1

INTRODUCTION: SOCIOECONOMIC ASPECTS OF BIOMASS CONVERSION

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ACRONYMS

CDM clean development mechanism
CFCs chlorofluorocarbons
dLUC direct land use change
GDP gross domestic product
GHG greenhouse gas
iLUC indirect land use change
JI joint implementation
LCA life cycle assessment
LUC land use change
R/P ratio reserves-to-production ratio [y]
TOE tonnes of oil equivalent(s) (= 41.87 GJ)
UNFCCC United Nations Framework Convention on Climate Change
1.1 ENERGY SUPPLY: ECONOMIC AND ENVIRONMENTAL CONSIDERATIONS

1.1.1 Introduction: The Importance of Energy Supply

In the past two centuries, since the Industrial Revolution in the 1700s that was initiated by the invention of the steam turbine, the world has undergone a drastic change due to the steeply increased contribution of fossil fuels (coal, oil, and natural gas) to modern societies’ energy supply (McKay, 2009). Though the Chinese society already used coal for energy supply in approximately 1000 BC and the Romans prior to AD 400 (World-Coal-Institute, 2005), the first written references indicating its use are from about the thirteenth century and beyond (Hubbert, 1949). These hydrocarbon fuels so far have been considered essential, as they are comparatively cheap and convenient energy carriers used for heating, cooking, lighting, and mechanical as well as electric power production and have been widely used as transportation fuels and feedstocks for the manufacture of bulk and fine chemicals as well as other materials with a wide range of applications. Rapid global population growth, expansion of economies, and higher standards have caused an enormous increase in worldwide energy consumption, which was partly made possible by the supply of cheap fossil fuels.

1.1.2 Development of Global Energy Demand

Figure 1.1 shows a scenario toward the year 2030 presented by the oil company BP concerning population growth in relation to developments in total primary energy utilization and gross domestic product (GDP). The figure shows that global energy
demand will rise substantially from the current level with an increasing share from China and India. This rise of the primary energy demand is projected to be larger than the population growth, and this will cause a stress on the limited global resources. The projected GDP even increases stronger, so it is expected that average living standards increase, which will result in additional strain on the available resources.

1.1.3 Sustainability of Energy Supply

One of the major questions in the world, arising from the general picture sketched in Section 1.1.2, is how mankind can ensure a global sustainable development for the (near) future. In this context, sustainability of our energy supply is of paramount importance. The key issues are discussed in the following text, both from a point of view of global socioeconomics and ecological sustainability.

1.1.3.1 Socioeconomic Sustainability

As one of the most important economic drivers to secure and improve the living standards of people in the world, energy supply security is of crucial value for current and future generations. Fossil fuels run out sooner or later as can be seen in Figure 1.2; they are not renewable on an acceptable time scale.

This figure depicts the so-called R/P ratios for different sources. The R/P ratio is the ratio of the current proven reserves to production level. The unit is years and it is a measure of the expected time a certain fuel source is expected to be available.

On a global scale, it appears that oil and natural gas reserves will be available—given the figures of 2012—for an expected approximately 55 years, and coal substantially longer (>100 years). Of course, new contributions to the reserves may be

![Figure 1.2](image-url)
FIGURE 1.2 (Continued)
discovered in the (near) future, but that does not change the inherently limited supply nature of the fossil fuel sources. Regionally, there are also significant differences, which is important in the context of energy policy developments on the different continents.

For the price developments of the fossil fuels, not only their forecasted availability is of importance but also the market development in a landscape highly determined by politics. Already well before the last resources of a fuel will have been depleted the market will be severely stressed. For the economies in the world, fuel cost development is therefore also a primary point of concern. From past developments, particularly regarding oil, it has been shown that substantial fuel price fluctuations (volatility) occur, which has an impact on the global economy (e.g., food prices) that is difficult to predict. Supply and demand will determine the price evolution for each fuel source, but the development of the market structure is also essential: there is a large difference between a free market and an oligopoly or monopoly situation. In this respect, diversification of fuel sources with associated differentiation in suppliers is advantageous as it makes societies less prone to price manipulation by, e.g., cartel formation and sudden disruptions of supply (Johansson et al., 1993).

Self-sufficiency concerning energy supply is often mentioned as target of countries for (longer-term) sustainable economic development. However, not all countries have access to resources within their territories that are sufficient for such a target; other countries, on the other hand, have a structural surplus. Relief of trade barriers can help mitigate this structural discrepancy. Also, in the context of economic sustainability, a good trade balance should be maintained in relation to the energy supply within nations.

Regarding social sustainability in the context of energy supply, reduction of poverty should be mentioned first; a good supply structure of energy carriers is one of the basic requirements for such a development, next to access to clean drinking water and good soil for agricultural activity. Associated herewith, expectedly substantial health improvement should result from a good energy supply infrastructure. Job creation and maintenance is another aspect of social sustainability, and certain energy supply forms can contribute significantly to this. Also, maintaining (or improving) societies’ social cohesion is an aspect that can be impacted by the energy supply structure.

**1.1.3.2 Ecological Sustainability** The energy supply structure should not compromise the sound development of our environment both from a local and global perspective. One of the major issues in this respect is global warming, which is for the main part attributed to the release of greenhouse gases (GHG) from fossil fuel combustion. Other issues are related to local emissions of acid rain precursors and particulate matter (PM).

*Climate Change, the Greenhouse Effect, and Greenhouse Gas Emission Reduction* The greenhouse effect occurs naturally to a large extent. Without this effect, the Earth’s average global temperature would reach only a low −18°C, rather than the current approximate +15°C. Water vapor is the largest contributor to this effect, with a complex role for clouds, but also CO₂ in the atmosphere plays a
significant role. More than a century ago, Arrhenius (1896) already identified this role in the Earth’s temperature control. Ice core studies reveal that on millennial time scales, changes in CO$_2$ content recorded are highly correlated with changes in temperature, although some temperature changes have occurred without a significant CO$_2$ concentration change, but the opposite does not appear to have happened (Falkowski et al., 2000). Less pronounced roles are played by CH$_4$, N$_2$O (nitrous oxide), and several types of chlorofluorocarbons (CFCs) and SF$_6$. It is the CO$_2$, CH$_4$, N$_2$O, and CFC concentrations in the atmosphere upon which man’s industrial

\[ \text{Radiative forcing (W/m}^2\text{)} \]

\[ \text{Carbon dioxide (ppm)} \]

\[ \text{Methane (ppb)} \]

\[ \text{Radiative forcing (W/m}^2\text{)} \]

\[ \text{Year} \]

\[ \text{Year} \]

\[ \text{Radiative forcing (W/m}^2\text{)} \]

\[ \text{Year} \]

\[ \text{Radiative forcing (W/m}^2\text{)} \]

\[ \text{Year} \]

\[ \text{Radiative forcing (W/m}^2\text{)} \]
and household activities have a measurable impact. Scientists largely agree on the point that in the last few centuries, the activities of humans have directly or indirectly caused the concentrations of the major GHG to increase. This is exemplified by Figure 1.3. The atmospheric CO$_2$ concentration varies to some extent from place to place and from season to season. It has been shown that concentrations are somewhat higher in the northern hemisphere than in the southern hemisphere as most of the anthropogenic sources of CO$_2$ are located north of the equator. The difference in land surface covered with forests, being more concentrated north of the equator, causes larger seasonal fluctuations due to comparatively shorter growth periods than in the generally milder southern hemisphere locations that are under the influence of larger oceanic surfaces.

