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Energy Balance of Biogas Production from Microalgae: Effect of Harvesting Method, Multiple Raceways, Scale of Plant and Combined Heat and Power Generation

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Abstract: A previously-developed mechanistic energy balance model for production of biogas from the anaerobic digestion of microalgal biomass grown in open raceway systems was used to consider the energetic viability of a number of scenarios, and to explore some of the most critical parameters affecting net energy production. The output demonstrated that no single harvesting method of those considered (centrifugation, settlement or flocculation) produced an energy output sufficiently greater than operational energy inputs to make microalgal biogas production energetically viable. Combinations of harvesting methods could produce energy outputs 2.3–3.4 times greater than the operational energy inputs. Electrical energy to power pumps, mixers and harvesting systems was 5–8 times greater than the heating energy requirement. If the energy to power the plant is generated locally in a combined heat and power unit, a considerable amount of "low grade" heat will be available that is not required by the process, and for the system to show a net operational energy return this must be exploited. It is concluded that the production of microalgal biogas may be energetically viable, but it is dependent on the effective use of the heat generated by the combustion of biogas in combined heat and power units to show an operational energy return.

Keywords: microalgae; algae; bioenergy; biogas; anaerobic digestion; energy balance

1. Introduction

The potential of microalgal biomass as a source of liquid and gaseous biofuels has been a highly topical issue in the past few years [1]. One common measure of the real or potential performance of a biofuel production system is the energy return on energy investment (EROEI or EROI), which is the ratio of the energy produced compared to the amount of energy invested in its production [2]. This "simple" ratio is useful in assessing the viability of fuels [3], and has been described as central to the evaluation of all biofuels [4]. A ratio of less than one indicates that more energy is used than is produced, and an EROI of 3 has been suggested as the minimum that is economically viable [5].

The relatively high lipid content of some microalgae has focused much of the published research work on the production of biodiesel from the microalgal lipids via trans-esterification [6–9]. Achieving an energy return based on the production of biodiesel alone is extremely challenging, however, with ~50% of studies on microalgal biodiesel reporting an EORI of <1 [10–13]. Anaerobic digestion of wet microalgae is potentially an energetically more favourable option as it utilises the entire biomass and does not require drying before digestion [9,14–16]

One of the major challenges in achieving an energy return from the production of biofuel from microalgae is harvesting and concentrating the algae [3,17,18]; this is due to a number of factors including the dilute nature of the algal suspension at 0.02%–0.05% dry solids [19,20]; the small size of micro-algal cells (most algae are below 30 µm) [21]; the similarity in density of the algal cells to that of the growth medium [22]; and the negative surface charge on the algae that results in dispersed stable algal suspensions [23–25].

This work used a previously developed and validated mechanistic mass and energy balance model [26] to examine the energy balance for microalgal biogas production from open raceway systems for a number of production scenarios, including the examination of the harvesting method, the process scale and utilisation of the combined heat and power generation.

2. The Model and Modelling Assumptions

The previously developed and validated model [26] was used to investigate a number of algal harvesting options and scenarios in terms of energy return, based on yearly totals and annual average values. While it is not the aim of the current paper to examine seasonal variations, this can be addressed using the same modelling approach for part-year operation, and may be a sensible strategy where local data are available and it is desired to size downstream plants and processes.

The model is divided into three main operational areas: growth, harvesting and anaerobic digestion (AD). These are linked by a requirement for pumping power, which has not been fully accounted for in many previous studies. The energy inputs in raceways are for mixing and gas transfer. The main energy inputs for AD are heat energy to raise the feedstock temperature and replace heat losses through the walls, roof and base of the digester; and mixing energy to distribute enzymes and microorganisms and prevent settling of solids. In the current work, the embodied energy within process equipment is not considered within the energy balance. The embodied energy of materials has also been excluded, except where referenced in the discussion. The inputs are thus the operational energy requirements, in terms of heat and electricity, of the process. The output is the higher heating value (HHV) of the biomass or, where biogas is the end product, of the methane in the predicted biogas production. The concept of energy return on operational energy invested (EROOI), i.e., the ratio of the energy output to the operational energy input, is used to assess the energetic viability of the process scenarios studied.

2.1. Modelling Assumptions for "Pragmatic Case"

In previous work using this model [26], equipment, harvesting and methane yield efficiencies of 100% were assumed to allow assessment of the effect of selected process variables on the required concentration factor (ratio of microalgal concentration in the concentrate and the initial solution) to achieve an EROOI of $\geq$1. Although useful for the intended purpose, these assumed efficiencies lead to an underestimate of the energy inputs in 'real' systems. In this work, a so-called "pragmatic" case was therefore defined to allow a more realistic and detailed analysis of energy balances for the entire microalgal biogas production process. The pragmatic case was based on values in the middle to upper range of currently reported performance. The main assumptions made for this purpose are summarised in Table 1.

