Chapter 2
Energy Balance: Cumulative Fossil Fuel Demand and Solar Energy Conversion Efficiency of Transport Biofuels

2.1 Introduction

The adjective 'sustainable' is frequently used regarding biofuels (e.g. Abrahamson et al. 1998; Krotscheck et al. 2000; Buckley and Schwarz 2003; Bhattacharya et al. 2003; Goldemberg and Teixeira Coelho 2004; Butterworth 2006; Demirbaş 2007; Robèrt et al. 2007; Goldemberg et al. 2008; Karp and Shield 2008; Royal Society 2008). Also, biofuels are a regular subject in scientific journals dealing with renewable or sustainable energy. The apparent rationale of using 'sustainable' and 'renewable' in the context of biofuels is the following: biomass may be argued to temporarily store solar energy, based on photosynthesis (see Chap. 1). In doing so, carbon is sequestered, and on burning transport biofuel, it is de-sequestered. In the meantime, photosynthesis proceeds, generating new feedstocks for biofuels. As solar irradiation and photosynthesis are expected to last for many millions of year, doing so would seem sustainable and transport biofuels renewable. However, this is not the 'whole story'. Energy inputs in the world economy are currently, as pointed out in Chap. 1, overwhelmingly fossil fuels, and the use of fossil fuels extends to the production and distribution of transport biofuels. This is at variance with renewability and sustainability, as fossil fuels are non-renewables, and their use cannot be sustained indefinitely at the present level. The cumulative life cycle fossil fuel demand of biofuels will be discussed in Sect. 2.3.

For converting solar irradiation into transport kilometres, there are a variety of technologies available with widely varying efficiencies. Such efficiencies matter: they are major determinants of spatial requirements of energy supply. These spatial requirements, in turn, are important determinants of competition of energy supply with food production and habitats for living nature. Because this competition is an important matter in the current transport biofuel debate and will return later in this book, this chapter will deal with the solar conversion efficiency of transport biofuels (Sects. 2.4 and 2.5). Other methods for solar energy conversion do not involve organisms but rely on physical conversion technologies. Photovoltaic cells generating electricity are examples thereof, for which the solar conversion efficiency will be discussed in Sect. 2.6.

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Biofuels and the output from photovoltaic cells can be used to perform work or to deliver energy services. Work (a thermodynamic concept) or energy services (an economic concept) include, for instance, car kilometres. The performance of work often includes the use of intermediaries (e.g. power plants, batteries or motors). The energy efficiencies of such intermediaries will be discussed in Sect. 2.6. In Sect. 2.6, we will also consider the overall efficiency of a variety of methods to convert solar energy to car kilometres, giving a ‘seed-to-wheel’ perspective.

As pointed out in Chap. 1, the production of biofuels is often accompanied by by-products or co-products. For instance, in making biodiesel from rapeseed, both glycerol and an ingredient of animal feed (rapeseed cake) are produced. Before we go into the calculations of cumulative (fossil) energy demand, it should be decided how much of that demand is allotted to biodiesel and how much to glycerol and rapeseed cake. This is called ‘allocation’ and will be discussed in Sect. 2.2.

2.2 Allocation

There are three major ways to allocate. The first is based on prices, the second on physical categories, such as weight or energy, and the third on subtracting avoided processes (also called substitution). We will look at these in turn. The first way to allocate is on the basis of price (market values). The idea behind this type of allocation is that prices drive production (Weidema 1993). This method is, however, not without problems. Firstly, market prices are not constants. So, if, for example, ethanol prices go up, whereas the prices of other outputs do not, the emissions and cumulative fossil energy demand allocated to this transport fuel increase. The same happens when by-products go down in price, but the transport biofuel price remains constant (or increases). A good example of the latter is the tenfold price decrease of glycerol between 2004 and 2006 (Yazdani and Gonzalez 2007).

A second problem is that currently, much transport biofuel production is not driven by market value but by market value plus subsidy. This leads to the question of whether, for instance, in the case of ethanol production from cornstarch, allocation should be on the basis of the market value of cornstarch or on the basis of the subsidized value. Another problem arises when wastes are considered. These may well have negative prices (being a cost to the producer). For instance, the producer of the waste may have to pay a price for the incineration or treatment of his waste. If so, allocation on the basis of price may mean that the waste, because of its negative price, is apparently associated with a negative cumulative energy demand (Reijnders and Huijbregts 2005). Usually, this has been felt unsatisfactory by proponents of allocation based on prices, and this often leads to the decision the give a zero price to wastes. However, this seems inconsistent. An implication of a zero price is that the life cycle leading to the generation of wastes has no impact on the environmental evaluation of such biofuels. The problem may also arise as to whether something is a waste or a by-product. An example thereof is sawdust. This may be used for firing industrial installations or power plants, and then may be categorized as by-product (with a positive monetary value), but sawdust may also be left in the woods and may then be categorized as a waste (with zero monetary value). Decisions regarding such categorizations may be far from easy and may have a substantial impact on the greenhouse gas emissions calculated.

Alternatively, one may allocate on the basis of physical categories such as 'energy content' (heating value) or weight. For instance, the European Union in its 2008 draft Renewables Directive has proposed to allocate on the basis of energy (Eickhout et al. 2008). This type of allocation has the advantage of stable outcomes, unaffected by movements of prices. However, there are curious consequences, too. For instance, in this allocation system, there is an obvious way to improve the environmental performance of a transport biofuel, and that is to produce more waste. To evade this problem, there is a tendency to restrict allocation to product outputs. Matters related to quality may also emerge. If one, for instance, allocates to the outputs of electricity and low temperature heat on the basis of 'energy content', one may be criticized for neglecting the quality of these outputs and be advised to use exergy instead of energy. Thus, allocation on the basis of physical categories may encounter criticism if the physical property chosen is at variance with the perceived value of the co-products.

