compared to current best available technologies. The GEA-Efficiency pathways also see gas-based direct reduced iron much more widely applied, yielding about 25% efficiency improvements compared to the basic oxygen blast furnace. Electricity and hydrogen use for iron and steel making are also considered as longer term options in GEA-Efficiency pathways (see also 17.3.2.3). Enhanced material flows, better steel quality and re-design of steel products yield an additional 5% efficiency savings (IEA, 2009b).

Chemical and Petrochemical Products

About one third of the oil and gas input to the chemical and petrochemical industries is for energy use, with the remaining two thirds for feedstock. Process energy savings available through new technology include membrane processes, new catalytic conversion routes, new olefin production processes (e.g., based on ethanol feedstock) and process intensification. Although adoption of best available technology can yield about 15% savings on energy and feedstock use, in the GEA-Efficiency pathways the widespread deployment of new, more efficient technology can raise this to 25% (Saygin et al., 2010; Taibi and Gielen, 2010).

Cement Making

Energy efficiency of the cement making process is limited by the minimum process energy needs for clinker making. This limits the potential of new technology to enhance energy efficiency beyond best available technologies in the GEA-Efficiency pathways. There is some potential to increase the share of alternative cementing materials, including Bainite cement, volcanic ash, geopolymers, and limestone additives, offering 5–15% savings on total cement making energy use (WBCSD/IEA, 2009). The use of fly ash as an alternative in the GEA-Efficiency pathways is dependent on, and so limited by, the use of coal in other sectors, particularly electricity generation.

Pulp and Paper Making

Process re-design offers interesting opportunities for lignin removal in chemical pulping plants. More efficient use of black liquor residues, perhaps through gasification, and new drying technologies for paper making, offers further potential to reduce energy use to a total of 10–15% of the sub-sector's energy use in the GEA-Efficiency pathways. In terms of the level and type of demand for paper products, structural shifts from paper to electronic media helps to partially offset the rising demand for packaging and other types of paper. In total, paper saving can yield a further 10% savings of energy use.

Aluminum Making

Wetted drained cathodes and inert anodes offer the prospect of a similar level of electricity use as the best available technology (the modern Hall-Heroult cell) while eliminating the use of carbon anodes. This equals a saving of around 15 GJ/t aluminum, or 25% of final energy use in primary aluminum making. While recycling requires less energy than primary aluminum making, the potential for a further increase of recycling rates is limited to a few percentage points (IEA, 2009b).

17.2 Appendix C: Energy Resources and Potentials

The following sections provide an overview of the energy resource potentials that have served as an input to the scenario analysis in Chapter 17. They extend the discussion that is presented in Box 17.3 of the chapter in a very aggregate manner and address fossil and nuclear energy resources as well as renewable energy potentials.

17.2.1 Fossil Fuel Reserves and Resources

Estimating fossil fuel reserves entails economic and technologic variables. With an improvement in technology or change in purchasing power, the amount that can be considered as reserve fluctuates accordingly. Table 17.C1 shows the total fossil fuel reserve in GEA scenarios for the base year 2005 and figures from Chapter 7 for the year 2009. In GEA scenario exercises, the reserves for the conventional fuels are almost identical across the pathways; however, a large range is considered for unconventional oil and gas. The values adopted in the GEA pathways fall into the range of estimates compiled in Chapter 7.

Table 17.C1. Comparison of global fossil fuel reserves and resources assumed in the GEA pathways and the assessment of Chapter 7.

Source	MESSAGE	IMAGE	Chapter 7	
	Reserves+Resources [ZJ]	Reserves+Resources [ZJ]	Reserves [ZJ]	Resources [ZJ]
Coal	259	376	17.3 – 21.0	291 – 435
Conventional oil	9.8	11.1	4.0 – 7.6	4.2 – 6.2
Unconventional oil	8.9 – 23.0	15.1	3.8 – 5.6	11.3 – 14.9[2]
Conventional gas	16.8	11.6	5.0 – 7.1	7.2 – 8.9
Unconventional gas	23.0-39.2	96.4	20.1 – 67.1	40.2 – 122

Coal is the largest resource among fossil fuels with more than 100 ZJ, and it accounts for more than 50% of reserve and resource estimates in the GEA pathways even at the higher end of assumptions, which include considerable amounts of unconventional hydrocarbons. However, following the discussion in Chapter 17, Section 17.3.4.3, neither coal nor unconventional gas can be expected to play a very large role in the ambitious GEA transformation pathways, because of limited carbon budget related to the stringent climate change objective. Oil is the most vulnerable fossil fuel, as it is estimated to have less than 10 ZJ of conventional oil and possibly less than 10 ZJ of unconventional oil. Natural gas is more abundant in both the conventional and unconventional categories, but with between 40 ZJ to 55 ZJ, it is unlikely to remain the main energy supplier of the world for a prolonged time.

