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An energy evaluation of coupling nutrient removal from wastewater with algal biomass production

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ABSTRACT

Recently, several life cycle analyses of algal biodiesel from virtual production facilities have outlined the potential environmental benefits and energetic balance of the process. There are a wide range of assumptions that have been utilized for these calculations, including the addition of fertilizers and carbon dioxide to achieve high algal yields in open ponds. This paper presents an energy balance of microalgal production in open ponds coupled with nutrient removal from wastewater. Actual microalgal yields and nutrient removal rates were obtained from four pilot scale reactors (2500 gallons each) fed with wastewater effluent from a conventional activated sludge process for 6 months, and the data was used to estimate an energy balance for treating the total average 12 million gallons per day processed by the wastewater treatment plant. Since one of the most energy intensive steps is the dewatering of algal cultures, several thickening and dewatering processes were compared. This analysis also includes the energy offset from removing nutrients with algal reactors rather than the biological nutrient removal processes typically utilized in municipal wastewater treatment. The results show that biofuel production is energetically favorable for open pond reactors utilizing wastewater as a nutrient source, even without an energy credit for nutrient removal. The energy content of algal biomass was also considered as an alternate to lipid extraction and biodiesel production. Direct combustion of algal biomass may be a more viable energy source than biofuel production, especially when the lipid content of dry biomass (10% in this field experiment) is lower than the high values reported in lab scale reactors (50–60%).

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1. Introduction

Many different sources for biofuels are being explored to reduce the nation's current dependence on foreign oil. Algae have been investigated for more than two decades due to their high lipid content, rapid growth rate, and ability to sequester atmospheric or waste CO₂ from coal fired power plants [1]. Unlike other biofuel feedstocks (i.e., corn and soy), algae do not compete with existing food commodities, can grow on marginal lands not suitable for conventional agriculture, and do not require large volumes of fresh water factors that limit the economic and environmental benefits of terrestrial crop feedstocks. Moreover, algae can grow in nutrient rich wastewaters, and may perform nitrogen (N) and phosphorus (P) removal, thus reducing nutrient loads to receiving water bodies. Algal production has been estimated to yield from 3200 to 14,600 gallons of oil/acre/year [2,3] a 130 fold increase over soybean, the leading feedstock for biodiesel production. However, these estimates have generally been calculated from lab scale

cultures under controlled growth conditions; in contrast, all mass culture efforts reported to date have yielded 10–20 times less oil than expected [3]. For the production and conversion of algae to biofuel or biomass to be worth full scale consideration and/or further research, a total energy surplus must be achievable. Though environmental benefits may be measurable, the cultivation of biomass, dewatering, and conversion of algal solids to a usable energy source must first be economically profitable.

Many algal studies and energy evaluations have been completed since the 1970s with widely varying results. Some of this variation can be attributed to the complexity of algae cultivation, the lack of availability of field data, and the fact that life cycle analysis was not a mature methodology in the 1970s and 1980s, when algae was being studied extensively. Recently, there have been several “cradle to tailpipe” life cycle analyses (LCA) of biodiesel from microalgae in ponds. Most of these assumed that algal ponds would be supplemented with chemical fertilizer to meet the necessary nitrogen and phosphorus requirements, which provides an immense upstream burden to the LCA. Clarens et al. concluded that algal biodiesel would actually generate greenhouse gas emissions and require significantly more energy to produce than conventional corn and canola feedstocks, although the authors

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acknowledged that most of the environmental burdens associated with algae would be offset if wastewater were used as a nutrient source [4]. Others have concluded that microalgal biodiesel production is energetically viable, but that energy and fertilizer consumption must be decreased for the process to be economically viable [5,6]. Batan et al. [7] reported a net energy ratio (NER) for the microalgae biodiesel process of 0.93 MJ consumed per MJ produced; 0.43 of this represents feedstock inputs (fertilizer, water, etc.) which could be offset to increase the NER.

The objective of this study is to provide an assessment of how coupling nutrient removal from wastewater with algal biomass production may impact the energy balance of algal biodiesel production. Most LCAs utilize lab scale data of algal productivity and lipid content to design virtual facilities because there is limited field data of algal productivities and N and P removal rates in wastewater fed open pond systems. In this study, actual microalgal yields and nutrient removal rates were obtained from four pilot scale reactors (2500 gallons each) fed with wastewater effluent from a municipal wastewater treatment plant for 6 months, and the data was used to estimate an energy balance for treating the total 12 million gallons per day processed by the wastewater treatment plant. Since one of the most costly steps is the dewatering of algal cultures, several thickening and dewatering processes were compared, and two final uses for algal biomass, biofuel production and biomass combustion, were considered.