Table 1. Assumptions for Pragmatic Case.

Parameter	Unit	Value
Environmental		
Solar insolation	$kWh \cdot m^{-2} \cdot year^{-1}$	2000
Photosynthetic efficiency (PE)	%	3
Ambient temperature	°C	20

Table 1. *Cont.*

Parameter	Unit	Value
Raceway		
Area	m^2	10,017
Depth	m	0.3
Average fluid velocity	ms^{-1}	0.3
Hydraulic retention time (HRT)	days	2
Algal Concentration (dry weight, DW)	$g \cdot DW \cdot L^{-1}$	0.17
Gaseous exchange		
CO_2 concentration in supply	%	12
Anaerobic Digestion		
% of Buswell estimated CH_4 yield	%	100
Hydraulic retention time (HRT)	days	20
Mesophilic digester temperature	°C	35
Equipment efficiencies		
Paddlewheel efficiency	%	50
Gas transfer efficiency	%	80
Blower efficiency	%	80
Pump efficiency	%	80
Mixer efficiency	%	80
Heater efficiency	%	80
Percentage heat recovery	%	50

2.1.1. Raceway and Paddlewheel

Previous work [26] showed that varying the raceway dimensions between widths of 10 and 20 m to give areas of 0.5 to 1 ha made only a negligible difference to the energy balance. A raceway area of ~1 ha (channels 20 m wide and 219 m long) was therefore assumed in all scenarios used here.

Reported efficiencies (ratio of electrical input to hydraulic power) for paddlewheels of the type generally used to mix and maintain circulation in microalgal raceways are low, at 10%–20% [27–30]. Efficiencies of 40% have been suggested for optimised paddlewheel designs in raceways [31], and efficiencies of up to 75% have been found for advanced designs aimed at extracting energy from flows at low head differences [32]. Methods of reducing the energy input for mixing raceways have not yet been extensively studied [30,33,34] and it would appear that considerable improvements could be made to microalgal raceway paddlewheel design. While changes in paddlewheel efficiency may not significantly affect the EROOI of the overall system, they represent an important component in the cultivation system and a potential area for energy saving [35] For the scenarios considered in the current study, an improved overall paddlewheel efficiency of 50% was therefore assumed.

2.1.2. Anaerobic Digestion Methane Yield and Heat Recovery

The pragmatic case assumed a methane yield of 60% of the theoretical maximum value based on biomass composition, using the Buswell equation [36,37]. This was equivalent to an estimated specific methane yield of 0.33 $g \cdot CH_4 \cdot g^{-1}$ of Volatile solids (VS) for algae with a 20% lipid content, corresponding to the higher end of the range for quoted methane yields [15,20,38]. Recent studies have found a 60% yield for *Dunaliella salina* [39] and 59%–79% yield for five commercially exploited microalgal species [40].

The model calculates heat loss through the walls and floor of the digester without any allowance for losses from pipework, external heat exchangers, etc. The scenarios considered in the previous work also assumed no heat recovery. In the current work, heat recovery was included, with the selected value assumed to cover all otherwise unaccounted-for losses. Reported values for heat recovery in AD systems include 33%–66% [41] and 40% [42]. Boissevain [43] found that year-round operation of a mesophilic AD system at an average external temperature of 10 °C was possible with a waste heat recovery of 40%. Heat recovery of 50% was thus assumed for the pragmatic case.

2.1.3. Equipment Efficiencies

Efficiencies of 80% were assumed for the pumps, mixer, heater and blower. These are at the upper end of typical values reported in the literature [31,44].

3. Results and Discussion

3.1. Raceway Dissolved Oxygen Concentration

Using the model, the maximum dissolved oxygen concentration for the pragmatic case was calculated as 22 g·m^{-3}, in good agreement with reported DO concentrations of 20–25 mg·L^{-1} reached at around noon in an experimental raceway reactor using flue gas for carbon supplementation [45]. Although this is over twice the saturation level of O_2 in air, it is below the limit of three times considered to inhibit microalgal growth [46,47]. Other authors have reported similar or even higher dissolved oxygen concentrations [48,49] indicating this is a potentially serious issue for microalgal cultivation in open raceways, and more energy may be required to ensure effective gas transfer for deoxygenation.

3.2. Maximum Harvesting Energy to Achieve a Net Energy Return

The pragmatic case was used to estimate the maximum permissible harvesting energy input to achieve an EROOI = 1 for a range of concentration factors. A 90% harvesting recovery rate was assumed and two raceway hydraulic retention times (HRTs) were used, of 2 and 4 days. Results are shown in Figure 1.