Another way to deal with a multi-output process is to 'correct the system'. In the case of biofuels, one may consider biofuel to be the only output and correct for the other outputs by subtracting 'avoided processes' which such outputs can substitute (Ekvall and Finnveden 2001). This approach has also been called substitution. For instance, in the case of ethanol production from corn or wheat, it has been argued that by-products such as dried distillers grains (DDG) or dried distillers grains with solubles (DDGS) may be a substitute of soybean meal in cattle feed (Kim and Dale 2005). Thus, producing DDG(S) may be valued on the basis of the avoided process of producing soybean meal. However, soybean meal and DDG(S) are not identical. This then raises the question of the basis for conversion: should it be on the basis of price, or protein content, or metabolizable joules (energy)? Moreover, DDG(S) is not a straightforward substitute of soybean meal, as its composition is relatively variable, and its consumption by animals may be linked to increased mycotoxicosis risk and increased intakes of mycotoxins (Taylor-Pickard 2008). This has led to a more limited recommended use of DDG(S) in animal feed than in the case of soybean meal (Taylor-Pickard 2008). Then there is the matter of applications other than animal feed. For instance, soybean meal may also be used to generate vegetarian alternatives to meat, and DDG(S) may be used to produce protease and peptones (Romero et al. 2007), methane (Murphy and Power 2008) or ethanol. Such alternative applications may have environmental impacts that are very different from the use as an ingredient of animal feed. Suppose, finally, that DDG(S) is indeed valued on the basis of avoiding soybean meal; the problem is that soybean meal is a co-product, just as DDG(S) is. This may be argued to imply that substitution in this case means plugging one hole with another.

So, each way to allocate has its weak points, and there is no agreement on the best way to allocate. In this book, we will not make a choice in favour of a specific way to allocate but rather will explicitly indicate what type of allocation has been used in arriving at specific results.

2.3 Cumulative Fossil Fuel Demand

2.3.1 Transport Biofuels from Terrestrial Plants

Most studies regarding cumulative fossil energy demand have been done for transport biofuels from terrestrial plants, and most agree that the seed-to-wheel cumulative demand for fossil fuels associated with transport biofuels from terrestrial plants is lower than the well-to-wheel demand of fossil transport fuels. However, Patzek and Pimentel (Pimentel 2003; Patzek 2004; Patzek and Pimentel 2005; Patzek 2006) have presented calculations for cornstarch-derived ethanol, soybean- and sunflower-derived biodiesel and lignocellulosic ethanol that suggest a higher cumulative demand for fossil fuels. The difference between these studies of Patzek and Pimentel and other studies is partly caused by difference in allocation, partly by higher estimates of fossil fuel input in agriculture and industrial processing, and partly by factoring in the energy demand of the infrastructure needed for transport biofuel production (factories, vehicles, etc.) into the calculations. However, along with assumptions that are more favourable to transport biofuels, there seems no denying that in western industrialized countries, the cumulative fossil energy demand for transport biofuels made from starch, sugar and edible oils may be quite high when allocation is on the basis of price. For ethanol from US corn or European wheat or rye, it would seem unlikely that, when allocated on this basis, the 'seed-to-wheel' cumulative fossil energy demand would be much lower than 80% of the corresponding demand for petrol (Hammerschlag 2006; Hill et al. 2006; von Blottnitz and Curran 2007; Reijnders and Huijbregts 2007; Zah et al. 2007). In the case of biodiesel from rapeseed and soybean, qualitatively good estimates usually suggest that, when allocated on the basis of price, the cumulative energy demand may well be in the order of 60–80% of the corresponding demand for diesel (Hill et al. 2006; Zah et al. 2007).

Cumulative fossil energy demand for transport biofuels may be considerably lower when biofuels based on high-yielding crops from developing counties, such as oil palm and sugar cane, are considered, especially when lignocellulosic biomass is used for powering processing facilities (von Blottnitz and Curran 2007; Reijnders and Huijbregts 2008a). When the latter applies, for instance, cumulative fossil fuel inputs in ethanol from sugar cane may become energetically less than 10% of the ethanol output (Macedo et al. 2008). Also, much lower cumulative fossil fuel demands have been estimated for transport biofuels from lignocellulosic biomass such as wood or switchgrass when processing is also powered by lignocellulosic biomass (von Blottnitz and Curran 2007). When allocation is based on the energy content or weight of outputs, cumulative fossil energy demand allocated to transport biofuels will tend to be lower than in the case of allocation based on price. Note that cumulative mineral oil demand is often lower than cumulative fossil fuel demand, because natural gas and coal can be significant contributors of energy to the transport biofuel life cycle (Hammerschlag 2006; Kim and Dale 2008). For instance, coal is often an important contributor to electricity supply, which is sometimes used by mills producing ethanol (Kim and Dale 2008). Natural gas is important in production of fixed nitrogen to be used in agriculture (Hammerschlag 2006).

2.3.2 Transport Biofuels from Wastes

Zah et al. (2007) have studied cumulative energy demand associated with methane production from a variety of wastes using allocation on the basis of price and a zero value for the waste itself. Thus, the calculation of energy demand and emissions linked to methane production from wastes was restricted to the waste-to-wheel stages of the life cycle. Comparison was with natural gas. The wastes considered were: sewage sludge, 'biowaste', manure and manure plus co-substrates. Cumulative fossil energy demand for methane from these wastes was typically in the order of approximately 45% of the fossil reference. The outcomes of the study of Zah et al. (2007) are more favourable to transport biofuels made from wastes than to transport biofuels made from food crops. Zwart et al. (2006) made a more detailed study of the conversion of manure from cattle and swine into biogas (methane) in the Netherlands and concluded that the fossil fuel input energetically roughly equalled the biogas output. One should keep in mind that these outcomes are based on the assumption that life cycle impacts up to the waste can be neglected. When wastes change into secondary resources, fetching a price, or when the seed-to-wheel allocation is based on mass or energy, this would raise cumulative fossil energy demand of transport biofuels made from residues (cf. Reijnders and Huijbregts 2005).

2.3.3 Transport Biofuels from Aquatic Biomass

Fossil fuel inputs in producing microalgae tend to be high. When microalgae are grown in bioreactors, outputs are unlikely to energetically outperform inputs (Wijffels 2008; Reijnders 2008). A claim has been made for ultrahigh bioproductivity from algae in thin channel ultradense culture bioreactors indirectly irradiated by the sun (Gordon and Polle 2007). The cultures are irradiated with pulsed light emitting diodes, powered by photovoltaic cells. The efficiency of converting solar radiation into biomass is probably below 0.2%, and the corresponding energetic yield is likely to be exceeded by fossil fuel inputs (Wijffels 2008).