Oscillations of atmospheric CO$_2$ concentrations between about 180 and 280 ppm, have occurred in the past approximately 480,000 years in cycles of 100,000 years, but it appears now we have abandoned this cycling behavior in a remarkably short time frame.

Studies at the NASA Goddard Institute for Space Studies in New York (United States) have shown that over the past few decades, the combined warming effect of non-CO$_2$ GHG should have been comparable to that of CO$_2$ alone. However, while each of the GHG mentioned earlier acts to warm the surface of the Earth, the long-term climatic effects of the other GHG differ from those of CO$_2$. Methane, e.g., has an atmospheric lifetime of only about 12 years. By comparison, newly added CO$_2$ will remain for a time span of tens to thousands of years. As a result, about 65% of the carbon dioxide that human activities have generated since the start of the Industrial Revolution is in the air we breathe today. A historical record of the amount of CO$_2$ in the atmosphere can be found in bubbles of air in arctic ice layers, dating back as far as 600,000 years. The depth of such a layer is a measure of its time of formation.
Another difference is that the principal anthropogenic sources of methane-bacterial fermentation in rice paddies and in the intestines of cattle are related to food production and, hence, are roughly proportional to the number of people on the planet. Because CH$_4$ has such a short atmospheric lifetime, the amount that is in the air is a good indicator of how much is being added with time. Should the global population double over the next half century, the concentration of CH$_4$ could also double, but it is not likely to rise by much more than that. This would add, at most, a few tenths of a degree to the mean temperature of the Earth. Future CO$_2$ increases could, in contrast, warm the climate by 10°C or more.

Nitrous oxide (N$_2$O) and CFCs are in some ways more like CO$_2$ in that once released they remain in the atmosphere for a century or more. The production of N$_2$O, however, is only indirectly dependent on human activities. Its principal source is a natural one, the bacterial removal of nitrogen from soils, and although the world population swells in coming years, the amount in the air should increase only slowly.

The outlook for many CFCs is even more promising. Today, the most abundant of these man-made compounds, freon-11 and freon-12, are being phased out of production altogether by international agreements because of their damaging effects on stratospheric ozone. Indeed, the concentration of one of these gases, freon-11, peaked in 1994 and is now in a slow decline that should continue for the next century or so. The freon-12 concentration has not yet leveled off, but is expected to do so within the next few years. In terms of climatic effects, the main threat from CFCs comes from other long-lived compounds that may be used to replace the ones that have been phased out and that could also act as GHG. Since these possibly harmful replacement gases are as yet present in only small amounts and since, as noted earlier, projected increases in CH$_4$ and N$_2$O are so much less severe, we shall for the rest of this discussion focus solely on the most important anthropogenic GHG: CO$_2$.

Some experts have estimated that the Earth’s average global temperature has already increased by more than 0.5°C since the mid-1900s due to this human-enhanced greenhouse effect; also impacts on sea level (rising) and snow coverage (tending to decrease) have been investigated, the results of which are summarized in Figure 1.4.

Like most other planets and planetoids in the universe, the Earth contains a great deal of carbon, which is slowly and continually transported from the mantle to the crust and back again, in the course of volcanic eruption and subduction phenomena. The portion that finds itself near the surface is continually exchanged and recycled among plants, animals, soil, air, and oceans. In some of these temporary stocks, carbon is more securely held, while in others it more readily combines with oxygen in the air to form CO$_2$. In order to predict how atmospheric CO$_2$ levels and climate may change in the future, it is important to understand where carbon is stored and what its dynamic cycling behavior looks like. The carbon reservoirs that are most relevant to global warming are listed in Table 1.1, with the total amount of carbon that they contained in 2000.

The atmosphere contains approximately 720 Gt C in the form of CO$_2$; current measured atmospheric CO$_2$ concentrations are nearly 400 ppmv. The rate of change in this carbon stock not only depends on human activities but also on biogeochemical and climatological processes and their interactions with the global carbon cycle.
FIGURE 1.4 Observed changes in (a) global average surface temperature, (b) global average sea level from tide gauge (light grey circles; blue circles in the original publication) and satellite (light grey line through the data points and extending from early nineties to beyond the year 2000; red line in the original publication) data, and (c) northern hemisphere snow cover for March and April. All differences are relative to corresponding averages for the period 1961–1990. Smoothed curves represent decadal averaged values, while circles show yearly values. The shaded areas are the uncertainty intervals estimated from a comprehensive analysis of known uncertainties (a) and (b) and from the time series (c). (Source: Reproduced with permission from IPCC (2007), figure 1.1; figure SPM.3. © IPCC.)
Oceans store approximately 50 times more CO₂ than the atmosphere. There is a dynamic exchange by diffusion of about 90 Gt C per year between oceans and the atmosphere, showing the importance of the oceans in CO₂ capture processes. This capture by dissolution leads to ionic bicarbonate formation and increased acidity of the water. Buffering of changes in atmospheric CO₂ concentrations is limited and is very much related to the release of cations from comparatively slow rock weathering. Relevant reactions are:

\[
\text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{HCO}_3^- + \text{H}^+ \quad (\text{RX.1.1})
\]

\[
\text{HCO}_3^- + \text{H}_2\text{O} \leftrightarrow \text{CO}_3^{2-} + \text{H}^+ \quad (\text{RX.1.2})
\]

\[
\text{CaSiO}_3 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{SiO}_2 \quad (\text{RX.1.3})
\]

In the deep ocean (below ~300 m), the concentration of carbonates is higher than at the surface level, which is a consequence of two processes, called the oceanic “solubility pump” and “biological pump” mechanisms. The first is related to the better solubility of CO₂ in cold saline waters, which are in particular present at the Earth’s higher latitudes. These take up CO₂, sink to lower levels, and redistribute the solution laterally. However, a CO₂-induced global temperature rise leads to a more stable height profile of water (a phenomenon called stratification), by which transport of