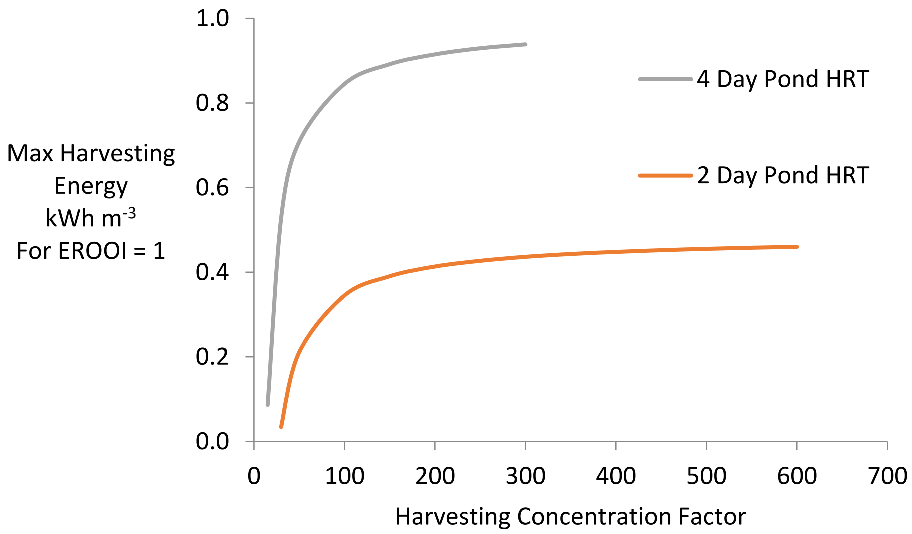

Figure 1. Maximum harvesting energy to achieve an energy return on operational energy invested (EROEI) = 1 in pragmatic case assuming 90% recovery rate (concentration factor is defined as the ratio of algal biomass (%DW) in feed-stream to algal biomass (%DW) in the harvested output stream).

The permissible harvesting energy input to achieve a net energy output is small at low concentration factors, and increases rapidly with increasing concentration factor. Permissible harvesting energy reaches a maximum of around 0.4 kWh·m^{-3} for a 2-day HRT. At a 4-day HRT, the concentration of microalgal biomass leaving the raceway is estimated by the model as about 0.033% dry weight (DW), and unless higher concentrations can be achieved the maximum harvesting energy for a net energy return will be <1 kWh·m^{-3}. HRT is known to be critical in maximising algal biomass productivity [26]. A recent model has shown that dynamic control of depth (0.1–0.5 m) and HRT (2–20 days) to match local and seasonal climatic conditions increased productivity by 0.6%–9.9% while decreasing water demand by 10%–61% compared to the standard approach of constant depth and HRT [50]. Raceways appear to produce stable cultures at 2 to 3 days HRT [51], but "crashes" regularly occur at 4 days [52]. Zamalloa, Vulsteke, Albrecht and Verstraete [20] recommended a HRT of 2 days and increasing this above 4 days may not be practicable for operational reasons. However, if algal concentration entering harvesting can be increased, by extended HRTs (>4 days) or by dynamic depth and HRT control, harvesting energies >1 kWh·m^{-3} could produce a net energy return.

3.3. Effect of Viscosity

In previous studies using the model [26], the viscosity of the fluids in all sections was set to that of fresh water, as low-concentration algal suspensions have a similar viscosity to water [53]. High-concentration algal suspensions (>5% DW) with a higher viscosity might occur after harvesting by methods such as centrifugation. The model was therefore run assuming a harvesting recovery rate of 90%, a concentration factor of 120, and a harvesting energy input of 1 kWh·m^{-3}. Two values for post-harvest viscosity were used, of 0.001 and 0.035 Pa,s, representing fresh water and an 8% DW algal suspension [54], in order to evaluate the effect on process energy input.

Only one small change was apparent as a result of the increase in post-harvest viscosity: this was for the post-harvest AD supply pump where the energy input increased by 0.05% from 0.260 to 0.262 kWh·day^{-1}. The overall change in total energy input was negligible, and therefore the assumption that the post-harvest viscosity was equivalent to that of fresh water was maintained for all further scenarios tested.

3.4. Microalgal Biogas Production with Centrifugal Harvesting

In this scenario, the model was used to estimate the EROOI for the production of microalgal biomass with harvesting by centrifuge using the pragmatic case assumptions as described in Table 1 above. The harvesting recovery efficiency and concentration factor were respectively assumed to be 90% [55,56] and 120 [21]. Two values for energy input per unit volume were assumed, of 1.0 kWh·m^{-3} [21] and 1.4 kWh·m^{-3} [57]. The modelled EROOIs in both cases were substantially below 1 (Table 2, with 2–3 times more energy required for operation than is produced as biogas.