As to producing microalgal biofuels in open ponds, it is a remarkable aspect of several recent publications strongly advocating algal transport biofuels (e.g. Chisti 2007; Huntley and Redalje 2007; Chisti 2008a; Dismukes et al. 2008) that inputs of fossil fuels are not addressed. Two less recent studies are available that looked at energy inputs and outputs in open pond cultures of microalgae. They did not take account of all inputs, though. For instance, fossil fuel input into the handling and clean-up of discharges from ponds (which will probably be necessary in view of the extreme pH and/or salt concentrations and high nutrient levels in algal ponds) was considered by neither of the studies. Sawayama et al. (1999) studied operational life cycle energy inputs in growing and processing *Dunaliella tertiolecta* to supply bio-oil. Processing was by thermal liquefaction (also Yang et al. 2004). Operational energy inputs (fossil fuels) exceeded energetic output by 56% when microalgal yield was 15 Mg ha^{-1} $year^{-1}$. Hirano et al. (1998) studied *Spirulina* production and processing to supply methanol (via synthesis gas). Here the assumed yield was approximately 110 Mg ha^{-1} $year^{-1}$. Both fossil fuel inputs in infrastructure and operation were considered. The energetic output exceeded the life cycle fossil fuel input by 10%. At more realistic estimates of *Spirulina* yield, which are in the order of 10–30 Mg ha^{-1} $year^{-1}$ (Vonshak and Richmond 1988; Jiménez et al. 2003), fossil fuel inputs would have exceeded energetic outputs. Chisti (2008b) has argued that the energetic inputs used in the studies of Hirano et al. (1998) and Sawayama et al. (1999) are 'grossly overestimated'. However, even at Chisti's (2008b) estimate, the fossil fuel input energetically would equal an output of approximately 30 Mg dry weight algal biomass ha^{-1} $year^{-1}$, which is at the upper end of the range for the commercial production of *Spirulina* (Jiménez et al. 2003).

Though experimentally, yields have been demonstrated that may energetically exceed fossil fuel inputs (Hirano et al. 1998; Chisti 2008b), it is far from certain that such yields can be achieved in actual commercial practice. Large differences between experimental yields and average commercial yields are also common in the production of terrestrial crops, as will be explained in Sect. 2.4.1.

A 'high yield' has furthermore been claimed for oil from *Haematococcus pluvialis* produced by a combination of a closed bioreactor and 1.3 days in a pond (Huntley and Redalje 2007). This yield probably corresponds with a photosynthetic efficiency in producing biomass of just over 1% and a photosynthetic efficiency in producing algal oil of roughly 0.6% (Vasudevan and Briggs 2008). No data have been published about the cumulative energetic inputs in this type of culture, but from the above, it would seem unlikely that the energetic value of algal oil would much exceed the cumulative energy input into the infrastructural and operational inputs.

Studies regarding algal production of H_2 suggest that the cumulative energy demand for algal H_2 production is probably of the same order of magnitude as the energetic output, when the solar energy conversion efficiency does not exceed 1% (Burgess and Fernández-Velasco 2007).

On the other hand, it may be that the yield of microalgae grown in water saturated by CO_2 from power stations may exceed fossil fuel inputs when there is no allocation of the fossil fuel input into electricity production to these algae. However, whether this application will actually become operational is unclear, as algal performance has so far been disappointing, and sequestration of CO_2 in abandoned gas and oil fields and aquifers has a higher efficiency (Benemann et al. 2003; Vunjak-Novakovic et al. 2005; Odeh and Cockerill 2008).

The emergence of some saltwater and freshwater macroalgae and macrophytes as pests offers scope for their conversion into transport biofuels. Only for one of the macrophytes (water hyacinth) are data available about the overall energy efficiency of conversion into ethanol. These data suggest a negative energy balance (Gunnarsson and Petersen 2007).

2.4 Conversion of Solar Energy into Biomass

The intercept by the Earth of solar energy exceeds the present input of fossil and uranium fuels into the world economy by a factor of about 10,000 (Lewis and Nocera 2006). The average daily solar irradiation varies, dependent on latitude, climate and season. When on the equator, maximum irradiation is on a horizontal plane, but away from the equator, for the maximum intercept of solar radiation by a fixed plane, the plane should have an angle corresponding to latitude (e.g. Çelik 2006). Average daily solar irradiation (measured on a horizontal surface) that may support feedstock for biofuel production varies roughly between 7 and 25 $\mathrm{MJ\,m^{-2}}$. The daily worldwide average irradiation is about 15.5 $\mathrm{MJ\,m^{-2}}$, or 180 $\mathrm{W\,m^{-2}}$. Differences between days can be large. For instance, in Amsterdam (52°21′ N), the average daily irradiation is approximately 3 $\mathrm{MJ\,m^{-2}}$ in January and 17 $\mathrm{MJ\,m^{-2}}$ in July (Akkerman et al. 2002). The greatest annual input of solar radiation tends to occur in subtropical regions at latitudes between 20 and 30° and little cloud cover. Humid tropical regions have somewhat lower irradiation (Sinclair and Muchow 1999). When going poleward from a latitude of about 30°, solar irradiation tends to decrease. As for major areas for current biofuel production, in Brazil, where sugar cane ethanol is produced, daily solar irradiation is on average about 220 $\mathrm{W\,m^{-2}}$ (approximately 19 $\mathrm{MJ\,day^{-1}\,m^{-2}}$ or 694×10^2 $\mathrm{GJ\,year^{-1}\,ha^{-1}}$). In the US, average daily irradiation varies between 12 and 22 $\mathrm{MJ\,m^{-2}}$, whereas in the US Midwest, where there is large-scale corn ethanol production, solar irradiation is about 170 $\mathrm{W\,m^{-2}}$ (approximately 14.7 $\mathrm{MJ\,day^{-1}\,m^{-2}}$ or 536×10^2 $\mathrm{GJ\,year^{-1}\,ha^{-1}}$) (Kheshgi et al. 2000; Vasudevan and Briggs 2008).