<table>
<thead>
<tr>
<th>TABLE 1.1 Global carbon reservoir overview</th>
<th>Pools</th>
<th>Quantity (Gt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere</td>
<td>720</td>
<td></td>
</tr>
<tr>
<td>Oceans</td>
<td>38,400</td>
<td></td>
</tr>
<tr>
<td>Total inorganic</td>
<td>37,400</td>
<td></td>
</tr>
<tr>
<td>Surface layer</td>
<td>670</td>
<td></td>
</tr>
<tr>
<td>Deep layer</td>
<td>36,730</td>
<td></td>
</tr>
<tr>
<td>Total organic</td>
<td>1,000</td>
<td></td>
</tr>
<tr>
<td>Lithosphere</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sedimentary carbonates</td>
<td>&gt;60,000,000</td>
<td></td>
</tr>
<tr>
<td>Kerogens</td>
<td>15,000,000</td>
<td></td>
</tr>
<tr>
<td>Terrestrial biosphere (total)</td>
<td>~2,000</td>
<td></td>
</tr>
<tr>
<td>Living biomass</td>
<td>600–1,000</td>
<td></td>
</tr>
<tr>
<td>Dead biomass</td>
<td>1,200</td>
<td></td>
</tr>
<tr>
<td>Aquatic biosphere</td>
<td>1–2</td>
<td></td>
</tr>
<tr>
<td>Fossil fuels</td>
<td>4,130</td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>3,510</td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td>230</td>
<td></td>
</tr>
<tr>
<td>Gas</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td>Other (mainly peat)</td>
<td>250</td>
<td></td>
</tr>
<tr>
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<td>4,130</td>
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<td></td>
</tr>
<tr>
<td>Other (mainly peat)</td>
<td>250</td>
<td></td>
</tr>
</tbody>
</table>

Reproduced with permission from Falkowski et al. (2000). © AAAS.

\(^{a}1\text{ Gt is }10^{9}\text{ metric tons }= 10^{12}\text{ kg.}\)
CO₂ from higher levels to the deep sea is hampered. Increased saturation levels and stratification will weaken absorption capabilities of the oceans.

The “biological pump” is related to fixation of CO₂ by phytoplankton in photosynthesis, which is of the order of 11–16 Gt C per year. This leads to a partial conversion to CaCO₃ by plankton species sinking down to the lower oceanic levels. This process, though sequestering some of the original atmospheric CO₂ in solid form, also leads to partial CO₂ release again.

**Question:** Why would this be the case?

The biological pump mechanism thus counteracts, decreasing action of the solubility pump. If anthropogenic CO₂ release is to be effectively counteracted, then this mechanism somehow should be boosted. However, understanding of the mechanism and its implications is lacking, and one cannot rely on this process to be effectively controllable in a foreseeable time frame.

The carbon stored in the lithosphere, which is the crust and mantle part of our Earth, is present in both organic and inorganic forms. Inorganic carbon deposits in the lithosphere constitute natural carbonate rock materials (e.g., limestone, dolomite), also present in coal inclusions and oil shales. Organically bound carbon in the lithosphere includes litter, humic soil substances, and other organic compounds. CO₂ is released by different natural geophysical and geochemical processes, such as via volcanic eruptions. On the other hand, carbonates in sediments and sedimentary rocks are also removed from the crust by subduction (due to differences in density of continental and ocean tectonic plates) to lower lithosphere levels and partially molten beneath tectonic boundaries.

Terrestrial vegetation, another carbon reservoir, contains about 600–1000 Gt C, stored mostly as cellulose in the stems and branches of trees. Carbon fluxes related to terrestrial respiration and decay of CO₂ comprise a value of approximately 61 Gt C·year⁻¹ (Falkowski et al., 2000). Photosynthesis is the chemical process by which chlorophyll-containing plants and some bacteria can capture CO₂ and organically convert it with water under the influence of irradiated solar energy. This process is vital for life on Earth by balancing the amounts of CO₂ and O₂ in the atmosphere (Raven et al., 2005). This chemical reaction forming a carbohydrate polymer can be described by the following simple equation:

\[
6n\text{CO}_2 + (5n + 1)\text{H}_2\text{O} + \text{solar energy} \rightarrow C_{6n}(\text{H}_2\text{O})_{5n+1} + 6n\text{O}_2 \quad (\text{RX. 1.4})
\]

A number of processes return CO₂ partially back to the atmosphere, namely:

- Autotrophic plant respiration, due to consumption by the plant of part of the carbohydrate polymer to sustain its metabolism
- Heterotrophic respiration, whereby soil microbes oxidize plant-derived organic matter
- Fires
The main terrestrial carbon storage capacity, being about three times the current atmospheric carbon quantity, is predominantly situated in forests, with resistance against plant matter decay being very important. As one of the major organic constituents of plant biomass, lignin plays a key role in preventing microbiological decay (see also Chapter 2). Terrestrial net primary production (NPP) is an important indicator of natural carbon sequestration and is defined as the difference between gross primary biomass production and respiration. The terrestrial carbon sequestration degree is not yet reaching the limitation posed by current CO₂ concentrations (Schimel, 1995). Thus, it forms a potential sink for anthropogenic carbon emissions, although, depending on plant type, the saturation level is reached sooner or later. Furthermore, nutrient availability (fixed nitrogen and phosphor) may hamper growth already before the saturation level has been reached.

In the context of the United Nations Framework Convention on Climate Change (UNFCCC) on December 11, 1997, the Kyoto Protocol was adopted, aimed at the “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system” (see tinyurl.com/35t7t7). By September 2011, 191 countries had signed and ratified the Protocol; this has been extended recently at Doha to the year 2020. The reference year for the emissions counted is 1990. The European Union as a whole targets for a −8% difference compared to that year. Countries have a certain degree of flexibility in how they make and measure their GHG emission reductions. In particular, an international “emissions trading” regime will be established, allowing industrialized countries to buy and sell emission credits among themselves. This mechanism is targeted toward accounting for external costs, which would otherwise be overlooked by the market, into the price of energy sources. Countries will also be able to acquire “emission reduction units” by financing certain kinds of projects in other developed countries through a mechanism known as Joint Implementation (JI). In addition, a “Clean Development Mechanism” (CDM) for promoting sustainable development will enable industrialized countries to finance emission reduction projects in developing countries and receive credit for doing so.

