Chapter 8
Biofuels from Microalgae: Biodiesel

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Abstract It has been argued that the energy output from microalgal biofuel production should at least be 5–8 times the energy input, apart from solar irradiation driving algal photosynthesis. There is as yet no commercial production of microalgal biodiesel or large-scale demonstration project to check whether this criterion regarding the energy balance can be met in actual practice. There is, however, a set of relatively well-documented peer-reviewed scientific papers estimating energy inputs and outputs of future autotrophic microalgal biodiesel production. Energy balances for biodiesel from autotrophic microalgae grown in ponds tend to be better than for biodiesel from such microalgae grown in bioreactors. The studies regarding energy balances for biodiesel derived from microalgae grown in open ponds are considered here. None of these energy balances meets the criterion that the energy output should exceed the energy input by a factor 5–8. Estimated energy balances are variable due to divergent assumptions about microalgal varieties, applied algal and biodiesel production technologies, assumed parameters and yields and due to differences in system boundaries, allocation, and the use of credits. The studies considered here could have done better in handling uncertainties in estimated energy balances.

Keywords Biodiesel · Energy balance · Variability · Uncertainties

1 Introduction

'Microalgal biodiesel' is used here in the narrow sense: methanol- (or ethanol-) esters of microalgal fatty acids, obtained by the transesterification of triglycerides (oil) from autotrophic microalgae. To qualify as a fuel of good quality, the biodiesel

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derived from microalgal fatty acids has to be upgraded, which includes hydrogenation of unsaturated fatty acids (Reijnders 2017b).

The energy balance is defined here as energy generated by microalgal biodiesel divided by the energy input in its cradle to gate production, apart from solar irradiation driving algal photosynthesis. Energy balances can be calculated or estimated on the basis of cradle to gate life cycle assessments (see Chap. 6).

An energy balance is an important characteristic of microalgal biofuels. Chisti (2013a, b) has argued that the energy balance of algal biofuels should preferably have a value of at least 7 or 8. Reijnders (2013) has proposed an energy balance of at least 5 if the biofuel is to make a major contribution to future energy supply. These are not extreme requirements for types of energy supply derived from solar energy. For instance, recent mean cradle-to-grave energy balances for photovoltaic solar energy are >8 (Koppelaar 2017).

There is as yet no commercial production of autotrophic microalgal biodiesel or large-scale demonstration project to check whether criteria regarding the energy balance can be met in actual practice. There is, however, a set of relatively well-documented peer-reviewed scientific papers estimating energy inputs and outputs of future autotrophic microalgal biodiesel production (see Table 1). These studies are considered here. In the absence of large-scale commercial or demonstration projects and in view of limited knowledge about technologies that will actually be applied in the future, estimates of energy balances for future microalgal biofuel production may well be relatively variable and characterized by relatively large uncertainties (Reijnders and Huijbregts 2009; Colotta et al. 2016a). Variability in estimated energy balances partly originates in choices regarding microalgal varieties, production processes, process parameters, and physical output and input data (e.g., Sills et al. 2012; Naraharisetti et al. 2017). Other choices too matter significantly to energy balances estimated by life cycle assessments. These choices in part regard valuation of physical inputs. For example, flue gas, derived from fossil fuel burning and used for the production of microalgal biodiesel, may be energetically valued at zero but may also be energetically valued in positive or negative terms (Reijnders and Huijbregts 2009). Furthermore, choices as to system boundaries matter (Reijnders 2017a, b). System boundaries demarcate what is included and what is excluded in life cycle assessment. For instance, the production of water inputs and of capital goods, upgrading biodiesel, and biodiesel production wastewater treatment can in practice be included or excluded in life cycle assessments of microalgal biodiesel (Reijnders 2013, 2017b). Furthermore, there is usually more than one output from biofuel production processes. The life cycle energy inputs should be allocated to all outputs. This can be done in several ways. Allocation can take place on the basis of monetary units (prices), on the basis of physical units (energy, exergy, mass) or on the basis of substitution (embodied energy of a similar output). Different types of allocation may lead to significantly different outcomes of life cycle assessments (Reijnders 2017a). It may be noted that allocation to outputs may also be associated with additional uncertainties. For instance, allocations based on prices tend to use current prices, but these are not necessarily the same as future prices. Also, in the case of allocation by substitution, microalgal meal (one of the potential outputs of biodiesel production) has been considered a substitute for soybean meal (Maranduba et al. 2016). The equivalence of algal meal and soybean meal has however not been proven. Choices regarding the valuation of inputs, system boundaries, and allocation to outputs should be explicitly stated. It would moreover be preferable to include in assessments a sensitivity analysis indicating the impact of different choices on estimated energy balances ('scenario uncertainty'; Huijbregts et al. 2003).