Table 2. EROOI for microalgal biogas production with centrifugal harvesting.

Operational Parameters	Units	Typical Concentration Factor of 120		10% Algal Output	
Concentration factor		120	120	604	604
Algae DW concentration in feed to AD Digester	%	2	2	10	10
Harvesting equipment energy input	kWh·m^{-3}	1.4	1	1.4	1
Energy Return on Operational Energy Invested EROOI		0.3	0.5	0.4	0.5

Disc-stack centrifuges can achieve microalgal concentrations of more than 2% DW [17]. Even at an assumed output concentration of 10%, however, the EROOI remained ≤0.5 with more energy being used than is produced (Table 2) for both levels of centrifugation harvesting energy inputs.

These results confirm that the use of a disc-stack centrifuge as the sole harvesting method in the production of microalgal biogas is not energetically viable: a similar outcome to that found previously for microalgal biodiesel production [58]. Sedimentation and flocculation potentially offer the lowest energy input for micro-algal harvesting [19,59,60], and thus it was necessary to investigate lower energy methods of harvesting such as sedimentation, flocculation and combination of methods.

3.5. Microalgal Biogas Production with Sedimentation Harvesting

Sedimentation or settlement is a low-cost and low-energy method of harvesting, but recovery rates and concentration factors are relatively low [61,62]. A recovery rate of 60% with a concentration factor of 20 was assumed for three harvesting energy inputs:

a. 0.1 kWh·m^{-3}. This value was chosen as it is a typical design value for lamella settlers, a well-known and widely utilised technology for liquid–solid separation with limited space requirements [19,63].

b. 0.05 kWh·m^{-3}. This value was based on data obtained from various manufacturers of lamella settlers which suggested that the energy requirement may be less than 0.1 kWh·m^{-3}.

c. 0.005 kWh·m^{-3}. This value is typical of scraped conical settlement tanks [64]. For this case, the head loss in the harvest supply pump was increased to 3 m to achieve an upflow velocity in the settlement tank of $\leq$1.5 m·h^{-1} [65].

Results from modelling of these three scenarios are given in Table 3. For all three harvesting energy inputs, the EROOIs are <1, indicating no net energy production. Concentration factors would have to be increased to 46, 36 and 31 and harvester output algal concentrations to 0.76%, 0.60% and 0.51% to achieve an EROOI of 1 for the harvesting energy inputs of 0.1, 0.05 and 0.005 kWh·m^{-3} respectively.

Table 3. EROOI for microalgal biogas production with sedimentation harvesting [a].

Operational Parameter	Harvesting Energy Input	Concentration Factor	Algae DW Concentration Exiting Settler	EROOI
	kWh·m^{-3}		%	
Typical recovery rate and concentration factor	0.1	20	0.33	0.6
	0.05	20	0.33	0.6
	0.005	20	0.33	0.7
EROOI of 1	0.1	46	0.76	1.0
	0.05	36	0.60	1.0
	0.005	31	0.51	1.0
Maximum DW concentration of 1.5%	0.1	91	1.50	1.4
	0.05	91	1.50	1.7
	0.005	91	1.50	2.1

[a] Harvesting recovery rate taken as 60% throughout.

Microalgal concentrations of up to 1.5% (DW) have been achieved by sedimentation and, assuming this value, EROOIs of 1.4–2.1 can be obtained. A microalgal biogas process with sedimentation harvesting could therefore theoretically give a positive net energy balance: unfortunately, however, the majority of microalgae do not settle readily [66,67]. Sedimentation could be a viable technique for harvesting of some types of microalgae, or could potentially be combined with other harvesting techniques to increase the concentration of VS entering the digester. The above results support the view that research to identify biochemical and/or operational factors which can promote sedimentation should be a priority area for energy-efficient microalgal biofuel production.

3.6. Microalgal Biogas Production with Flocculation Harvesting

The addition of flocculant can improve the rate of sedimentation, and has been suggested as a superior method for algal separation as it is suitable for large volumes and a wide range of microalgae [19].