Operational guidelines will pursue emission cuts in a wide range of economic sectors. The Protocol encourages governments to cooperate with one another, improve energy efficiency, reform the energy and transportation sectors, promote renewable forms of energy, phase out inappropriate fiscal measures and market imperfections, limit methane emissions from waste management and energy systems, and protect forests and other carbon “sinks.” The measurement of changes in net emissions (calculated as emissions minus CO₂ removals) from forests is methodologically complex and still needs to be clarified. The Protocol will advance the implementation of existing commitments by all countries. Under the Convention, both developed and developing countries agree to take measures to limit emissions and promote adaptation to future climate change impacts; submit information on their national climate change programs and inventories; promote technology transfer; cooperate on scientific and technical research; and promote public awareness, education, and training. The Protocol also reiterates the need to provide “new and additional” financial resources to meet the “agreed full costs” incurred by developing countries in carrying out these commitments.
Other Emissions from Energy Conversion Processes Leading to Air Pollution  The chemical conversion of fuels to generate (mechanical) power and heat, generally involving a combustion step, also results in emissions other than CO₂. For example, acid rain precursor emissions, such as NOₓ (NO and NO₂) and SOₓ (SO₂ and SO₃), are of concern. These gaseous compounds lead to the formation of nitric acid and sulfuric acid in aqueous droplets in the atmosphere. These acids can precipitate both wet (e.g., via droplets) or dry (adhered to solids that deposit on Earth), causing water and soil acidification. In particular, forests and lakes are impacted by this effect. Also, infrastructural works, such as buildings, are prone to decay due to chemical attack by acid rain on metals (corrosion), paints, and stone materials. Though recognized already in the nineteenth century, further research followed upon increased awareness and action was initiated in the 1970s (see, e.g., Likens and Bormann, 1974). Substantial abatement efforts and stringent policies to reduce NOₓ and SOₓ emissions have already been carried out worldwide since the 1970s; this resulted in reduced emissions in large parts of the world (Wright and Schindler, 1995). Still, there is concern for acidic environmental pollution in emerging economy areas such as China and India, where fossil fuel burning and motorized traffic have shown remarkable growths (Larssen et al., 2006). Emission abatement of acid rain precursor gases is dealt with in Chapter 9.

Another type of emission that is to be seriously considered, from both human, animal, and plant health and climate change perspectives, is PM (particulate matter). PM is released into the air in energy conversion processes that comprise combustion, in particular of solid and liquid fuels but also of gaseous fuels under nonoptimized combustion conditions. Especially, the respirable and very fine particles dispersed in the air, also termed aerosols, are of concern. Nature also generates them via natural processes such as fires, dust bowls, and storms (e.g., winds over salty seas) as well as volcanic activity. Aerosols have several effects with regard to atmospheric radiation (tinyurl.com/48sqk6o). Two effects are briefly described here. The so-called direct effect of PM comprises the effective scattering of radiation, causing negative radiative forcing (e.g., by fine salt aerosols), and the absorption of light, contributing to global warming (carbon black and sooty material). The “indirect effect” of PM relates to cloud formation. Clouds consist of droplets that form with initiation (partly) based on preexisting aerosols, so-called cloud condensation nuclei. When these particles increase in number concentration, increased scattering of radiation in the shortwave domain of frequency occurs. This effect is also attributed as cloud albedo effect. Another effect of increased number concentration of aerosols and thus droplets in clouds is the suppression of precipitation formation and augmentation of the lifetime of clouds. This is also referred to as the Albrecht effect.

Apart from these environmental effects, PM also has a direct negative impact on human health: particulates can lead to respiratory diseases, including lung cancer, and cardiovascular problems.

Several countries and regions in the world have set restrictions on PM emissions. These restrictions distinguish between PM10 and PM2.5, being PM with sizes up to 10 and 2.5 μm, respectively. Chapter 9 deals with technologies for the reduction of PM in the energy conversion industry where combustion plays a key role.
1.2 WAYS TO MITIGATE THREATS TO A SUSTAINABLE ENERGY SUPPLY

As discussed in the previous section, fossil fuel utilization puts pressure on our global ecosystem by contributing to global warming and harmful emissions. Moreover, the reserves of fossil fuels are finite. There are three ways to deal with this global challenge, and they all require drastic innovation development in the respective technologies:

- The energy efficiency of conversion systems should be drastically improved, going hand in hand with reduced use (savings); related to this is also a moderate population growth.
- Renewable energy sources should be used in order to supply nonfossil-based energy.
- Clean use of fossil fuels also will be needed for several decades to come, including carbon capture and storage (CCS). Nuclear energy usage also largely reduces CO₂ emission, but the generation of nuclear energy is associated with the creation of radioactive waste (fission) and potential issues with unwanted extended military (nonproliferation) or even terrorist usage.

The principle of these three energy utilization strategies is also called the “Trias Energetica,” as illustrated by Figure 1.5.

This book concentrates on the pathway of sustainable development via utilization of renewable energy sources and focuses particularly on one type: energy from biomass or bioenergy. Biomass consists of material that has an organic origin. It includes

![Figure 1.5 Concept of the “Trias Energetica,” based on Lysen (1996).](image)
matter derived from plants and animals and their waste or residual material and, in the broader sense, all conversion products such as paper or cellulose, organic residuals from the food industry, and organic waste from households, trade, and industry. Distinction from fossil fuels starts with peat, which is defined not to belong anymore to biomass (Kaltschmitt and Hartmann, 2001; Spliethoff, 2009). The definition of biomass for energy given in the European Directive 2009/28/EC is the following: “the biodegradable fraction of products, waste and residues from biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste.”

The major sources of renewable energy are:

- Solar energy (solar thermal and photovoltaic (PV) technologies)
- Wind energy
- Hydropower
- Tidal energy
- “Blue energy” (based on osmosis driven by the salt concentration difference of two water streams)
- Geothermal energy
- Bioenergy

The use of biomass for the generation of energy has many positive aspects, but there are also critical issues associated with its use (see, e.g., Giuntoli, 2010). The pros and cons are listed below.

Pros

- Biomass is abundantly available stored solar energy, which is thus indirectly used.
- Biomass is available as a comparatively constant supply source as it can be stored under certain biomass-specific conditions, so it may act as a “natural battery.” This is important in view of enabling energy supply security. Solar energy and wind energy, on the contrary, are available as fluctuating sources for which energy storage is still an area of development.
- Bioenergy is the only renewable energy source that can be coprocessed with fossil fuels in existing energy conversion systems (such as oil refineries or coal gasification plants) so as to ensure a gradual energy transition to a renewable energy source.
- As biomass is formed (indirectly) on a relatively short time scale via photosynthesis from CO₂ and water, which are released again in energy conversion systems, in theory, one can speak of a “carbon-neutral” fuel.
- Waste streams and biogenic by-products can be valorized into valuable power, heat, and chemicals.
Biomass is already grown for food, animal feed, and natural fiber applications as well as in forestry with its derived products; it is comparatively easily accessible, and man has experience in dealing with this source. The impact of extended growth on the environment usually is much less an issue than that of, e.g., hydropower installations, which affect the ecology and living surroundings of people and animals.