There are two basic options for cultivating autotrophic algae: in open ponds and in closed bioreactors. These options can be used singly, but hybrid systems involving both bioreactors and open ponds have also been proposed (Khoo et al. 2011; Adesanya et al. 2014; Huntley et al. 2015). Published comparative life cycle studies suggest that biodiesel from microalgae cultivated in open ponds tends to have a better energy balance than biodiesel from microalgae cultivated in bioreactors (e.g., Stephenson et al. 2010; Clarens et al. 2011; Slade and Bauen 2013; Hallenbeck et al. 2016; Monari et al. 2016; Togarcheti et al. 2017). Moreover, costs of microalgal biodiesel from bioreactors are likely to be higher than the costs of microalgal biodiesel from open ponds (e.g., Dutta et al. 2016; Hallenbeck et al. 2016). For these reasons in the next sections, the focus will be on open pond-based cultivation systems for microalgae.

Table 1 Peer-reviewed life cycle assessments of energy balances associated with biodiesel derived from microalgae grown in open ponds

Authors	Estimated cradle–to-gate energy balance
Lardon et al. (2009)	<2
Batan et al. (2010)	~1
Brentner et al. (2011)	<1
Clarens et al. (2011)	<4.1
Khoo et al. (2011)	<1
Razon and Tan (2011)	<1
Shirvani et al. (2011)	<1
Xu et al. (2011)	<3
Sills et al. (2012)	<3
Frank et al. (2012)	<2
Quinn et al. (2014)	<2
Mu et al. (2014)	<2
Adhikari and Pelegrino (2015)	<1
Orfield et al. (2015)	<2
Yuan et al. (2015)	<2
Dutta et al. (2016)	<2
Crowdhury and Francetti (2017)	<3
Naraharisetti et al. (2017)	<2

2 Estimated Energy Balances

The set of relatively well-documented peer-reviewed estimates of energy balances for biodiesel derived from microalgae grown in open ponds is summarized in Table 1.

This table shows that in none of the studies considered here estimated energy balances met the criterion of a factor 5–8. As furthermore can be seen in Table 1, the variability of published energy balances for microalgal biodiesel is large (also: Quinn et al. 2014). In the following, several important causes of this variability are discussed. These regard assumptions about biomass yield and allocation and the combinations with wastewater treatment and power plants fueled by carbonaceous substances. Thereafter, the handling of uncertainties is considered.

3 Combining Microalgal Biodiesel Production with Wastewater Treatment

In studies considered here, relatively good (high) energy balances tend to be obtained when wastewater containing microalgal nutrients is used for cultivation. So far, the use of wastewater for microalgae cultivation has only been subject to small-scale investigations (Laurens et al. 2017). In the life cycle assessments considered here, the use of wastewater containing nutrients has been handled in a variety of ways. Firstly, it can be assumed that the cultivation of microalgae substitutes for conventional wastewater treatment. Based on this assumption, the input energy for conventional wastewater treatment is then subtracted from the cradle-to-gate microalgal biodiesel production (e.g., Clarens et al. 2010; Mu et al. 2014; Chowdhury and Franchetti 2017). Such subtraction does not take account of the limitations to algal purification of wastewater. For instance, wastewater tends to contain relatively large organic molecules, which cannot be metabolized by currently applied microalgae (Perez-Garcia et al. 2011). Furthermore, wastewater may well contain pathogens, predatory zooplankton, and microorganisms that might outcompete microalgae (Pittman et al. 2011; Cai et al. 2013). For this reason, wastewater may need treatment (e.g., sterilization) to minimize infection risk. Energy needed for such treatment has not been included in the life cycle assessments considered here.

In addition, or alternatively, to energy credits associated with the substitution of conventional wastewater treatment, it can be assumed that the nutrients in wastewater substitute for the inputs of synthetic nutrients and that the energy input of these nutrients present in wastewater can be valued at zero. It can be assumed too that the treatment of wastewater from microalgal biodiesel production is not within the system boundaries of life cycle assessment. Exceptions regarding the latter assumption are the studies of Lardon et al. (2009) and Clarens et al. (2011). The assumptions outlined here are contestable. One might argue from an industrial ecology perspective that nutrients derived from wastewater should have an energy value >0, as they are apparently useful for microalgal biodiesel production. Furthermore, when the substitution of conventional wastewater treatment is *within* the system boundaries, there would appear to be no good case for keeping wastewater treatment of effluents from microalgal biodiesel production, which should at least serve the recycling of nutrients (Laurens et al. 2017), *outside* the system boundaries (Stephenson et al. 2010; contrast, e.g., Mu et al. 2014). The same would appear to hold for treatment of wastewater (e.g., sterilization) to minimize infection risk for microalgal cultivation.

Furthermore, it should be noted that so far the autotrophic algal productivity of triglycerides in wastewater has been found to be low, that the supply of wastewater is unlikely to allow for producing large amounts of algal triglycerides, and that by-product usage may be problematical due to the presence of hazardous substances and pathogens (Rawat et al. 2016; Luangpipat and Chisti 2017).