The conventional oil and gas are distributed unevenly, with a few regions dominating the reserves. Nearly half of the reserves of conventional oil is found in Middle East and North Africa, and close to 40% of conventional gas in found in Former Soviet Union. Coal shows much more geographical diversity, where the Former Soviet Union, Pacific OECD, North America, and Centrally Planned Asia and China all possess more than 10 ZJ of reserves.

Similar to conventional oil, much of the unconventional oil resides in the Middle East and North Africa. However, with North America and Latin America showing wide ranges in the unconventional oil estimate, the share of Middle East and North Africa could be high as 42% or as low as 24%. The unconventional gas changes mostly proportionally between the low and the high cases in all regions, so the balance of reserves does not change. It is distributed quite well throughout the world, with North America holding the most, roughly 25% of the world reserve.

17.2.2 Nuclear Energy Resource Potential

Estimates of available uranium resources vary considerably, which could become relevant if advanced nuclear fuel cycles (e.g., the plutonium cycle, including fast breeder reactors, and the thorium cycle), including reprocessing, are not considered to be options, as is the case in the GEA transition pathways. A more comprehensive discussion for the various reasons to exclude these cycles from the analysis is provided in Chapter 14. Figure 17.C1 shows the levels of uranium resources assumed available in the MESSAGE interpretations of the three GEA pathway groups. These span a considerable range of the estimates in the literature, but at the same time none of them fall at the extreme ends of the spectrum (see Chapter 7.5.2 for a more detailed discussion of uranium resources). Alternatively, these resource constraints can be interpreted as limitations on the amount of radioactive waste generated that would need to be safely stored over geological time periods in case no waste processing (e.g., transmutation) is applied. The implementation of these limitations at the global level is very much compatible with the notion of the nuclear fuel cycle being under international control (see, e.g., Panasyuk et al., 2009).

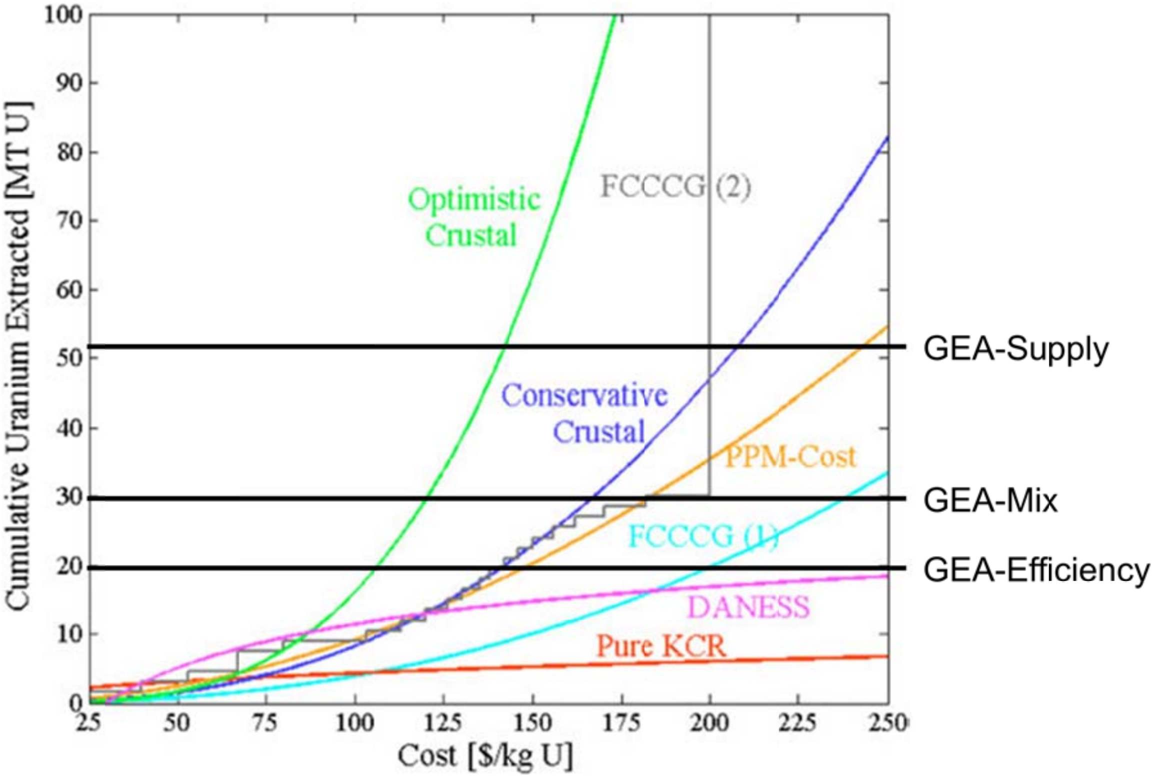

Figure 17.C1. Global uranium resources in the MESSAGE interpretation of the 3 GEA pathway groups compared to ranges in the literature. Source: Schneider and Sailor, 2008