Biomass growing, harvesting, storage and transportation, trading, and processing to end use for energy conversion purposes can enhance rural economic development (Nag, 2009), via the creation of additional jobs, more than in the fossil fuel processing sector. This leads to extra income for rural regions of both developed and developing countries and eventually offers a way to counteract the constant depopulation of such areas.

For obtaining energy from biomass, nonscarce materials are used. In contrast, several other major sustainable energy sources rather make use of rare materials to construct the required energy conversion devices (e.g., gallium and indium in solar PV cells and niobium and neodymium in wind turbines).

**Cons**

- Conversion of solar energy into biomass is generally low (of the order of 1%, depending on the species); this means that relatively large surfaces are needed to harvest sufficient material for application in energy conversion.
- Biomass is characterized by a low energy density (see Chapter 2 for more details) compared to fossil fuels, which challenges logistics. As a consequence of this and the previous point, biomass has a limited effective availability, and therefore, it can only partly (but still substantially) contribute to the world’s energy demand.
- Although biomass itself is renewable, during the whole life cycle, fossil fuels are commonly used to produce fertilizers and pesticides, grow and collect the plants, transport the harvested material, and, finally, upgrade it to an actual fuel. Therefore, biofuels still have a fossil carbon footprint to some extent.
- Widely different disciplines are involved in the successful implementation of the whole integrated chain from seeding to final conversion and use, ranging from policy development and logistics to chemical, process technology, and agricultural sciences; in this light, implementation of effective policies is complex as bioenergy policies might conflict with other existing environmental or economic policies. For other energy sources, often, the only key is the energy conversion technology, whereas for biomass the whole system is crucial (Sims, 2002).
- There is concern with respect to biomass usage for energy supply as it may compete with food production (Diouf, 2008), depending on the types of biomass and technologies used.
- Issues with deforestation, associated with serious loss of biodiversity and carbon stock, may result if energy plantations are realized at the expense of, e.g., tropical rain forests.
- Competition for scarciencing water sources (Falkenmark, 1998) may become a serious issue.
A drawback of using biomass as a direct source for electricity production would be that useful work (exergy) is destroyed. It might be more efficient from an energy system’s point of view to use biomass as a primary source for (petro)chemical synthesis.

Figure 1.6 presents the forecasted energy demand per energy resource and the role of different strategies to mitigate the CO₂ emissions according to recent IEA scenarios (OECD/IEA, 2012). The 6DS scenario is characterized by the absence of efforts to reduce GHG emissions, leading to a projected 6°C increase of the global mean temperature. The 4DS scenario includes pledges that countries have made to reduce such emissions as well as to increase efforts to improve energy efficiency. It is consistent with the World Energy Outlook’s New Policies Scenario through 2035 (IEA, 2011) and would lead to an expected global mean temperature increase of 4°C. The 2DS scenario, projecting a long-term global temperature rise of 2°C, is targeted by IEA in their Energy Technology Perspectives 2012 (OECD/IEA, 2012) and comprises a cut of energy-associated CO₂ emissions by more than 50% in 2050, as compared to 2009.

**FIGURE 1.6** IEA scenarios for primary energy use and mitigation of CO₂. World total primary energy supply per energy source in 2009 and in three scenarios for 2050, with DS being °C global temperature increase perspective (top). Key technologies for reducing CO₂ emissions (bottom); note that percentages in the legend represent cumulative contributions to emission reductions relative to the 4DS scenario. (Source: Reproduced with permission from OECD/IEA (2012). © IEA.)
to 2009. This requires a substantial restructuring of the energy sector. Figure 1.6 shows the different contributions of mitigation actions in such a way that if all were to be realized, then the 2DS scenario would be followed with a probability of 80%. As can be seen, biomass and waste are expected to play a significant role both in future energy supply and in reducing the GHG emission problem.

1.3 WHAT IS SUSTAINABLE SUPPLY OF BIOMASS?

A globally raised awareness confrontation with the limitations of the oil availability in the early 1970s as a result of the first oil crisis and ecological concerns (see, e.g., Meadows et al., 1972) gave rise to a first renewed interest in biomass for energy supply and also virtually all other forms of renewable energy. After the oil crisis, however, the prices of fossil fuels decreased again due to their higher availability, and this impeded the further development of bioenergy technology. In the 1980s and 1990s, the concern grew that global warming and the resulting climate change were enhanced by CO₂ emissions. This led to the Kyoto Protocol (UNFCCC, 1997) aimed at a reduction of the emission of GHG described in Section 1.1.3 and again stimulated research in the area of renewables and in particular biomass as one of the key carbon mitigating sources.

In order to enable the large-scale introduction of sustainably produced bioenergy and biomass-derived products, a number of technical and nontechnical issues have to be addressed and solved, such as the configuration of the production technology chain, storage and transportation options, integration into the existing energy system, and social acceptance. The transition from the present fossil fuel-based energy system to a sustainable bio-based energy system is expected to be fragmented and to involve a diverse mixture of fossil and renewable energy sources.

A “development which meets the needs of the present without compromising the ability for future generations to meet their own needs” has been a globally referred definition of sustainability. It was first characterized as such by the UN Brundtland Commission in 1987 (Brundtland, 1987). Figure 1.7 shows an overview of the economic, environmental, and social aspects that play a role in the sustainability of bioenergy supply systems. In Sections 1.3.1 and 1.3.2, the socioeconomic impact and ecological implications of biomass for energy supply are addressed.

1.3.1 Sustainable Biomass in Terms of Socioeconomic Considerations

Economic development relies on a secure energy supply. Related to this is the price development of alternative fuels, in this case biofuels. Costs associated with introducing bioenergy technologies are investments to be made in capital for process equipment and infrastructure as well as the needed human capital. Furthermore, of importance for a sustainable development in terms of economic parameters are the allowed financing schemes in countries promoting bioenergy technologies. There is a wide international debate on certification, dealing with the quality of biomass products and related practices; this determines availability and thus pricing. Finally,
countries still use tariffs for importing and exporting biomass products, which causes trade barriers that impact the economics of bioenergy supply and also hampers countries with large potential for export to make a business out of biomass.

Social impact is another important aspect of sustainability. Food (including drinking water) is of first importance to life, and biomass growing schemes must not compromise this. Labor opportunities offered in the field of biomass growing and use for energy supply can substantially contribute to employment, which is of social benefit to mankind. Care should be taken, however, that this is not at the cost of child development, and biomass growth and processing should not be based on child labor. In order to stimulate agricultural practices, smallholders (farmers) should be supported in their activities to cultivate biomass and develop the land. Herein, education and training regarding the bioenergy whole chain approach should be pursued to sustain the practices. This further drives rural development and community building, thereby partly mitigating extreme urbanization with its associated problems. Finally, for any activity to be sustainable in the sense of social development, the bioenergy-related activities should be such that the people’s perception remains positive and supportive.