Where flocculants are used to improve sedimentation harvesting, and the resulting EROOI values are compared with those for systems without flocculant addition, the embodied energy of the flocculant needs to be included in the harvesting and operational energy inputs. The embodied energy of a typical organic flocculant has been reported as 5.56 kWh·kg^{-1} [68]. Alum (aluminium chloride), which is commonly used in water treatment to remove algae and is perhaps the most effective inorganic flocculant for microalgae [21,69], has an embodied energy of 4.04 kWh·kg^{-1} [70]. A major drawback of using mineral salts is that higher flocculant doses are required, ranging from 120 to 1000 g·m^{-3}, compared to 1–10 g·m^{-3} for organic flocculants [17]. The harvesting recovery efficiency of flocculation-assisted sedimentation ranges from 50% to 90% [56,71,72] and the concentration factor from 35 to 800, although concentration factors of 800 are generally not achievable for microalgae [21,73].

Flocculants need to be mixed into the microalgal suspension prior to settlement. A Root Mean Square velocity gradient (G) for mixing of 300 s^{-1} was assumed, based on recommended values for flocculation of municipal wastewater [74,75]. This gave a flocculant mixing energy input of 90 $W \cdot m^{-3}$, in reasonable agreement with the "engineering rule of thumb" for mixing flocculants of 100 $W \cdot m^{-3}$ [44,76,77].

The EROOI was estimated for alum at a dosage of 120 $g \cdot m^{-3}$, at concentration factors of 35 and 800 and a harvesting recovery rate of 90%; and for an organic flocculant at a dosage of 1 and 10 $g \cdot m^{-3}$ and harvesting recovery efficiencies of 70% and 90%. The results are shown in Table 4.

Table 4. EROOI for microalgal biogas production with flocculation [a].

Parameter	Unit	Alum		Organic Flocculant			
Algal harvesting efficiency	%	90	90	90	90	70	70
Concentration factor		35	800	35	35	35	35
Flocculant dose	$mg \cdot L^{-1}$	120	120	10	1	10	1
Algae concentration exiting settler	DW %	0.58	13.26	0.58	0.58	0.58	0.58
EROOI		0.6	1.0	1.1	1.2	1.0	1.1
Embodied energy as % of energy produced	%	65	65	10	1	13	1

[a] assuming 0.005 $kWh \cdot m^{-3}$ settlement energy input, 3 m harvesting pump head.

Addition of alum at a dosage of 120 $g \cdot m^{-3}$, the lowest found in the literature, achieves an EROOI of 1 only at the highest concentration factor for flocculation found in the literature of 800. The embodied energy in the alum was 65% of the total energy produced. Flocculation by alum is therefore not a viable option for the production of microalgal biogas. There are also operational issues associated with adding mineral salt coagulants, including increased volumes of digestate (the energy implications of these were not considered in the current work).

The low dosages of organic flocculant, despite its higher embodied energy per unit of mass, resulted in a lower input energy for flocculation than alum, with the embodied energy in the flocculant making up 1%–13% of the energy output. The EROOI for organic flocculants was estimated at between 1.0 and 1.2 for the lowest suggested concentration factor of 35, and thus the use of organic flocculants may give a viable harvesting method, especially if higher concentration factors are achieved. EROOI could be further improved by combining flocculation with other harvesting techniques.

3.7. Microalgal Biogas Production with a Combination of Harvesting Methods

The next scenarios considered a combination of sedimentation with centrifugation, and flocculated sedimentation with centrifugation, to achieve a target output concentration of 10% DW microalgae from the harvesting operation. The feedstock concentration of 10% was selected as being at the upper end of that typically encountered in Continuously Stirred Tank Reactor (CSTR digesters [78,79]; microalgal suspensions above 10% also behave as non-Newtonian fluids with a high viscosity and may be problematic to pump [53,80].

The parameters were as in the pragmatic case, with harvesting concentration factors, recovery rates and harvesting energy inputs as previously used in Sections 3.4–3.6.

The results are shown in Table 5. All the combinations of harvesting assessed produced a positive net energy output, with EROOIs ranging from 2.5 to 3.8. Settlement and flocculation greatly reduce the flow rate of material entering the centrifuge, and thus the required energy input for centrifugation.

Table 5. EROOI for microalgal biogas production with a combination of harvesting methods.