17.2.3 Renewable Energy Resource Potential

Scenarios do not typically consider the full technical potential of renewable energy resources, but include additional measures, such as sustainability criteria and economic measures which are not fully captured within models but lead to a significant reduction of the technical potential. For the GEA pathways, the ranges and literature sources summarized in the Table below have been used. The resource assumptions for all sources are within the ranges of resource uncertainties assessed in Chapter 7.

Table 17.C2. Comparison of global renewable energy deployment potentials in 2050 for the GEA pathways and Chapter 7.

Source	MESSAGE[1]	IMAGE[2]	Chapter 7
	Deployment Pot. In 2050 [EJ/yr]	Deployment Pot. In 2050 [EJ/yr]	Technical Potential [EJ/yr]
Bioenergy	145	145-170	160-270
Hydro	28	18.7	50-60
Wind	170	344	1250-2250
Solar PV	1650	1741	62000-280000
CSP	990[3]	-	
Geothermal	23[4]	-	810-1400

Notes: The deployment potentials for noncombustible renewable energy sources in the pathways are specified in terms of the electricity or heat that can be produced by specific technologies (secondary energy perspective). By contrast, technical potentials from Chapter 7 refer to the flow of energy that could become available as inputs for technology conversion (e.g., the technical potential for wind is given as the kinetic energy available for wind power generation, whereas the deployment potential as reported in this chapter gives the electricity that can be generated by wind turbines). In addition to the renewable energy potentials stated in this table, technology diffusion and systems integration constraints may apply in the pathways and prevent the potentials from being fully utilized. Note that elsewhere in Chapter 17 the substitution method is used to report primary energy from non-combustible sources and therefore primary energy numbers can exceed those reported as deployment potential in this table.

1. MESSAGE potentials based on Hoogwijk (2004); Hoogwijk and Graus (2008); Christiansson (1995); Tubiello and Fischer (2007); van Vuuren et al. (2009), and Chapter 7.
2. IMAGE potentials based on Bouwman (2006).
3. The potential is from MESSAGE as the IMAGE modeling framework does not include CSP.
4. Geothermal energy is exogenously determined in the IMAGE scenarios; therefore no deployment potential can be specified.

While potentials for renewable energy can differ quite substantially between different regions, they are more equitably distributed across the globe as compared to fossil fuels. In contrast to fossil fuels, however, renewable energy sources cannot be traded as easily before conversion to the secondary level, i.e. trade would typically occur after conversion to electricity or some processed solid, liquid or gaseous fuel. As an example, Figure 17.C2 shows the renewable energy resource for the 11 GEA regions by 2050 that serve as inputs to the GEA pathways developed with the MESSAGE modeling framework. The figure indicates the strong dominance of solar energy across almost all regions. The exceptions are bioenergy in tropical regions and wind energy in North America, the Former Soviet Union countries, and to some extent in Europe. However, at a first glance it becomes clear that regionally some of the resources are scarce and the potentials could be exhausted relatively quickly, in particular in those regions where high population density that implies restrictions on land use limitations for some of the renewable energy sources and high growth of the demand for energy services come together. This is particularly the case in Asia, most notably in South Asia, but also in Pacific Asia and partly in China).