Important for a sustainable utilization and expansion of biofuels and bioelectricity is a stable, long-term sociopolitical framework to increase investor confidence and to stimulate agricultural enterprises. Simultaneously, countries should remove subsidies for fossil fuel utilization. Moreover, internationally agreed sustainability criteria for
BOX 1.1: EXAMPLE OF SUSTAINABILITY CRITERIA IN NATIONAL POLICIES

In the Netherlands, a committee under the supervision of former minister Cramer has worked out criteria for sustainable bioenergy development, the so-called Cramer criteria (Cramer et al., 2007). They relate to nine principles:

1. The greenhouse gas balance of the production chain and application of the biomass must be positive.
2. Biomass production must not be at the expense of important carbon sinks in the vegetation and in the soil.
3. The production of biomass for energy must not endanger the food supply and local biomass applications (energy supply, medicines, building materials).
4. Biomass production must not affect protected or vulnerable biodiversity and will, where possible, have to strengthen biodiversity.
5. In the production and processing of biomass the soil and the soil quality are retained or improved.
6. In the production and processing of biomass ground and surface water must not be depleted and the water quality must be maintained or improved.
7. In the production and processing of biomass the air quality must be maintained or improved.
8. The production of biomass must contribute towards local prosperity.
9. The production of biomass must contribute towards the social well-being of the employees and the local population.

the sourcing, logistics, and use of biomass should be further worked out without creating unwanted trade barriers such as import and export tariffs (Tanaka, 2011). In this respect, also similar criteria should be applied to existing fossil fuel sourcing and distribution practices to create a similar level playing field.

1.3.2 Sustainable Biomass in Terms of Ecological Considerations

Regarding the environmental impact, the GHG footprint has already been discussed in Section 1.1.3 as an important point of attention when introducing certain biomass-to-energy supply schemes.

Not only GHG but also other emissions to the air determine the acceptability in terms of sustainable bioenergy development. These concern, e.g., acid rain precursors, NOx and SOx. Nitrogen and sulfur are bound in biomass, and oxidation processes lead to the emission of species that are further converted to acidic species in the atmosphere, as has been discussed in Section “Other Emissions from Energy Conversion Processes Leading to Air Pollution.” Also, trace elements in biomass, such as Cu,
Zn, and Hg (present in sewage sludge in relatively high amounts), lead to potentially harmful emissions when thermally converted. These are often related to the coemission of fine PM, which should be cleaned. Moreover, when fertilization is applied to lands in excessive amounts, *eutrophication* of the environment may take place, which means that nitrates and/or phosphates are released into the water. This will lead to excessive growth of phytoplankton, algae, and certain water plants, resulting in a serious oxygen depletion so that water life (e.g., fish population) is endangered tremendously. A so-called life cycle assessment (LCA) can be used to quantify the aforementioned impacts on introducing a bioenergy supply chain in a certain region. We refer the reader to a number of books for more in-depth information on LCA (Guinée et al., 2002; Wrisberg and Udo de Haes, 2002).

Another important point is concern for the utilization of and quality impact on water resources of the introduction of bioenergy; this is crucial in many countries where water supply is a serious bottleneck for any development. Impact on soil characteristics should also be considered. This may turn out to be positive, though, like growth of perennial grasses that can improve the soil structure so as to counteract fatal phenomena of erosion by wind or flooding by rainfall; also carbon stock characteristics may be improved in this way. As this is not always the case in changing land use, it is a point of attention. Moreover, nutrient supply and biomass harvesting should be kept in balance to be sure that agricultural practice can be sustained. Finally, the conservation of biodiversity should be respected so as not to run the risk of failure through pests and diseases to which single crops might be subjected; a diverse environment should be ensured also for mankind, flora, and fauna to flourish.

Growing biomass for energy supply is not inherently beneficent or even GHG emission neutral. Of course, in order to be so, there should be a replacement of fossil fuels, preferably the ones with high CO₂-equivalent emissions per GJ. The climate change mitigation also depends on the geographical location. Land use strategies form an important factor in the dynamics of carbon sequestration and release. On the one hand, stimulation of higher productivity on all forms of land helps to reduce pressure on land use change (LUC). On the other hand, the world faces population growth, which leads to increasing need of agricultural lands and fertilization. In this respect, it is important to address the aspect of LUC, which can be either direct or indirect. LUC may have impact on GHG emission in several ways (Berndes et al., 2011):

- Burning of biomass in the field for the purpose of land clearing.
- Land management practices may be such that carbon stocks in soils and vegetation change.
- Land use intensity may change, causing increased fertilizer intensity with associated N₂O emissions.
- LUC may be associated with alterations regarding carbon sequestration rates as a result of different CO₂ assimilation behavior of the new plantation.

In addition to impacts on GHG emissions, LUC may influence the Earth’s reflection of sunlight; depending on the changes made, this can either increase or decrease the effect.
1.3.2.1 Direct Land Use Change  Direct land use change (dLUC) is the case when other biomass is grown on land that was previously forest or other high carbon stock land. This may lead to a (usually negative) change in the soil carbon content. The impact of such a change is still comparatively straightforward when considering the next form of LUC.

1.3.2.2 Indirect Land Use Change  Indirect land use change (iLUC) occurs when farmers start to grow certain biomass on a land with the purpose of being taken up in a bioenergy supply chain, but with an associated displacement of, e.g., food production that then is started on land elsewhere where forest or other high carbon stock land is converted to arable land. Considerable debate exists among scientists about the extent of the impact of iLUC on GHG emissions.

When biomass is grown for energy supply on purpose, it should not compete with food, feed, and fiber production; therefore, cultivation on lower-quality lands with comparatively low carbon stock is advisable. One can distinguish the following such land types (Kampman et al., 2010):

- Marginal land: this is a land that is currently not cultivated as cropland. Although it is technically feasible to produce crops, its yields are too low and costs too high for competitive agricultural practice.
- Degraded land: this is a land that has been cultivated in the past but has become marginal due to degradation of its soil, erosion, or other causes as a consequence of inappropriate management or external factors such as climate change.
- Abandoned land: this is a degraded land with low productivity and a land with high productivity that is currently not in use.

Figure 1.8 illustrates the difference between dLUC and iLUC.