In establishing the overall conversion efficiency of technologies for the conversion of solar energy, there should be a correction for the cumulative energy demand associated with the biofuel life cycle and the life cycle of physical conversion technologies (Reijnders and Huijbregts 2007). For instance, if the lower heating value of fossil fuel inputs amounts to 20% of the lower heating value of a biofuel, the solar energy conversion efficiency will be corrected by this percentage. The result thereof is the overall energy efficiency of the biofuel. This is summarized in the following equation:

$$SCE_x = \frac{Y_x \cdot E_x \cdot FE_x}{E_{\text{solar}}} \cdot 100$$

where SCE_x is the solar energy conversion efficiency of biomass or biofuel type x (%), Y_x is the yield of biomass type x (kg/ha/year), E_x the energy content of biomass or biofuel type x (MJ/kg), FE_x the correction factor for fossil fuel input in the life cycle of biomass or biofuel type x (MJ/MJ), and E_{solar} is the yearly solar irradiation (MJ/ha/year). SCE_x is a measure that can help in estimating the ability of biofuels to displace fossil fuels.

As pointed out in Chap. 1, conversion of solar energy into biomass occurs by photosynthesis. Harvestable biomass that can be used for energy generation (yield) depends on a number of factors. At the present atmospheric CO_2 concentration for C_4 terrestrial plants, the maximum conversion efficiency is estimated at 5.5–6.7% and for C_3 plants at 3.3–4.6% (Hall 1982; El Bassam 1998; Heaton et al. 2008b). A 6.7% solar energy conversion efficiency would correspond with a dry biomass yield of approximately 250 Mg ha^{-1} year^{-1} at 40° latitude (El Bassam 1998). Actual yields are much lower than theoretical yields, because there are factors – such as in the case of terrestrial plants, the absence of a full canopy, shading, photosaturation and limited availability of nutrients and water – which in practice reduce the efficiency. Due to such factors, the theoretical differences in conversion efficiency between, for instance, C_3 and C_4 plants may not materialize in real life differences in conversion efficiency. For instance, sorghum is a C_4 plant that tends to be roughly as efficient as the C_3 cereals. And C_3 plants such as sugar beet and oil palm are in practice often more efficient in converting solar radiation into biomass than the C_4 plant *Miscanthus*.

2.4.1 Terrestrial Plants

Terrestrial plants vary widely in their yearly yields per hectare. Yields are dependent on insolation, temperature, the presence of nutrients and water and the nature of plants (Coombs et al. 1987). In natural ecosystems on average, the efficiency of photosynthesis in converting solar energy into plant material is usually in the order of 0.1–0.3% (Mezhunts and Givens 2004; Rosing et al. 2006). In the case of cultivated plants, higher conversion efficiencies are achievable. The highest yields are usually achieved in experiments under ‘excellent’ conditions that are highly conducive to plant growth. In large-scale commercial cultivation, yields are much lower. In the following, we will use data from large-scale cultivation, as this should be the basis for substantial feedstock production. As there is a tendency of gradual yield increases over time, such data may be biased in favour of crops that have a long tradition of large-scale cultivation. After a similar history of cultivation, the yields of relatively new crops that may serve as biofuel feedstocks such as *Miscanthus* and switchgrass may well be substantially higher than those that will be presented here.

In practice, the C_4 plant sugar cane is relatively efficient in converting solar energy into biomass (Sinclair and Muchow 1999). In subtropical areas, sugar cane may annually yield about 80 Mg per hectare of harvestable biomass (dry weight) when the conditions are excellent (Bastiaanssen and Ali 2003; Braunack et al. 2006). Average sugar cane yields during the mid 1990s in Brazil were about 36.8 tons of biomass (dry weight) ha^{-1} year^{-1} (Kheshgi et al. 2000). Under excellent conditions, another C_4 plant, *Miscanthus*, may yield annually up to about 30–60 Mg of dry weight harvestable biomass per hectare (Long et al. 2006; Heaton et al. 2008a), but more commonly, yields are in the range of 10–13 Mg aboveground dry weight biomass ha^{-1} $year^{-1}$ (Lemus and Lal 2005; Christian et al. 2008).

Oil palms in Southeast Asia yield about 20 Mg $year^{-1}$ ha^{-1} as fresh fruit bunches (dry weight) (Reijnders and Huijbregts 2008a). For sugar beets, good yearly dry weight yields of biomass from large-scale commercial cultivation are also in the order of 20 Mg ha^{-1} (Şahin et al. 2004; Tzilivakis et al. 2005). For eucalyptus, yearly biomass yields per hectare tend to be in the order of 10–20 tons (Sims et al; 1999; van den Broek et al. 2001). Yearly dry biomass yields of large-scale cultivation under good conditions for switchgrass are in the order of 10–15 Mg ha^{-1}, for willow 9 Mg ha^{-1}, and for poplar 11 Mg ha^{-1} (Lemus and Lal 2005; Heaton et al. 2008a). Total yearly (dry weight) aboveground biomass accumulation per hectare in the USA is in the order of 17–18 Mg for corn (Heaton et al. 2008a), and under good conditions, 10–11 Mg for wheat (world average is 5.5 Mg; Wright et al. 2001), in the order of 9 Mg for peas and 4–5 Mg for canola (Lemus and Lal 2005; Malhi et al. 2006). High yields of photosynthesis in practice usually depend on substantial inputs of synthetic nutrients derived from non-renewable natural resources (Samson et al. 2005). Sustainable yields that can be achieved when only recycling nutrients that are present in biomass tend to be much lower as will be discussed in Chap. 3 (also Pimentel et al. 2002; Reijnders 2006). Table 2.1 shows the overall energy conversion efficiency (taking account of inputs of fossil fuels) for a variety of crops with relatively good yields.

The overall solar energy conversion efficiencies in Table 2.1 are below 1% and range roughly between 0.15% (for rapeseed/canola) and 0.9% (for sugar cane). For comparison, a percentage is added for sustainably grown wood in Western Russia (Nabuurs and Lioubimov 2000). In this case, the conversion efficiency is about 0.05%.

There have been efforts to improve the solar-energy-to-biomass conversion by transgenic approaches. These have focused on increasing the net carboxylation efficiency of 1,5-biphosphate carboxylase and the introduction of enzymes characteristic for C_4 plants in C_3 plants (Heaton et al. 2008; Raines 2006). So far, such efforts have not led to a substantial improvement in the conversion of solar energy to biomass (Raines 2006).