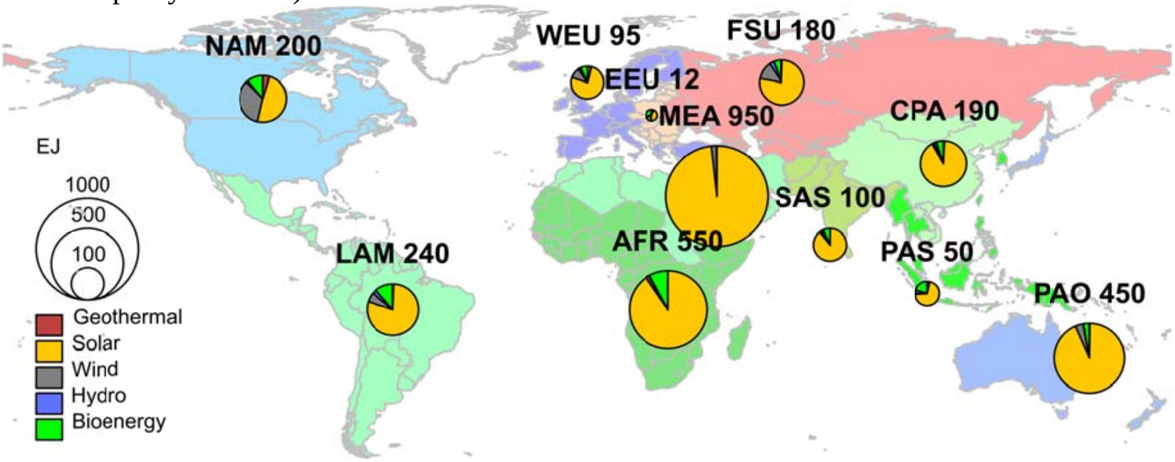

Figure 17.C2. Renewable energy deployment potentials by region in 2050 (from MESSAGE modeling framework).

17.2.4 Bioenergy Resource Potentials

The global bioenergy potential has been assessed using the IMAGE model (van Vuuren et al., 2009; van Vuuren et al., 2010). In the literature, a very wide range of estimates of the biophysical potentials can be found. These are partly related to the controversies surrounding bioenergy, but they also apply to a wide range of underlying assumptions. The list below summarizes the important factors:

- *Future land use and crop yields*: While it is expected that increasing food demand will be mostly met via increasing yields, scenarios still envisage an expansion of land used for agriculture (typical values are around 5–45%). Obviously, in scenarios with higher yield gains and lower demand for land for food production, bioenergy potential can be higher.
- *Land use planning*: Depending on land use planning, bioenergy may compete with food production if it is produced from the same crop or is economically preferred. The impacts of

bioenergy on food security and biodiversity can be limited if production can be concentrated on degraded areas, abandoned agricultural land or natural grasslands.

- *Different crops and production routes*: Land use efficiency and net greenhouse gas emissions vary widely between different bioenergy crops and production cycles. While there is a wide variation for first generation (food crops) bioenergy , second generation (cellulosic) bioenergy typically performs better.
- *Sustainability criteria*: Concerns over water scarcity, biodiversity and nature protection, and land degradation may limit bioenergy production.
- *Agricultural residues*: The use of agricultural residues for bioenergy does not lead to additional land use, but there remain wide discrepancies in estimates both of the availability of agricultural residues and also their alternative potential uses.

Figure 17.C3 summarizes the bioenergy potentials and corresponding ranges in the IMAGE model for different assumptions for the above factors. If yields develop along a median path, the potential is around 160 EJ per year, using all abandoned agricultural land and half the natural grassland. Strict sustainability criteria (limited use of natural areas; expansion of bio reserves and excluding areas with severe water scarcity or soil degradation) lead to a potential below 100 EJ in 2050, and possibly considerably lower. It should be noted that in 2100, the bioenergy potential is considerably higher through further expected improvements in yields and decline in global population (see Section 17.3.1). As a result, the potential could be in a 200–400 EJ range, but strict sustainability criteria could again limit potential to below 200 EJ in 2100. Resulting potentials from assuming strict sustainability criteria in IMAGE have also been incorporated into MESSAGE for the GEA pathways analysis. In the sequel, we will discuss the implications of each of the factors on the bioenergy potentials in more detail.

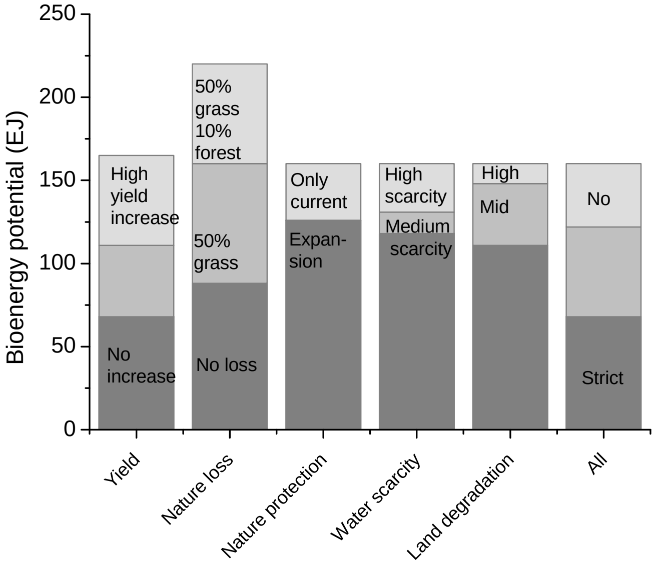

Figure 17.C3. Bioenergy potential for 2050 under different assumptions and uncertainties (van Vuuren et al., 2010). The “Yield” column shows the range from no increase in yields to yields 50% above current assessments of potential yields. The “Nature loss” column shows the production of bioenergy on abandoned agriculture only versus a 50% loss of grassland ecosystems and a 10% loss of forests ecosystems. The “Nature Protection” column shows the impacts of an expansion of current reserves to the level considered in the Sustainability First scenario of UNEP’s Global Environmental Outlook. The “Water scarcity” column shows the

potential in areas with no water scarcity (demand/supply ratio < 0.2), medium water scarcity (0.2–0.4) and high water scarcity (>0.4). The "Land degredation" column identifies areas with high, mild and low land degradation (on the basis of the GLASOD map). The final "All" column combines the criteria on nature protection, water scarcity and land degradation.