1.3.2.3 Upfront Carbon Debt Creation  Linked to the issue of LUC is the point of establishing carbon debt for different scenarios of biomass growth for energy supply. The assumption—often widely taken for granted—that the use of bioenergy always results in zero GHG emissions, i.e., that use of biomass is always carbon neutral regardless of the time horizon considered, is incorrect. Land clearing usually leads to CO₂-equivalent emissions that create a carbon loss from the beginning, the so-called upfront carbon debt creation. It is clear that all sources of woody bioenergy (replacing fossil energy) from sustainably managed forests will result in emission reductions in the long term, but diverse bioenergy sources have various impacts on the short-medium term. Therefore, some sources of wood for the generation of bioenergy do not contribute to reducing GHG emissions within the time frame of climate mitigation policies, whereas other sources may have this potential (Zanchi et al., 2012).
Prior to the discovery and large-scale utilization of inexpensive fossil fuels during the Industrial Revolution, mankind was strongly depending on plant biomass to meet its energy demands. In prehistoric times, already, biomass was not only the key source for the supply of food, animal feed, and materials for clothing but also for heating, cooking, and lighting. Later in preindustrial times, biomass served quite diverse purposes, such as early charcoal production for iron making and heat generation for the processing of metals.

In modern societies, the use of biomass as an energy source was gradually abandoned after the discovery of huge amounts of cheap fossil fuels that were easier to process and use. Furthermore, the “modern age” fuels...
allowed applications that were not so easy to realize with biomass: transportation based on liquid fuels from crude oil and cooking on fossil gases. The future for biomass as an energy source appeared to be deemed to fade away, although at the very origin of modern engines, biomass-derived fuels were proposed and used, e.g., peanut oil in Rudolf Diesel’s diesel engine and ethanol in internal spark ignition Otto cycle-based engines (Henry Ford’s trials). Nowadays, biomass is again becoming recognized as a green source for a multitude of energy conversion processes and as a leading practical option for the near and midterm future according to several studies, although also critical comments concerning costs and biomass supply limitations have been made regarding this route.

In different future global primary energy demand scenarios, some of which are shown in Table 1.2, biomass plays a significant role. A substantial part is expected to be covered by liquid transportation fuels, such as ethanol and biodiesel, increasingly from nonedible biomass parts.

A variety of biomass sources can be converted to enable energy supply. These can be divided into six categories, based on their properties (Khan et al., 2009):

1. Forestry products, waste, and residues, which can be subdivided into:
   - Stem-wood logs and wood chips
   - Primary forestry residues:
     - Logging residues
     - Stumps

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Target year</th>
<th>Energy demand (EJ)</th>
<th>Renewables contribution (EJ)</th>
<th>Biomass contribution (EJ)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP Energy Outlook</td>
<td>2030</td>
<td>~712</td>
<td>~85</td>
<td>&lt;50%</td>
<td>a</td>
</tr>
<tr>
<td>EXXON 2012</td>
<td>2025</td>
<td>637</td>
<td>85</td>
<td>53</td>
<td>b</td>
</tr>
<tr>
<td>The Outlook for Energy</td>
<td>2040</td>
<td>696</td>
<td>102</td>
<td>53</td>
<td>b</td>
</tr>
<tr>
<td>IEA “New Policies”</td>
<td>2030</td>
<td>679</td>
<td>96</td>
<td>74</td>
<td>c</td>
</tr>
<tr>
<td>IEA “Current Policies”</td>
<td>2030</td>
<td>719</td>
<td>84</td>
<td>68</td>
<td>c</td>
</tr>
<tr>
<td>IEA “450 Scenario”</td>
<td>2030</td>
<td>610</td>
<td>120</td>
<td>86</td>
<td>c</td>
</tr>
<tr>
<td>Shell “Blueprints”</td>
<td>2030</td>
<td>692</td>
<td>138</td>
<td>59</td>
<td>d</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>769</td>
<td>232</td>
<td>57</td>
<td>d</td>
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<tr>
<td>Shell “Scramble”</td>
<td>2030</td>
<td>734</td>
<td>174</td>
<td>92</td>
<td>d</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>880</td>
<td>326</td>
<td>131</td>
<td>d</td>
</tr>
</tbody>
</table>

a [tinyurl.com/7hlmqxn](tinyurl.com/7hlmqxn)

b [tinyurl.com/6reyxb](tinyurl.com/6reyxb).
c IEA (2011).
d [tinyurl.com/5aamp8](tinyurl.com/5aamp8)
• Secondary forestry residues:
  o Wood processing by-products and residues
  o Bark, cutter chips, and sawdust

• Tertiary residues:
  o Demolition wood (e.g., from furniture)

2. Agricultural residues and wastes (also called herbaceous species), which are subdivided into three categories:
  • Primary (or direct harvest-related) residues, e.g., straw and vineyard residues
  • Secondary residues, which are generated after processing harvested material:
    o Bagasse (residue from sugar production from sugarcane)
    o Molasses and vinasse
    o Nutshells
    o Press cakes or pulp (from, e.g., olive and other vegetable oil processing)
    o Rice husks
  • Tertiary residues: manures from (domesticated) animals, such as chickens, cows, and pigs—dung and litter

3. Industrial and municipal organic wastes, e.g.:
  • Biodegradable part of municipal solid waste
  • Biogenic part of refuse-derived fuel

4. Derivatives, e.g.:
  • Residues from the food processing industry
  • Waste from the pulp and paper industry (“black liquor”)

5. Aquatic species, namely:
  • Microalgae
  • Macroalgae (seaweeds)

6. Energy crops, which are grown with the aim to supply energy carriers, e.g.:
  • Sugar-producing crops: sugar beet, sugarcane, and sweet sorghum
  • Crops rich in starch: barley, cassava, corn, potato, and rye
  • Vegetable oil-containing crops: *Jatropha*, palm oil, rapeseed, soy, and sunflower
  • Fast-growing reed and grass plants, such as hemp, kenaf, and miscanthus (these are sometimes called “energy plants”)
  • Short rotation wood (e.g., eucalyptus, poplar, willow)

Slade et al. (2011) have published an overview of many studies regarding the global availability of biomass in the near and further future. A summary of the findings is schematically illustrated in Figure 1.9. This figure shows that biomass can substantially contribute to primary energy supply, but the extent of the relative share depends on factors such as population growth, diet development and its associated meat-producing farming practice development, sustainable agriculture and forestry.
FIGURE 1.9 Biomass potential as primary energy source. (Source: Reproduced with permission from Slade et al. (2011). © Imperial College; the numbers below the top figure are references that can be found in the report.)
practice improvements, and residue usage. The study, though, does not point toward substantially opening up large nonland energy supply schemes based on the cultivation of (macro)algae, which is currently seriously considered.

1.5 A BRIEF INTRODUCTION TO MULTIPRODUCT BIOMASS CONVERSION TECHNIQUES

Biomass is a complex, heterogeneous, and versatile fuel source (see Chapter 2), so not surprisingly, the technology chain from source (Part I of this book) to multiple possible end uses (Part IV of this book) is quite complicated as can been seen in Figure 1.10. This integrated schematic also reflects the topics related to conversion technologies dealt with in this book (Part III with fundamentals of chemical engineering and process design dealt with in Part II).