Parameter	Unit	Sedimentation with Centrifugation			Flocculation with Centrifugation			
Harvesting					**Organic Floc' 1 mg·L^{-1}**		**Organic Floc' 10 mg·L^{-1}**	
Recovery rate sedimentation/floc'	%	60	60	60	70	90	70	90
Concentration factor sediment'/floc'		20	20	20	30	30	30	30
Recovery rate centrifugation	%	90	90	90	90	90	90	90
Concentration factor centrifugation		30	30	30	20	20	20	20
Harvesting equipment sedimentation	kWh·m^{-3}	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Harvesting equipment centrifugation	kWh·m^{-3}	1.4	1	0.35	1	1	1	1
Energy output								
Calorific Value of CH_4 production	kWh·day^{-1}	505.2	505.2	505.2	589.4	757.8	589.4	757.8
Energy inputs								
Raceway mixing	kWh·day^{-1}	43.7	43.7	43.7	43.7	43.7	43.7	43.7
Total pumping energy	kWh·day^{-1}	29.5	29.5	29.5	29.4	29.5	29.4	29.5
Raceway blower energy	kWh·day^{-1}	28.5	28.5	28.5	28.5	28.5	28.5	28.5
Harvesting energy	kWh·day^{-1}	72.2	53.8	23.8	52.4	62.6	129.2	139.4
Total AD input energy	kWh·day^{-1}	24.3	24.3	24.3	28.0	35.5	28.0	35.5
Total operational energy input	kWh·day^{-1}	198.1	179.7	149.7	182.0	199.7	258.8	276.5
Net energy	kWh·day^{-1}	307.1	325.5	355.5	407.5	558.1	330.6	481.3
EROOI		2.5	2.8	3.4	3.2	3.8	2.3	2.7

The concentration factor required for centrifugation following sedimentation is only 30, or one quarter of the typical centrifugation factor of 120 [21]. The concentration factor achieved by a disc-stack centrifuge is proportional to the flow rate [55,81,82], and this lower concentration factor could therefore allow a higher flow rate through the centrifuge. The energy per unit of flow for each unit of concentration factor, known as the Dewatering energy D_W, can be expressed as [54,61]:

Equation (1):

$$D_W = \frac{E}{C_f} \tag{1}$$

where E is the energy of centrifugation per unit volume and C_f is the concentration factor. For a centrifugal energy consumption of 1.4 kWh·m^{-3} and a concentration factor of 120, D_W is 11.7 W·m^{-3}, and for a concentration factor of 30, the centrifugal energy consumption would be reduced to 0.35 kWh·m^{-3}. Assuming a value of 0.35 kWh·m^{-3} in the estimate of energy inputs improves the EROOI to 3.4 for sedimentation with centrifugation. This reduced energy input for disc-stack centrifugation needs to be verified experimentally for large-scale equipment, as it is not possible to predict energy requirements precisely [55], and the linearity of the relationship between concentration factor and flow rate drops off dramatically above a critical flow rate specific to each centrifuge [82]. The reduction in the required concentration factor following initial concentration by sedimentation or flocculation may, however, reduce the centrifuge energy input significantly when compared to typical literature values of 1.0–1.4 kWh·m^{-3}.

Flocculation by an organic flocculant may be a more reliable and widely applicable means of pre-concentration than unassisted sedimentation, but the flocculant concentration is critical to the energy balance. At a flocculant dosage of 1 mg·L^{-1} for harvesting recovery rates of 70% and 90%, the EROOI is 3.2 and 3.8, i.e., higher than that for sedimentation and centrifugation at the same centrifuge energy input (Table 6). At a flocculant dose of 10 mg·L^{-1}, however, the EROOI is lower than for settlement. Flocculation at low doses followed by centrifugation at typical concentration factors and harvest recovery rates can produce EROOI greater than 3 for the production of microalgal biogas. An EROI (energy return on energy invested) ratio of 3 has been suggested as the minimum that is viable to "support continued economic activity" [5,83]. Microalgal biogas production using flocculation and sedimentation could therefore be a viable system, but a low-cost low-dose (~1.0 mg·L^{-1}) organic flocculant that is broken down in the digester is required, together with low or no cost and embodied energy for nutrients and CO_2.

Table 6. Effect of number of raceways on EROOI.

Parameter	Units	Single Raceway and AD	Multiple Hectare Raceway Supplying One AD Unit (~3000 m^3)				Four Raceways and One AD
			No Additional Piping	425 m Pipe Run	Settle Locally	Harvest Locally	
Number of 1-hectare raceways		1	108	108	108	108	4
AD volume	m^3	28	2987	2987	2987	2987	111
EROOI		2.8	2.9	1.4	2.9	2.9	2.8
Total pumping energy per hectare raceway	kWh·day^{-1}·ha^{-1}	29.5	29.6	214.9	29.7	29.6	29.5
Total AD heat energy per hectare raceway	kWh·day^{-1}·ha^{-1}	20.1	16.1	16.1	16.1	16.1	18.2

3.8. Multiple Raceways

The modelling assumed a single raceway supplying biomass to a single digester, but commercial digesters can have a considerably larger volumes [84] than those calculated in previous scenarios. The required digester volume assuming a single raceway in the sedimentation with centrifugation case was estimated at 28 m^3. As the digester volume increases, its surface area relative to volume decreases, and thus the heat loss per unit volume will also decrease.