Future Land Use

A critical factor for future bioenergy use is the development of land use as a whole. Future land use is determined by an interplay of complex factors such as food demand, trade, and changes in agricultural production methods. At the moment, the world uses about 1.5 Gha of cropland and 3.3 Gha of pasture land (for comparison, the total land area is about 14 Gha) (Figure 17.C4). Over the past few decades, the global agricultural area has been slowly expanding (by about 5% in the 1970–2005 period) as a function of an increasing demand for agricultural products, on the one hand, and increasing yields, on the other (FAO, 2008). The expansion of land is much slower than production increase over the same period, as much of this increase has been achieved through intensification (about 80%) rather than by expansion of agricultural area (about 20%).

For the future, the demand for food production is projected to increase further, driven by population growth and dietary changes. As a whole, the increase in production is expected to be slower than in the past as a result of a slowdown in population growth, although diets are projected to become more meat intensive (van Vuuren et al., 2008; Smith et al., 2010). This trend is relevant for future land use, since production of animal products requires much more (indirect) land than crops. For instance, the production of beef protein requires several times the amount of land than the production of vegetable proteins (Stehfest et al., 2009).

Most of the scenarios found in the literature indicate that production increase will again be mostly met via yield increases (van Vuuren et al., 2008; Smith et al., 2010). The contribution of expansion of harvested land to increase production ranges from as low as 5% to around 45%. In general scenarios with more detail on the agricultural system tend to be on the lower side of this range. Behind the trends at the global levels, often a considerable expansion of arable land is projected in developing countries (especially Africa and Latin America), but this is partly compensated for by a decrease of harvested area in temperate zones. The total land increase is certainly still within the scope of total land available for agricultural production (Fischer et al., 2009).

The potential for bioenergy is directly related to these developments. In scenarios with lower demand for land for food production, there will be more scope for bioenergy production without implications for food security.

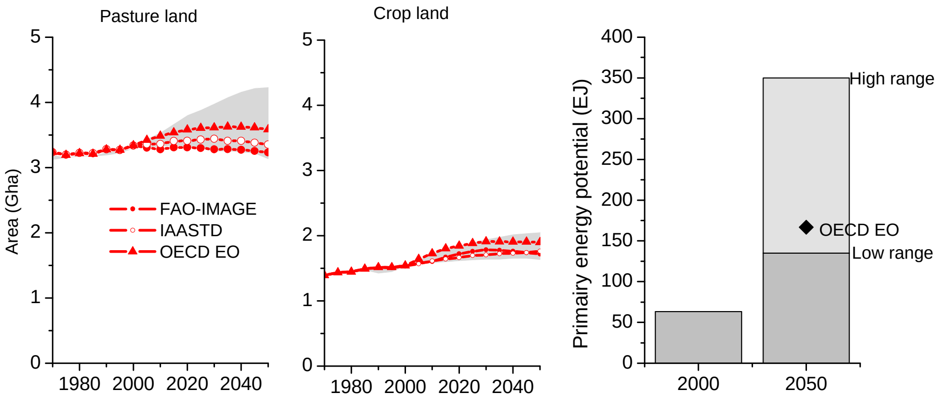

Figure 17.C4. Land use under different scenarios (left panel: pasture land, middle panel: crop land) and the potential for bioenergy in 2050 (right panel) as a function of the land use scenario (not accounting for additional sustainability criteria) .
Notes: OECD EO indicates the OECED Environmental Outlook scenario.

Yield Assumptions

Yield assumptions are important both with respect to the agricultural system as a whole and specifically for bioenergy production. The first play a key role in future land use trends already discussed in the previous section. Historically, on average the increase in crop yields has been around 1% per year. Higher yield increase would lead to less land demand for food production. Lower yield increase leads to the opposite situation. Some studies emphasize that yield increases might be slower in the future than in the past as a result of reaching productivity ceilings (Bringezu et al., 2009), but other studies more or less assume a continuation of current trends.