2.4.2 Terrestrial Biofuels

For some applications, biomass as it is produced in solar energy conversion may be used as such. This applies, for instance, to the generation of electricity, which in turn may be used for electrical traction. However, diesel or Otto motors or fuel cells need the use of specific biochemicals (transport biofuels) such as specific alcohols and acylesters, as discussed in Chap. 1. This has an impact on the efficiency of solar conversion. Only a part of the biomass originating in solar energy conversion can be turned into such chemicals. It may be that part of the biomass that cannot be con-

Table 2.1 Solar energy to biomass conversion efficiencies, with correction for fossil fuel inputs

Insolation (MJ/day m^2)	Crop under good conditions (unless otherwise indicated)	Yield of biomass ha^{-1} (Mg dry weight/year); aboveground except for sugar beet	Energy content biomass (lower heating value in MJ/kg dry weight)	Correction factor for fossil fuel input (MJ in crop – MJ fossil fuel input/MJ in crop)	Solar energy conversion efficiency (%)
19	Sugar cane (average)	36.8 (Kheshgi et al. 2000)	17.5	0.97 (Dias de Oliveira et al. 2005)	0.9
19	Oil palm	20 (fruit bunches)	31.7	0.95 (Reijnders and Huijbregts 2003)	0.87
19	*Eucalyptus*	10–20	19	0.9 (estimate)	0.25–0.50
14	Wheat	10–11	17.5	0.8 (von Blottnitz and Curran 2007)	0.27–0.30
14	Switchgrass	10–15	17.5	0.95 (estimate)	0.32–0.48
14	Sugar beet	20	17	0.9 (von Blottnitz and Curran 2007)	0.62
14	Corn	17–18	17.5	0.8 (von Blottnitz and Curran 2007)	0.46–0.49
14	Rapeseed/Canola	4–5	21.8	0.9 (Zah et al. 2007)	0.15
14	*Miscanthus*	10–13	17.5	0.98 (Lewandowski and Schmidt 2006)	0.34–0.44
14	Poplar	9.5 (Kheshgi et al. 2000)	19.8	0.98	0.36
14	Wood grown sustainably in Western Russia (Nabuurs and Lioubimov 2000)	1.4	19.8	0.95 (Reijnders and Huijbregts 2003)	0.05

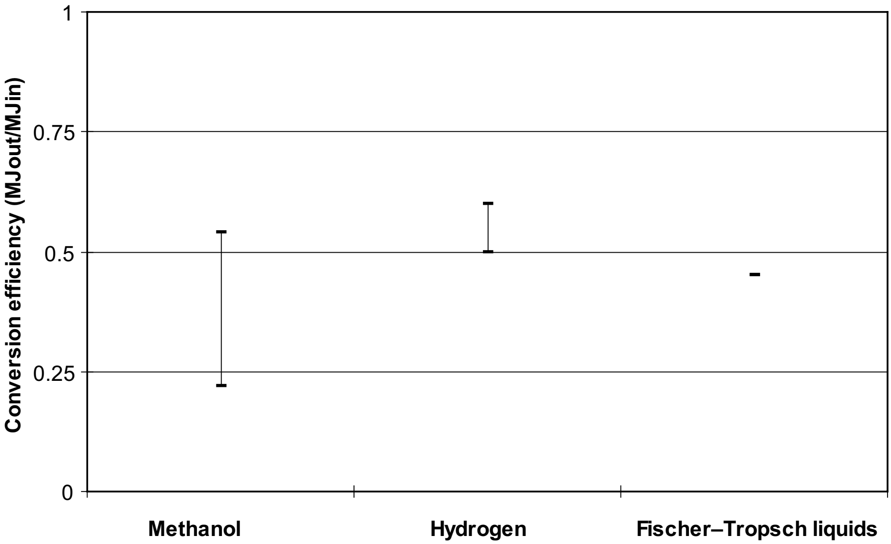

Fig. 2.1 Estimated biomass to transport biofuel conversion efficiencies via synthesis gas (Chum and Overend 2001; Ptasinki et al. 2002; Iwasaki 2003; Faaij 2006)

verted into the biochemicals needed is used to power the production from biomass of specific biochemicals. It may also be that a part of the original biomass emerges from processing as waste. Furthermore, in many processes generating biochemicals from biomass, there is an input of fossil fuels that is to be taken into account when determining overall conversion efficiencies. Figure 2.1 gives estimated efficiencies for some conversions of biomass into transport biofuels.

Table 2.2 shows solar conversion efficiencies for a number of biofuels from terrestrial plants. In this case, the allocation has been done on the basis of energy content of marketable products.

The efficiencies in the last column of Table 2.2 are typically lower than the efficiencies shown in Table 2.1. Most of them are below 0.2%. For ethanol from European wheat starch, the efficiency is 0.024–0.03%, and for biodiesel from European rapeseed, it is approximately 0.034%. Apart from *Jatropha*, which has quite an uncertain conversion efficiency, the best efficiency in Table 2.2 is for ethanol from switchgrass, with ethanol from sugar cane coming second. However, it was assumed in this table that in the case of sugar cane, only sugar is to be converted into ethanol. If also a substantial part of the lignocellulosic aboveground biomass of sugar cane is converted into ethanol, sugar cane may as efficient as or better than switchgrass.