The digester volume in the model was therefore set to 3000 m^3, typical of large-scale commercial digesters. It was estimated that this digester would need 108 $\times$ 1 hectare growth ponds to supply it with microalgal biomass. The assumptions used were as those in the sedimentation with centrifugation scenario, but with 108 raceways supplying a single digester. An average minimum pumping distance from the pond to the digester of 425 m was assumed based on geometrical considerations. The EROOI was calculated for no additional pumping distance (not possible, but used for initial comparison with the single raceway system) and with a pumping distance of 425 m, for three scenarios:

(a) Pumping (distance 425 m) from each raceway to a single central harvesting “zone” (sedimentation with centrifugation) adjacent to the digester.
(b) Sedimentation adjacent to each raceway and then pumped (distance 425 m) to a single central centrifugation harvesting “zone” adjacent to the digester.
(c) Harvesting (sedimentation with centrifugation) adjacent to the raceway and then pumped (distance 425 m) to the digester.

A further scenario of four raceways supplying a single digester was also considered. The pumping distance from the raceway through the harvesting system was assumed to be the same for each raceway in the 4-raceway scenario as in the single raceway sedimentation with centrifugation scenario.

The outputs for the various process configurations described above are shown in Table 6.

With no additional piping, compared to a single raceway, the EROOI improves from 2.8 to 2.9. This is due to the reduction in the heat energy requirement of the digester from 20.1 to 16.1 kWh·day^{-1}·ha^{-1}, as a result of the lower surface area per unit volume. It is not possible, however, to have 108 raceways supplying a single digester without additional pipework runs. When the additional average pipe run of 425 m to transport the microalgal suspension to the harvesting operation adjacent to the digester is included, the EROOI reduces to 1.4 as a result of a more than 7-fold increase in the total pumping energy. The results thus confirm the importance of this factor, which is often ignored in energy balance and life cycle assessments.

Local sedimentation reduced the amount of liquid to be pumped 20-fold, and increased the EROOI to 2.9, but local harvesting with settlement and centrifugation brings no additional improvement. Although concentration during local harvesting reduces pumping energy, it does not allow a reduction in the number of items of harvesting equipment with consequent economies of scale and reductions in capital cost.

Groups of four raceways could be arranged around a central harvesting and digester unit with little or no additional piping. Although no improvement was seen in the EROOI, this option may allow lower equipment costs due to economies of scale.

Pumping energy should be minimised wherever possible and this factor must be taken into account when considering multiple raceway layouts.

3.9. Energy Supply and Utilisation

The EROOI does not take into account the generation and transmission costs of input energy. These can more than double the energy requirement [85]. Energy transmission costs can be reduced by producing power locally and "parasitically" from the biogas produced. Combined heat and power (CHP) is the simultaneous production of electricity and heat from a fuel, and is more efficient than conventional separate electrical and heat generation, as shown in Figure 2. CHP units have been widely used to exploit biogas from AD. Biogas burned in a CHP unit requires minimal or no gas scrubbing to remove hydrogen sulphide (H_2S) and other impurities [86,87]. Upgrading of the biogas is normally required, however, if the gas is to be used as a vehicle fuel or added to the natural gas grid. The upgrading of biogas typically uses ~11% of the energy content in the biogas [85], although this is currently expected to decrease with improvements in the engineering design of upgrading units.