Also noted above the yield assumptions for bioenergy crops themselves are important. Bioenergy optimists emphasize that there is considerable scope for improvement as crops have not been optimized in the past for bioenergy production. Figure 17.C3 gives an indication of the impact of yield assumptions for bioenergy crops vis-à-vis the OECD Environmental Outlook scenario, showing that assumptions may lead to outcomes that vary over a wide range.

Assumptions with Respect to Land Use Planning

Another reason for controversy is related to different views on managing land use. Researchers focusing on biophysical potentials tend to emphasize that theoretically it is possible to produce bioenergy on abandoned agricultural land or natural grasslands, excluding land use for production and important areas for biodiversity (Smeets et al., 2007; Dornburg et al., 2008; van Vuuren et al., 2009). Other researchers, however, indicate that it is very difficult to implement policies that produce bioenergy only on these “ideal” areas, and that in reality bioenergy will always compete for food production, either because it produced from the same crop, or because they compete for the best agricultural area (Eickhout et al., 2008; Searchinger et al., 2008). As a result, agro-economic studies that directly model the competition of food and bioenergy crops tend to find clearly noticeable impacts of bioenergy production on the prices of food crops.

Different Crops and Production Routes

There are large differences in terms of the energy-efficiency, GHG emissions and land-use efficiency of various bioenergy routes. Often, a distinction is made between so-called first generation (food crops) and second generation (cellulosic) bioenergy routes. However, it should be noted that large differences also exist within these groups. The use of maize to produce ethanol does require a similar amount of energy input as produced in the form of ethanol, while the emissions also tend to be higher than those of fossil-fuel-based alternatives. In contrast, the production of ethanol from sugar cane has much better results. The expected performance of second generation bioenergy is considerably better. Studies suggest aiming for a higher energy output per unit of land and low direct emissions per unit of energy, as well as considering the possibility of producing bioenergy on lands other than those suitable for food crops.

Impact of Sustainability Criteria

There are several factors that may lead to a lower assessment of the bioenergy potential, such as criteria with respect to water scarcity, biodiversity protection and land degradation. Van Vuuren et al. (2009) looked into the impact of additional criteria with respect to these issues on bioenergy, and a summary of their results is shown in several formulations with respect to acceptable impacts of bioenergy that may have a considerable impact on the available potential. For instance, only allowing use of abandoned agriculture land may limit bioenergy use to only 60–70 EJ. Also, strict criteria with respect to water scarcity and land degradation could have a similar impact.

The discussion on land degradation is more complex. On the one hand, bioenergy potential in severely degraded areas should probably not be accounted for given the impacts on yields. However, bioenergy optimists argue that areas with medium degradation might actually be very suitable for bioenergy production, as perennial bioenergy crops might have a distinct comparative advantage over food crops in these areas based on the physiology of the crops. Growing bioenergy in these areas might lead to only very limited impacts on food production.

Agricultural Residues

The availability of agricultural residues for bioenergy production has been estimated to range from hardly any available material to over 100 EJ per year. Berndes et al. (2003) reviewed a wide range of studies, including studies on bioenergy (including residues) potentials and bioenergy use. They found that a typical range for residue use/availability in 2020–2030 might be 20–80 EJ per year (average 50 EJ per year), for 2050 it is 30–100 EJ (average 65 EJ), and for 2100 it is 30–150 EJ (average around 80–100 EJ). Much lower estimates have also been published, such as by Nonhebel (2007 , who states that of the 12 EJ per year of agricultural residues, most residues cannot be regarded as available, since it is used as livestock feed.

Overall Assessment of Biophyisical Potential

In 2050, most combinations of factors result in a bioenergy potential below 200 EJ. Only rather optimistic assumptions would result in a bioenergy potential above 400 EJ, all having a substantial impact on biodiversity. If yields develop along a median path, the potential is around 200 EJ per year with the use of all abandoned agricultural land and half the natural grassland. Strict sustainability criteria (limited use of natural areas; expansion of bio reserves, and excluding areas with severe water scarcity or soil degradation) lead to a potential below 100 EJ in 2050, and possibly considerably lower. It should be noted that in 2100, the bioenergy potential is considerably larger than in 2050, due to improvements in yields and the expected slow down in population growth. As a result, the potential could easily be in the 200–400 EJ range. Strict sustainability criteria, however, are likely to limit bioenergy potential below 200 EJ in 2100.

Given the direct relationship between bioenergy use, land use, food supply, and biodiversity, it seems very important in each case to closely monitor impacts of different energy and climate policies. Similarly, policies that would include direct or indirect (renewable) bioenergy targets need to be evaluated on a regular basis. This implies that the potentials mentioned above clearly depend on land use planning and sustainability criteria. It should be noted that a rise in fossil fuel prices (as a result of depletion) may make bioenergy competitive anyway. In such a situation, clear policies with respect to criteria and land use planning will be very important to prevent increasing food prices and irreversible biodiversity loss.