4 Combination of Microalgal Biodiesel Production with Co-located Power Plants Fueled by Carbonaceous Substances and Cement Plants

Combinations of cultivating microalgae with co-located power plants (e.g., Colotta et al. 2016b) can be conducive to good energy balances if ‘wastes’ of power plants (flue gas, ‘waste’ heat) can be used as inputs in microalgal biodiesel production at an assumed zero energy value, apart from energy input needed for the transport of ‘wastes’ (e.g., Brentner et al. 2011; Clarens et al. 2011; Xu et al. 2011; Yuan et al. 2015). A similar assumption may be made for the use of CO_2 from co-located cement plants that generate CO_2 from calcium carbonate (Colotta et al. 2016b). The assumption that inputs of such ‘wastes’ may be energetically valued at zero energy input is contestable. From an industrial ecology perspective, one might argue that ‘wastes’ should have an energy value >0, as they are apparently useful for microalgal biodiesel production. On the other hand, one may argue from a cost perspective in favor of an energy credit (negative energy input) for using ‘waste’ CO_2 in microalgae cultivation as the use of flue gas may lower external costs.

It may furthermore be noted that algae can only capture a modest fraction of the flue gas emitted by power plants (Benemann 2013). The co-location with power and cement plants will severely limit the geographical scope for algal cultivation. And future power production may well shift away from burning carbonaceous fuels.

5 Assumptions About Algal Biomass Yields and Allocation

Relatively good energy balances can be achieved in studies considered here when it is assumed that biomass and lipid yields are high, with biomass yields in the order of 90 Mg ha^{-1} $year^{-1}$ or larger (Slade and Bauen 2013; Rogers et al. 2014; Naraharisetti et al. 2017). Such biomass yields are well beyond current yields in commercial cultivation of autotrophic microalgae (Reijnders 2013; Rawat et al. 2016). Whether such high yields can be achieved in future widespread commercial practice is questionable (Reijnders 2017b). A major problem for open pond cultures is the contamination with other organisms, which can lead to instability of microalgal cultivation (Rodolfi et al. 2008). This may be prevented by growing microalgae under extreme conditions such as high pH or high salt concentrations. But these conditions are not conducive to high triglyceride yields (Reijnders 2017b). And there may be problems in maintaining extreme conditions of cultivation given the vagaries of weather, such as extreme rainfall (Reijnders 2013; Chisti 2016).

On the other hand, relatively poor energy balances may be achieved when part of the outputs is considered wastes and all of the energy input is allocated to non-waste outputs (e.g., biodiesel, biogas). This is at variance with the view that mature biodiesel production systems should be designed in such a way that practically all microalgal biomass should be converted to useful outputs (e.g., Xu et al. 2011; Laurens et al. 2017).

Relatively good energy balances may be achieved when biodiesel is a product of a production facility also generating currently highly priced co-products, when the allocation is on the basis of current prices. A focus on such co-products can be noted in the current development of microalgal bioenergy (Chew et al. 2017; Laurens et al. 2017). In the case of allocation based on prices, one should evaluate what future developments in input and output prices and the impact thereof on estimated energy balances may be (cf. Kern et al. 2017). This type of evaluation has not been included in the LCAs considered here. In view of recent history, one should especially consider whether high co-product prices will be maintained when production is much increased. The price of the biodiesel co-product glycerol collapsed when the production of biodiesel based on oils from terrestrial plants was much increased (Reijnders and Huijbregts 2009).

6 Handling Uncertainties

In the introduction, it has been noted that it would be preferable to include in assessments a sensitivity analysis indicating the impact of different choices regarding the valuation of inputs, system boundaries, and allocation to outputs on estimated energy balances (‘scenario uncertainty’). This type of sensitivity analysis is uncommon in the studies considered here. An exception in this respect is the study of Razon and Tan (2011). An important source of uncertainty regards future technologies, process parameters, physical inputs and outputs. The studies discussed here often considered examples of such uncertainties (e.g., Stephenson et al. 2010; Brentner et al. 2011; Clarens et al. 2011; Shirvani et al. 2011; Sills et al. 2012; Frank et al. 2012; Quinn et al. 2014; Yuan et al. 2015; Naraharisetti et al. 2017). Relatively good studies of uncertainty linked to process parameters would seem to be the studies of Clarens et al. (2011) and Sills et al. (2012) that included Monte Carlo analysis to quantify the role of uncertainty of parameters in determining the estimates of energy balances.

If compared with published methodologies for handling uncertainty in life cycle assessment (cf. Huijbregts et al. 2003; Gregory et al. 2016), the studies considered here could have done better in dealing with uncertainties.

7 Concluding Remarks

The peer-reviewed energy balances for microalgal biodiesel discussed here do not meet the criterion that the energy output should exceed the energy input by a factor 5–8. It would seem extremely likely that this would still be the case when defensible choices regarding yields, allocation, valuing the use of wastewater, and co-location with power plants would have been different as noted in this chapter. This is not favorable to a near-term widespread use of microalgal biodiesel. Moreover, microalgal biodiesel has a high near-term cost if compared with biofuels from terrestrial plants (Wijffels and Barbosa 2010; Jez et al. 2017; Zhu et al. 2017). The conclusion must be that the near-term outlook for widespread use of microalgal biodiesel is bleak (also: Chisti 2013a).

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