Table 2.2 Efficiency of solar energy conversion into specific biochemicals, when corrected for fossil fuel inputs and when allocation is based on prices

Crop/Process	Insolation (MJ day^{-1}/m^2)	Fuel	Yield of biofuel ha^{-1} (Mg/year)	Heat of combustion of biofuel (MJ/kg)	MJ biofuel – MJ fossil fuel input/MJ biofuel	MJ biofuel – MJ fossil/MJ crop	Solar energy conversion efficiency (%)
Oil palm	19	Palm kernel oil		40	0.7–0.9 (Reijnders and Huijbregts 2008a; de Vries 2008)		~ 0.15 (Reijnders 2008)
Sugar cane	19	Ethanol		26.4			0.16 (Kheshgi et al. 2000)
Wheat (Europe)	14	Ethanol	1.65 (from starch)	26.4	0.2–0.25 (Somerville 2007)		0.024–0.03
Switchgrass to be processed to ethanol	14	Ethanol	15	26.4	0.25 (Fleming et al. 2006; Champagne 2007)		0.2
Jatropha	19	Oil	0.65–5 (Fairless 2007; van Eijck and Romijn 2008)	40	0.9 or lower		0.035–< 0.26
Switchgrass	14	Fischer–Tropsch diesel	15	44		0.14 (Somerville 2007)	0.18
Wood from trees	14	Methanol generated by dry distillation	0.04 (Reinharz 1985)	19.8			0.0015
Wood (Europe)	14	Fischer–Tropsch diesel	1.4	44		0.12–0.33 (Huber et al. 2006)	0.014–0.039
Rapeseed	14	Biodiesel	1.15 (oil, before transesterification)			0.4 (Reijnders and Huijbregts 2008b)	0.034

2.4.3 Biofuels from Algae and Aquatic Macrophytes

As also pointed out in Chap. 1, estimates have been made of the maximum efficiency for the conversion of incident sunlight into biomass by algae. These vary between 5.5 and 11.6% (Heaton et al. 2008b; Vasudevan and Briggs 2008). Several authors have suggested that algal transport biofuels can beat terrestrial transport biofuels in the conversion of solar energy to transport biofuel by at least one order of magnitude (e.g. Chisti 2007; Chisti 2008a; Groom et al. 2008; Nowak 2008; Li et al. 2008). Here we will survey the suggestions that have been made for producing transport biofuels from algae and aquatic macrophytes and what is known about the solar energy conversion efficiency of such biofuels.

Transport Biofuels from Marine Aquatic Biomass

As pointed out in Chap. 1, a variety of options for producing biofuels from marine biomass have been suggested, such as biofuels from *Macrocystis pyrifera* or giant kelp (Wilcox 1982; Bungay 2004), *Laminaria* (Horn et al. 2000; Chopin et al. 2001) and *Dunaliella* (Ben-Amotz et al. 1982). *Dunaliella* has been found more suitable to cultivation in open ponds (Joint et al. 2002; Ugwu et al. 2008). As to *Macrocystis pyrifera,* it seems doubtful whether the energy balance for biofuel can be positive (Bungay 2004).

Near-shore cultivation of macroalgae is substantial (Neushul and Wang 2000; Wikfors and Ohno 2001; Chopin et al. 2001; Critchley et al. 2006; Troell et al. 2006). For *Gracilaria* in Taiwanese coastal waters, average yields of 4 Mg ha^{-1} $year^{-1}$ (dry weight) have been reported (van der Meer 1983). Yields of commercial *Eucheuma* cultivation in the Philippines, Indonesia and Kiribati are about 6 Mg (dry weight) ha^{-1} $year^{-1}$ (Ask and Azanza 2002). Such yields suggest relatively low solar energy conversion efficiencies if compared with cultivated terrestrial plants (see Table 2.1). Cultivation is vulnerable to invasions of competing algae and herbivores, and major interventions may be necessary to limit losses in such cases (Buschmann et al. 2001; Ask and Azanza 2002; Neill et al. 2006). As pointed out in Chap. 1, prices for cultivated macroalgae are high, and thus it is hard to see the emergence of a practical large-scale biomass-from-the-sea-for-transport-fuel scheme based on macroalgae cultivation (Neushul and Badash 1998; Buschmann et al. 2001).

Microalgal Biomass in Ponds and Bioreactors

Most proposals for microalgal biofuels from open ponds or bioreactors focus on biodiesel made from algal oil (Scragg et al. 2002; Chisti 2007; Huntley and Redalje 2007; Wijffels 2008; www.oilgae.com; Liu et al. 2008). However, there have, for instance, also been proposals to convert algal biomass into methanol via synthesis gas or into bio-oil via pyrolysis (Hirano et al. 1998; Sawayama et al. 1999). The alga *Botryococcus braunii* has been looked into, in view of its ability to produce substantial amounts of hydrocarbons, which may be turned into transport biofuels by catalytic cracking (Bachofen 1982; Banerjee et al. 2002). As pointed out in Chap. 1, current strains of this microalga are slow growing, which has not been conducive to its application (Banerjee et al. 2002).

Of the microalgae commercially grown in open ponds, *Spirulina* apparently has the best yields per hectare per year in commercial cultivation (Belasco 1997). Maximum productivities in open ponds are achieved under tropical or subtropical conditions (Jiménez et al. 2003). Yields currently obtained in industrial facilities for the cultivation of *Spirulina* located in these regions range from 10 to 30 Mg dry biomass per hectare per year (Vonshak and Richmond 1988; Jiménez et al. 2003). Low yields of, for example, *Spirulina* may however occur due to, for example, phage infections and rainfall conducive to the growth of unfavourable organisms (Shimamatsu 2004). For instance, Li and Qi (1997) reported that the 80 Chinese *Spirulina* production plants had production on average of 3.5 Mg ha^{-1} $year^{-1}$.

It may be that in the future, microalgal yields from raceway ponds may be increased over current levels, for instance through improving photosynthetic activity by minimizing light harvesting chlorophyll antenna size (Neidhardt et al. 1998; Mussgnug et al. 2007). On the other hand, a focus on algal lipids for transport biofuel production may well lead to biomass yield limitations, because nutrient limitations are conducive to high lipid contents but not to maximizing biomass yield (Wijffels 2008; Liu et al. 2008).

Hirano et al. (1998) studied *Spirulina* production and processing to supply methanol (via synthesis gas) and assumed a yield of approximately 110 Mg ha^{-1} $year^{-1}$. When both fossil fuel inputs in infrastructure and operation are considered, this would correspond with an overall solar energy to biofuel conversion efficiency of about 0.12%.