17.3 Appendix E: Methodological Summary for the Synergies Analysis of Section 17.7

In populating the scenario ensemble with a large number of potential energy futures, the illustrative GEA-Mix scenario was used as a starting point. In other words, assumptions for population and GDP development and the availability of technologies are the same as in GEA-Mix. Then, within the MESSAGE modeling framework, the constraints imposed by climate policies in GEA-Mix were relaxed in order to develop a baseline scenario with business-as-usual energy system development. From this baseline, several hundred scenarios were developed by imposing varying combinations of policy constraints at varying levels of stringency across several different dimensions. The standard GEA-Mix scenario is but one of these scenarios.

For estimating air pollutant emissions and pollution control costs within MESSAGE, data and output from IIASA's Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model was utilized Amann et al., 2009.[1] At each of the different levels of pollution control stringency, emissions factors by pollutant and region were obtained from GAINS for each corresponding energy technology in MESSAGE. In addition, for a given level of pollution stringency, GAINS was used to estimate the cost of installing all necessary pollution control equipment by energy technology (higher stringency requires more expensive control technology). Care has been exercised to avoid double-counting MESSAGE and GAINS technology costs.

Finally, after using MESSAGE to generate a large ensemble of scenarios, the emissions trajectories of each scenario were fed to the MAGICC global climate model (Wigley, 2008). MAGICC calculates internally consistent projections for atmospheric GHG concentrations, radiative forcing, global annual-mean surface air temperature, and sea level rise, given annual emissions paths of a range of gases (CO_2, CH_4, N_2O, CO, NO_x, VOCs, SO_2, and various halocarbons, including HCFCs, HFCs, PFCs, and SF_6). For this analysis, a modified version of MAGICC v5.3 was used, which allows for an explicit treatment of black and organic carbon (BC and OC).[2] Due to uncertainties in key climate system parameters (e.g., climate sensitivity, ocean diffusivity, and aerosol forcing), the MAGICC model is run stochastically for a single emissions trajectory (i.e., MESSAGE scenario) in order to generate probabilistic estimates of climate system responses (e.g., temperature increase or atmospheric GHG concentrations), a methodology described in Keppo et al. (2007) and O'Neill (2010). The uncertainties in the climate system parameters are described with probability density functions (PDF); see Meinshausen et al. (2009) and O'Neill (2010) for reviews of the various climate sensitivity PDFs). In particular, the uniform prior climate sensitivity PDF from Forest et al. (2002) is focused upon in this analysis.

17.4 Appendix F: Illustrative Examples of Primary Energy Diversity Indicators used in Sections 17.6 and 17.7

Energy Systems diversification is often used as a proxy for aggregate measures of risks that may arise by over-reliance on a single dominant energy carrier, and it is associated vulnerabilities against volatile price swings and supply-disruptions, as well as technological uncertainty and failures (accidents). The diversity of the primary energy mix is measured in Section 17.6 with two simple diversity indicators, one that only takes into account the diversity of primary energy resources (I1) and another that also takes into account from where those resources are sourced,

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[1] The authors gratefully acknowledge Shilpa Rao, Peter Kolp, and Wolfgang Schöpp for their invaluable roles in translating the pollutant emissions factor and cost estimates from GAINS to MESSAGE.

[2] The authors gratefully acknowledge Dr. Steve Smith of the Pacific Northwest National Laboratory (USA) for sharing a modified version of MAGICC (v5.3), which takes user-specified trajectories of BC and OC as inputs.

whether from imports or domestic production (I2), thus combining diversity with sovereignty energy security considerations. The latter indicator is further used to explore the security dimension of the pathways in Section 17.7. In either of the indicators, the higher the diversity index, the greater the diversity, and with respect to the second indicator, higher levels of imports work against diversity. The mathematical formulations used are:

$$I_1 = -\sum_j (p_j \cdot \ln p_j) \tag{3}$$

$$I_2 = -\sum_j \{(1 - m_j) \cdot (p_j \cdot \ln p_j)\} \tag{4}$$

where:

- I_1: Shannon Wiener energy diversity indicator #1 (SWDI) (resources only)
- I_2: compound energy diversity indicator #2 (resources + imports)
- p_j: share of primary energy resource j in total primary energy supply
- m_j: share of primary energy resource j that is supplied by (net) imports