The research, development, deployment, and implementation in society of bioenergy solutions thus comprise a broad, complicated, and challenging working field and are therefore fascinating to work on.

FIGURE 1.10 Overview of source to end use of biomass for energy supply; the dark gray boxes represent thermochemical conversion technologies, and the light gray boxes (bio)chemical conversion technologies.
CHAPTER SUMMARY AND STUDY GUIDE

This chapter describes the global energy situation in terms of expected population development, associated demand for energy supply, and implications of energy supply schemes on the environmental development. A major issue in this respect is climate change, which has been recognized to be partly induced by man’s activities involving utilization of fossil fuels. The GHG effect is described and ways to mitigate its extent. Ways to establish sustainable development include energy savings, utilization of renewable energy sources and clean fossil, and nuclear energy usage. Regarding the second aspect, bioenergy as part of a sustainable energy mix is dealt with in this book. At present, biomass is again valued as an important contributor to secure and clean energy supply and is expected to form a substantial part of the (near) future energy mix. Types of biomass sources and their potential are discussed. In addition, aspects of economy, social context, and environmental impact of biomass for energy supply are illustrated and discussed.

KEY CONCEPTS

Primary energy demand, different scenarios
Population development
Relevant emissions from energy conversion processes
Global warming
Greenhouse gas effect
GHG emission mitigation strategies
Sustainability (economics, social aspects, and environmental impact) criteria
Trias Energetica
Biomass availability
Biomass source types
Conversion processes

SHORT-ANSWER QUESTIONS

1.1 How can modern biomass-to-energy conversion technologies mitigate poverty as compared to traditional biomass processing (heating/cooking)?

1.2 Which factors limit the RP ratio as a factor to predict how long a fossil energy will be available?

1.3 Explain in your own words the greenhouse effect and the human contribution to it.

1.4 Why is CO₂ the most important anthropogenic source of all greenhouse gases?

1.5 Explain why naturally occurring fires to some extent contribute to carbon sequestration.
1.6 What are the main sources of methane emissions? What can be done to reduce these?

1.7 What are the main sources of N₂O emissions? What can be done to reduce these?

1.8 In which ways can mankind adapt to climate change impacts, and which roles can biomass play in such adaptations?

1.9 Are there also natural sources that lead to acidification of water?

1.10 Show, by means of a chemical reaction equation, how marble is attacked chemically by acid rain caused by SOₓ emissions.

1.11 Particulate matter (PM) emitted by combustion processes is of concern to both health and climate. Explain why.

1.12 Explain the effects of direct land use change (dLUC) and indirect land use change (iLUC) on the emission of GHG compounds. Give an example of a GHG emission increase scenario for both forms of LUC.

1.13 Would the use of biomass residues that otherwise would be considered as waste lead to LUC or changes in GHG emissions?

1.14 What are the differences between two policy strategies to mitigate CO₂ emissions, Clean Development Mechanism (CDM) and Joint Implementation (JI)?

1.15 Which mechanism (CDM or JI) do you think would be more effective in GHG emission reduction?

1.16 In literature, biomass is often referred to as first-, second-, and third-generation biomass. What is meant by these terms? Can you identify some biomass types for each of these generations?

1.17 What is the phenomenon of eutrophication; is there a risk of this when growing biomass for energy supply?

1.18 Why is maintaining biodiversity so important when planning crop implementation for bioenergy production?

1.19 There are multiple ways to classify biomass into different categories; compare some of these and mention pros and cons of such approaches.

1.20 How would you categorize cotton used for energy conversion? Is it wise to use this plant species?

1.21 Miscanthus is a fast-growing energy crop species; it is characterized as a “C4 plant”; what is meant by this term and what distinguishes it from “C3 plants”?

1.22 Figure 1.9 shows the biomass potential for primary energy supply on a global scale. Why do the reported magnitudes among the references differ (even if they are given by the same authors)?

1.23 What should be done in order to decrease biomass feedstock costs?
Would it be possible to realize a net removal of CO₂ from the atmosphere using biomass conversion processes?

**PROBLEMS**

1.1 The current primary energy use is approximately 12 GTOE (Gigatonnes of oil equivalent); what is this expressed in EJ?

1.2 From Figure 1.1, estimate the energy use per capita in the world in 2030 relative to that in 2010. How does this compare to the values of China and India, respectively?

1.3 Consider that man emits 7 Gt·year⁻¹ carbon into the atmosphere in the form of CO₂. Assume the atmosphere is 20 km high. What will be the yearly increase of the CO₂ mass fraction in the atmosphere if no additional sorption in the seas and land can be accommodated?

1.4 If energy crops are going to be used to supply 100 EJ of global primary energy input and given that an energy crop has a yield of 15 t·ha⁻¹ with an energy content of 15 MJ·kg⁻¹ (as received basis), how many hectares (ha) are needed as crop-land? Comment on the result of your calculation. What might be complications in such a scenario?

1.5 In 1977, Marchetti (1977) introduced a type of analysis of fuel source market penetration for the global energy market, characterized by the following equation (with $F$ being the fraction of the market penetrated):

$$\frac{1}{F} \frac{dF}{dt} = \alpha (1 - F)$$

a. What is $F$ as a function of $t$?

b. Comment on the predictions made by this researcher concerning the current global energy source mix.

1.6 Regarding resource availability, Hubbert’s “peak oil” development is a well-known model (Brandt, 2007). Look up in the literature what it comprises and provide the expression. Is this model always valid for natural resources?

**PROJECTS**

P1.1 Investigate the literature about the usage of biomass for energy supply to manufacturing processes before the Industrial Revolution. Concentrate, e.g., on the Chinese, Greek, and Roman Empire or on Europe in medieval times.
P1.2  a. Make an overview for your country of available biomass types (quantity and quality in terms of heating value) and their prospected prices. Make a graphic representation of your findings.

b. Compare your findings with the potential of solar and wind energy. What can you conclude? What could be reasons to use biomass for energy supply in the context of the situation in your country?

P1.3 Compare the world’s current need for food supply and energy supply on an energy content basis.

P1.4 Based on a literature survey, make a critical comparison between different energy demand and supply scenarios for the future; take 2050 as the reference time scale.

P1.5 Review the literature on primary energy consumption expectations, now distinguishing the world regions.

P1.6 If you have access to analytical equipment in your lab, with, e.g., an infrared spectrophotometer (online, gas specific) or an FTIR spectrophotometer, you can determine the CO₂ concentration in the air and monitor the cycle in a year’s time. What is the background of this yearly variation?

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