Actual yearly yields much exceeding 30 Mg ha^{-1} $year^{-1}$ have been claimed for microalgae growing in water that has been saturated in CO_2 (Kheshgi et al. 2000; Wang et al. 2008). Algal ponds that are to be saturated in CO_2 have been proposed to capture the CO_2 of power plants (Kheshgi et al. 2000). Also, closed bioreactors have been proposed for algal capture of CO_2 from power plants (Skjånes et al. 2007). The efficiency of algal CO_2 capture in open ponds has been estimated to be in the order of 30% (Benemann 1993; Kadam 2002), whereas an efficiency of 40% has been suggested for algae in photobioreactors (Ono and Cuello 2006). Whether such percentages can be achieved is not certain. Yields from open ponds saturated with CO_2 have proved disappointing, and maintaining desired algal cultures in such ponds has turned out to be difficult (Benemann et al. 2003). There is also the matter of the efficiency of CO_2 sequestration by algae. The suggested efficiency for photobioreactors of 40% is, for instance, higher than efficiencies so far reported by Hsueh et al. (2007) and Jacob-Lopes et al. (2008) for flue gases with high concentrations of CO_2 handled by photobioreactors. Moreover, the latter efficiencies were achieved under good irradiation, whereas the CO_2 emission of power plants may also occur at night and when solar irradiation is poor. CO_2 capture and sequestration (CCS) in aquifers or abandoned natural gas or oil fields would be able to reduce the emission of power plants with an efficiency of about 90% (Odeh and Cockerill 2008). Thus, whether the application of CO_2 capture by algae will be important in the future depends to a large extent on the emission requirements for such plants.

Microalgal yields from closed bioreactors subject to solar irradiation may be much higher than from current commercial open ponds (Eriksen 2008). For the production of algal oil, a value of about $16\,Mg\,ha^{-1}\,year^{-1}$, has been suggested as 'possible with state of the art technology' in closed systems (Wijffels 2008). However, growing algae aiming at high outputs in bioreactors requires large inputs of energy for building the reactors and for nutrients and intensive mixing. It has been estimated that this could lead to a negative energy balance for flat panel bioreactors and an even more negative energy balance for tubular bioreactors (Wijffels 2008).

H_2 Produced by Microalgae

The use of a variety of algae has been considered because of their direct and indirect biocatalytic effect on the splitting of water in H_2 and O_2 (Melis and Happe 2001; Hallenbeck and Benemann 2002; Nath and Das 2004; Savage et al. 2008). In spite of a nearly 70-year history of research, actual production of H_2 by algal systems is still very low, about 2 g of H_2 per square metre of culture area per day (Melis and Happe 2001), and H_2 has to be withdrawn continually as the overall conversion of glucose into H_2 is energetically only slightly favourable to H_2 (Savage et al. 2008). At realistic solar irradiation, solar conversion efficiencies in optimized systems for direct and indirect biophotolysis seem to be in the order of 1% or lower, when pure cultures can be maintained (Hallenbeck and Benemann 2002; Yoon et al. 2006; Rupprecht et al. 2006; Burgess and Fernández-Velasco 2007). And as pointed out before, the cumulative energy demand for algal H_2 production is probably of the same order of magnitude as the energetic output, when the solar energy conversion efficiency does not exceed 1% (Burgess and Fernándo-Velasco 2007).

Freshwater Macrophytes

The best-studied macrophyte is the water hyacinth (*Eichhornia crassipes*) (Gassmann et al. 2006; Gunnarsson and Petersen 2007). It has been found to produce up to $140\,Mg\,ha^{-1}\,year^{-1}$ of biomass (dry weight) (Gunnarsson and Petersen 2007). Two energetic applications of *Eichhornia crassipes* which may produce transport biofuels have been studied. The first is ethanol production from hemicellulose present in water hyacinths. A yield of 0.14–0.17 (g ethanol) (g dry weight)$^{-1}$ has been reported (Mishima et al. 2008). However, studies of the overall energy efficiency of the production of ethanol from the water hyacinth have so far suggested that the energy balance is negative (Gunnarsson and Petersen 2007). An alternative option is the anaerobic conversion of water hyacinth biomass into CH_4. Though the feasibility thereof has been demonstrated, the process is complicated, among other things by the floating behaviour of water-hyacinth-derived material (Malik 2007). Moreover, the water hyacinth is very effective in adsorbing pollutants (Gunnarsson and Petersen 2007; Malik 2007), and these may interfere with, for example, the sustainable use of residuals ('digestate') remaining after anaerobic conversion. More limited research has been done regarding another invasive macrophyte: water lettuce (*Pistia stratiotes* L.), which has growth characteristics similar to water hyacinth (Mishima et al. 2008). The yield of ethanol from hemicellulose conversion is 0.15–0.16 g per gram of dry weight (Mishima et al. 2008); no study has been found regarding the overall energy efficiency of this conversion.

2.5 Solar Conversion Efficiencies of Physical Methods

Besides biological processes, there are also physical conversion processes for solar energy. Efficiencies for a number of physical methods of converting solar radiation into heat, H_2 or electricity are in Table 2.3. It can be seen that solar conversion efficiencies of photovoltaic cells are much higher than the conversion efficiencies for the transport biofuels in Table 2.2.

Table 2.3 Efficiencies for the conversion of solar radiation to electricity or heat

Type of conversion	Output	Conversion efficiency	Correction factor for fossil fuel input into conversion apparatus (MJ output – fossil fuel input/MJ output)	Overall energy efficiency (%)
Photovoltaic silicon (Mohr et al. 2007; Fthenakis et al. 2008)	Electricity	~14	0.75–0.8	~10.5–12
Hybrid photovoltaic silicon/collector	Electricity/heat	15% (electricity) +40% heat (He et al. 2006; Tripanagnostopoulos et al. 2006)	0.9–0.95	49.5–52
Photovoltaic III–V	Electricity	15–30 (Green et al. 2003)	0.8–0.9 (dependent on insolation) (Meijer et al. 2003; Mohr et al. 2007)	12–27
Solar thermal electricity turbine	Electricity	10–28% (Mancini et al. 1994)	0.93 (Norton et al. 1998)	9.5–26.5

2.6 Overall Energy Efficiencies in Performing Work

Table 2.4, finally, shows overall estimated conversion efficiencies for solar irradiation to car kilometres, corrected for the input of fossil fuels, which are calculated by

$$TSCE_{x,i} = SCE_x \cdot CE_{x,i}$$

where $TSCE_{x,i}$ is the transport solar energy conversion efficiency (%) and $CE_{x,i}$ the efficiency drive train of transport option i derived from biofuel type x (%).