Figure 17.C5 gives an illustrative example for the resulting security indicators for three selected regions: North America (NAM), Western Europe (WEU), and Centrally Planned Asia and China (CPA) for the year 2005. While all three regions rank relatively low with respect to security, the reasons for these rankings are different. Both NAM and WEU have a much more balanced and diversified primary energy mix with considerably higher contributions from, for example, natural gas. By contrast, the CPA region, which is dominated by China, is heavily reliant on coal as the primary fuel. In addition, traditional biomass is the main non-fossil alternative in CPA, while both NAM and WEU are characterized by a more balanced contribution of modern renewables, as well as nuclear. On aggregate, this translates for CPA into a comparatively low value for the SWDI (indicator #1, I_1=1.0) compared to WEU and NAM (I_1=1.4). Taking into account the dependency on energy imports among the regions also changes the picture considerably. With a share of about 10% imports in total primary energy, CPA is relying the least on foreign resources (though this is changing rapidly), while in NAM about a quarter and in WEU almost half of the energy is imported from outside the region (Figure 17.C5). The compound effect of considering both diversity and dependency is illustrated by the compound indicator (indicator #2, I_2). Due to its heavy reliance on foreign imports, I_2 drops in WEU to 0.9 (compared to 1.4 for I_1). For CPA, imports hardly affect the security indicator (I_1=1.0 and I_2=0.95). Hence, WEU and CPA have comparable levels of security following the relatively simple indicators adopted here. NAM lies in the middle of the two other regions with respect to imports, with a security indicator of I_2=1.2 compared to I_1=1.4.

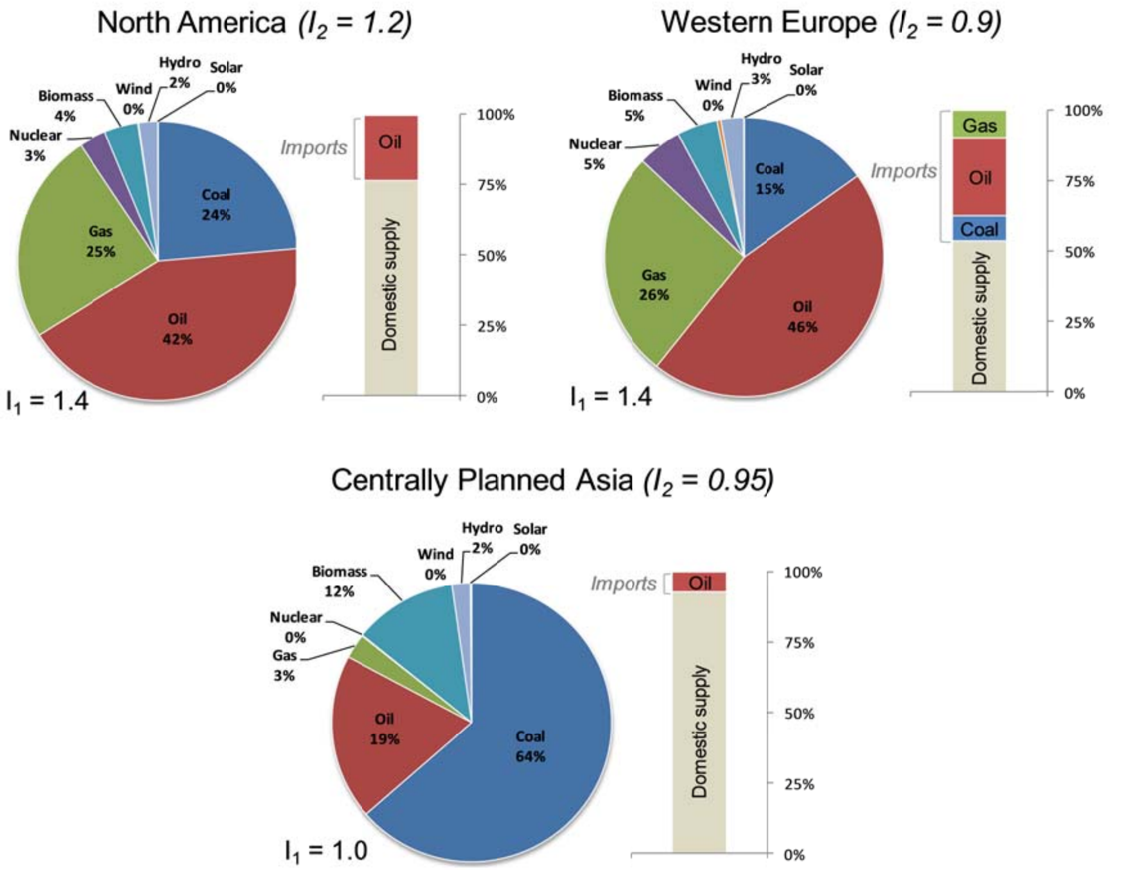

Figure 17.C5. Shares of primary energy use by carrier and corresponding security indicators (I_1, I_2) for selected regions (North America, Western Europe, and Centrally Planned Asia including China). All values correspond to the year 2005.