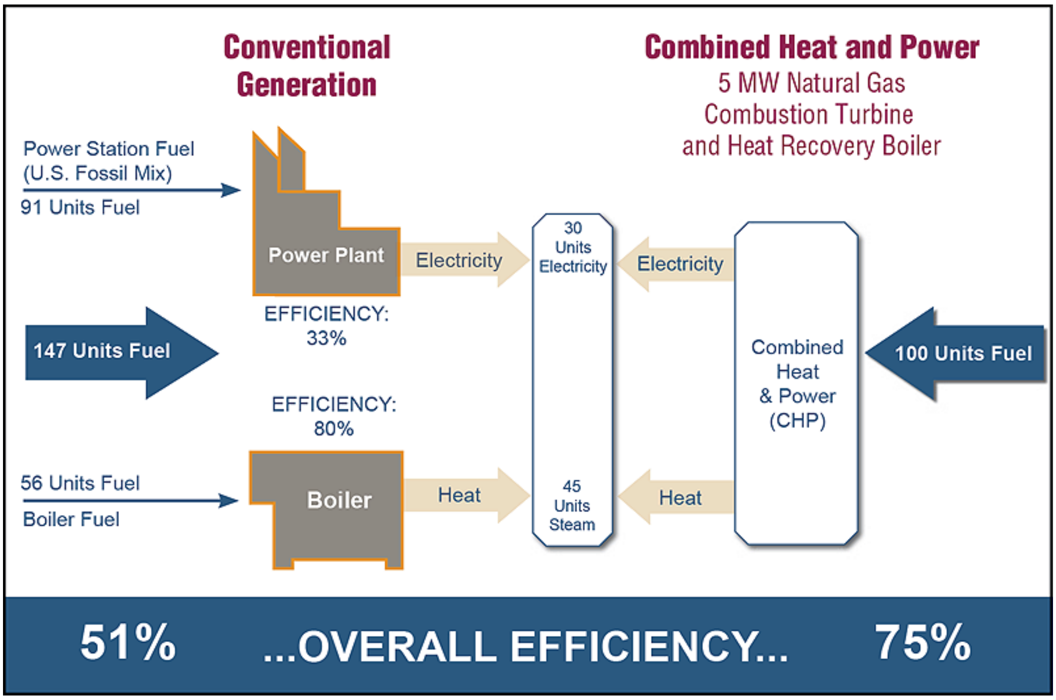

Figure 2. Overall conversion energy efficiencies of conventional generation and CHP [88].

If the biogas produced from microalgae can be used directly in a CHP unit, this raises the question of whether the heat and power produced can be exploited efficiently for the process needs of electrical and heating energy in microalgal biogas production. The ratio of electrical to heat energy produced from a CHP unit is ~0.67. The model was used to estimate the ratio of electrical to heat energy required by the microalgal production process based on the scenarios for sedimentation with centrifugation and flocculation with centrifugation (Section 3.7).

Table 7 shows the ratio of electrical to heating (warming the digester and compensation for heat losses) energy needs in microalgal biogas production. The ratio is very different to that generated by CHP units, with more electrical than heat energy required. If heat from the CHP unit is not fully exploited or if separate electrical and heat generators are used, the energy input into the microalgal biogas process more than doubles and the EROOI is reduced. The sedimentation with centrifugation scenario requires 178 and 20.1 kWh·day^{-1} of electrical and heat energy inputs, and produces 505 kWh·day^{-1} as methane (HHV) from the microalgal biogas. If all the biogas is burnt in a CHP unit, at the output ratio shown in Figure 2, then 151 kWh·day^{-1} of electricity and 227 kWh·day^{-1} of heat are produced with 126 kWh·day^{-1} of operational energy losses in the CHP unit. If only the 20 kWh·day^{-1} of heat required by the process is used, the total loss of energy from CHP unit in operational losses and "waste heat" totals 333 kWh·day^{-1}. The total input and waste energy is thus 531 kWh·day^{-1} giving an EROOI of less than 1.

Table 7. Ratio of electrical to heating energy in microalgal AD.

Parameter	Unit	Settlement with Centrifugation			Flocculation with Centrifugation			
Harvesting					**Organic 1 mg·L^{-1}**		**Organic 10 mg·L^{-1}**	
Harvesting settlement/floc'	%	60	60	60	70	90	70	90
Concentration factor settlement/floc'		20	20	20	30	30	30	30
Harvesting centrifugation	%	90	90	90	90	90	90	90
Concentration factor centrifugation		30	30	30	20	20	20	20
Harvesting equipment settlement	kWh·day^{-1}	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Harvesting equipment centrifugation	kWh·day^{-1}	1.4	1	0.35	1	1	1	1
Electrical energy	kWh·day^{-1}	178.0	159.6	129.6	150.2	161.9	150.2	161.9
Heating energy	kWh·day^{-1}	20.1	20.1	20.1	23.2	29.2	23.2	29.2
Ratio Electrical to Heat Energy		8.8	7.9	6.4	6.5	5.5	6.5	5.5

In order for microalgal biogas production to be energy efficient, a local source for exploitation of the excess heat generated needs to be found. Finding local uses for excess heat is one of the major operational problems in the current exploitation of CHP, and not just for microalgal fuel production. The alternative of small-scale biogas upgrading, with combustion of only the raw biogas needed to meet the heating requirements of the AD plant, may be an energetically more favourable option in this case.

4. Conclusions

The results of modelling showed that production of microalgal biogas with a positive net energy balance is possible, with potential EROOIs over 3 using the technologies proposed, but requires:

(a) A low dose and low embodied energy organic flocculant that is readily digested, or microalgal communities that settle readily
(b) Additional concentration after flocculation or sedimentation
(c) Exploitation of the heat produced from parasitic combustion of microalgal biogas in CHP units
(d) Minimisation of pumping of dilute microalgal suspension

The model provides a powerful assessment tool both for comparison of alternative options and potentially for the benchmarking of real microalgal biogas production schemes.

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