According to the estimates in Table 2.4 regarding seed-to-wheel solar energy conversion efficiency, ethanol from sugar cane outperforms ethanol from European wheat by about a factor of five to ten, and biodiesel from European rapeseed by about a factor of two to three. Electrical traction from lignocellulosic biomass, how-

Table 2.4 Overall efficiencies for the conversion of solar energy to car kilometres

Type of energy supply	Conversion efficiency solar radiation to automotive power source, corrected for fossil fuel inputs (%); see Tables 2.2 and 2.3	Efficiency drive train (%)	Overall efficiency energy storage (%)	Overall efficiency conversion solar radiation to automotive kilometres (%)
Ethanol from sugar cane (Brazil) for Otto motor	0.16	16–22 (Colella et al. 2005; Crabtree et al. 2004)		0.026–0.035
Ethanol from wheat (Europe) for Otto motor	0.024–0.03	16–22 (Colella et al. 2005; Crabtree et al. 2004)		0.0038–0.0066
Biodiesel from rapeseed (Europe) for diesel motor	0.034	29 (www.eere.energy.gov/vehiclesandfuels)		0.010
Electricity from lignocellulosic biomass (switchgrass) for electromotor	0.48	90–97 (Ahluwalia et al. 2005; Colella et al. 2005)	41–90 (Rydh and Sandén 2005)	0.18–0.42
Electricity from solar cells for electromotor	10.5–12	90–97 (Ahluwalia et al. 2005; Colella et al. 2005)	41–90 (Rydh and Sandén 2005)	3.9–10.5

ever, in turn outperforms ethanol from sugar cane by roughly a factor of two to four. The relatively high efficiency of using biomass for electricity production has also been noted by other authors, such as Zhang et al. (2007). All biomass-based automotive power is, however, far less efficient than electricity from solar cells that is stored for use in electrical traction. This way of powering motor cars is roughly at least two orders of magnitude better than ethanol from Brazilian sugar cane and three orders of magnitude better than ethanol from European wheat. In calculating the values for Table 2.4, it has been assumed that solar cells and the plug-in facility for cars are in the same region. When distances are large or conversion to H_2 is necessary for long distance transport, the efficiency will be lower than indicated in Table 2.4 because of transport-linked losses. For instance, an estimate has been made regarding the life cycle emission of greenhouse gases linked to electrolysis powered by concentrated solar power (CSP) in the Sahara, liquefaction of H_2 and transport to, and distribution of, hydrogen in Western Europe. In such a case, a reduction of the life cycle efficiency by somewhat less than 10% has been found (Ros et al. 2009). Such a reduction applied to electricity from solar cells (last row of Table 2.4) would reduce the overall efficiency in the last column to approximately 3.5–9.4%.

A lesson from this chapter is that conversions lead to substantial reductions in solar conversion efficiency. In Chap. 1, quite a number of proposals have been summarized that rely on such conversions. Examples are: the conversion of methane (from the anaerobic conversion of biomass) to methanol, the conversion of lipids and ethanol to hydrocarbons or H_2 and the conversion of methanol to hydrocarbons. As the starting products may in principle be used directly as transport biofuels, there is good reason to be sceptical about such sequential conversions in view of the negative impact that they have on the overall solar energy conversion efficiency.

The data presented in this chapter allow for estimates of the ability of biofuels to energetically displace fossil fuels. It appears that in this respect, palm oil and ethanol from sugar cane do much better, especially when processing is powered by harvest residues, than rapeseed oil or ethanol from corn or wheat, as produced in industrialized countries. It should be noted, though, that the ability to energetically displace fossil fuels may be at variance with their ability to do so in the economy. The latter is strongly impacted by prices and government policy. An interesting illustration thereof concerns the use of corn-derived ethanol in US gasoline, which has mainly been by E10 fuels, containing 10% ethanol and 90% conventional gasoline. The use of E10 fuels has been stimulated by a federal excise tax which in recent years led to E10 gasoline being cheaper than conventional gasoline (Tyner 2008; Vedenov and Wetzstein 2008), which in turn had an upward effect on the overall consumption of gasoline, thereby partly negating the downward effect of ethanol use on the consumption of conventional gasoline (Vedenov and Wetzstein 2008).

The data in this chapter also allow for estimates of land requirements linked to a large-scale displacement of fossil transport fuels by biofuels. This may be illustrated by the following back-of-the-envelope calculation. As explained in Chap. 1, mineral oil is the dominating fossil fuel for powering transport, and about 60% of all crude oil is used for this transport. Let us suppose that all mineral oil that is currently used as an input in worldwide transport were to be replaced by vegetable oil. Corrected for the difference in lower heating value between crude oil and vegetable oil (see Table 1.2) and the cumulative fossil fuel input into vegetable oil (estimated here at 40% of the energetic value of vegetable oil), this would require an increase of vegetable oil production by about a factor of 37.5. Part of this increase may be met with the increase of yields per hectare. Estimates made for the 23 most important food crops suggest that such an increase may range from 0.63–1.76% $year^{-1}$ for developing countries and from 0.59–0.79% $year^{-1}$ for developed countries up to 2050 (Balmford et al. 2005), to a large extent by intensification of cropping (Tilman et al. 2001). Using intermediate values, this would allow for an increase in yield by a factor of approximately 1.75 for developing countries and by a factor of approximately 1.42 for developed countries between 2000 and 2050 (Balmford et al. 2005), far below the factor of 37.5 needed to displace all mineral oil by vegetable oil. Moreover, it may well be that the average productivity of additional land is lower than that of land currently in use. Thus, even if yield increases in the future would be much larger than currently estimated, there would seem no way around large additional land requirements linked to large-scale displacement of fossil fuels by biofuels. Current policy targets are estimated to require between 55 and 166 million ha (Mha) (Renewable Fuels Agency 2008).

Moreover, expanding transport may well lead to even larger land claims in the future. Gurgel et al. (2007) studied an expansion of the production of cellulosic biofuel to supply up to 368 EJ in 2100. This, according to their scenario, would require about 2.5×10^3 Mha, an amount greater than any other land cover category. For comparison: worldwide, current cropland is about 1.6×10^3 Mha, and the land area that is currently considered fit for additional cropland is estimated at between 400 and approximately 1.2×10^3 Mha (Renewable Fuels Agency 2008).

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