2. Production system overview

Outdoor reactor experiments were conducted at the City of Lawrence wastewater treatment plant (WWTP), Lawrence, KS. The WWTP serves a population of 90,000, has an average flow of 12 million gallons per day (MGD), and performs biological nitrification (no denitrification or phosphorus removal). The wastewater effluent feed contained an average 19.5 ± 4.5 mg N/L and 3.2 ± 0.9 mg P/L during this experiment, which are similar concentrations to algal nitrogen limiting growth media. Four chemostat bioreactors (volume of 2600 gal each, volume depth of 4 ft.) were fully exposed to natural variability in ambient light and temperature over a 6 month period from April to October (Fig. 1). They were operated as continuous flow reactors and fed with treated effluent from a secondary clarifier with a hydraulic residence time of 10 days. In order to maintain mixing in each tank, each was constantly aerated through a fine bubble diffuser at a rate of 0.71



Fig. 1. Algal open pond reactors operated at the Lawrence WWTP, Lawrence, KS. Each of the four 2600-gallon reactors was fed with wastewater effluent from the conventional activated sludge process (influent TN 19.5 ± 4.5 ; TP 3.21 ± 0.93).

CFM. Reactors were sampled weekly during the experimental period to determine the biomass and lipid productivity and nutrient removal. This field set up served as the basis for a full scale system design that can process the entire 12 MGD average effluent flow from the WWTP.

A flow diagram of the design production system is included in Fig. 2. The process diagram shows many connections between a municipal WWTP and an algal nutrient removal and biomass production facility, including nutrient and CO_2 flow and heat recovery. Our analysis concentrates on the operating energy required to cultivate, thicken, and dewater algae for downstream biofuel or biomass production. In this analysis, it is assumed that the WWTP would receive an energy credit for removing nitrogen and phosphorus in the algal growth ponds, versus the energy intensive biological nutrient removal (BNR) system typically used by WWTP. Six algal harvesting scenarios are compared as alternate processes to determine which is most energetically favorable. The operating energy requirements of two thickening processes (gravity sedimentation and dissolved air flotation (DAF)) are compared in conjunction with three dewatering units (belt press, centrifugation, and evaporation). For each of the harvesting scenarios presented, the energy recovered from algal biomass is compared for two ultimate fates: algal biodiesel combustion and dry biomass combustion, as the energetic yields from these systems are well understood. At this point, the energy consumption of lipid extraction from algal biomass is largely unknown at scale. Our analysis calculates the maximum energy that lipid extraction and biodiesel production can utilize for the presented scenarios to be energetically favorable. These values are compared with energy requirements presented in recent algal biodiesel life cycle analyses.

2.1. Energy costs

2.1.1. Cultivation algal ponds

In order to process 12 MGD of wastewater effluent through algal open ponds with a depth of 1.2 m, which was used in the pilot reactors at the Lawrence WWTP, 37 hectares of algal ponds would be required. These ponds are similar to raceway systems used at full scale [3,8]. A pilot raceway facility in Roswell, New Mexico achieved maximum biomass productivities of $50 \text{ g m}^{-2} \text{ d}^{-1}$, with the average near $10 \text{ g m}^{-2} \text{ d}^{-1}$ [2]. Several life cycle analyses have assumed algal productivities of $15\text{--}30 \text{ g m}^{-2} \text{ d}^{-1}$ [5–7] when CO_2 is added to the system. Over a 6 month period at the Lawrence WWTP, algal biomass productivities ranged from 5 to $16 \text{ g m}^{-2} \text{ d}^{-1}$, without enrichment with CO_2 . The lipid content of the algal biomass averaged 10% of the dry mass, which is lower than what has been reported by others using lab scale, CO_2 enriched cultures that can obtain a lipid content of 50–60% by weight under ideal conditions [7]. For the following calculations, productivity values obtained in our outdoor pilot reactors are used as a base case (biomass yields of $12 \text{ g m}^{-2} \text{ d}^{-1}$ with a 10% lipid content). These estimates are lower than optimal since the ponds were not enriched with CO_2 . The specific algal biomass was a natural assemblage, not a pure inoculated strain, which would be expected to dominate a wastewater fed system [9]. When CO_2 is added to the system, algal productivities of $25 \text{ g m}^{-2} \text{ d}^{-1}$ may be expected, but this has not been shown in algal ponds using wastewater as the sole nutrient source.

The operational energy requirements for open pond systems include the cost of pumping, mixing, and bubbling CO_2 into the system, if performed. It is assumed that wastewater effluent will flow by gravity to the algal ponds. To maintain flow through the system, 75 HP is required for centrifugal pumping of 8333 gpm at 25 ft. of head with a 70% efficient pump. This will require approximately 1350 kW h d^{-1} , or 9.7 GJ ton^{-1} biodiesel (based on productivity and lipid content assumed in this system). The power requirement

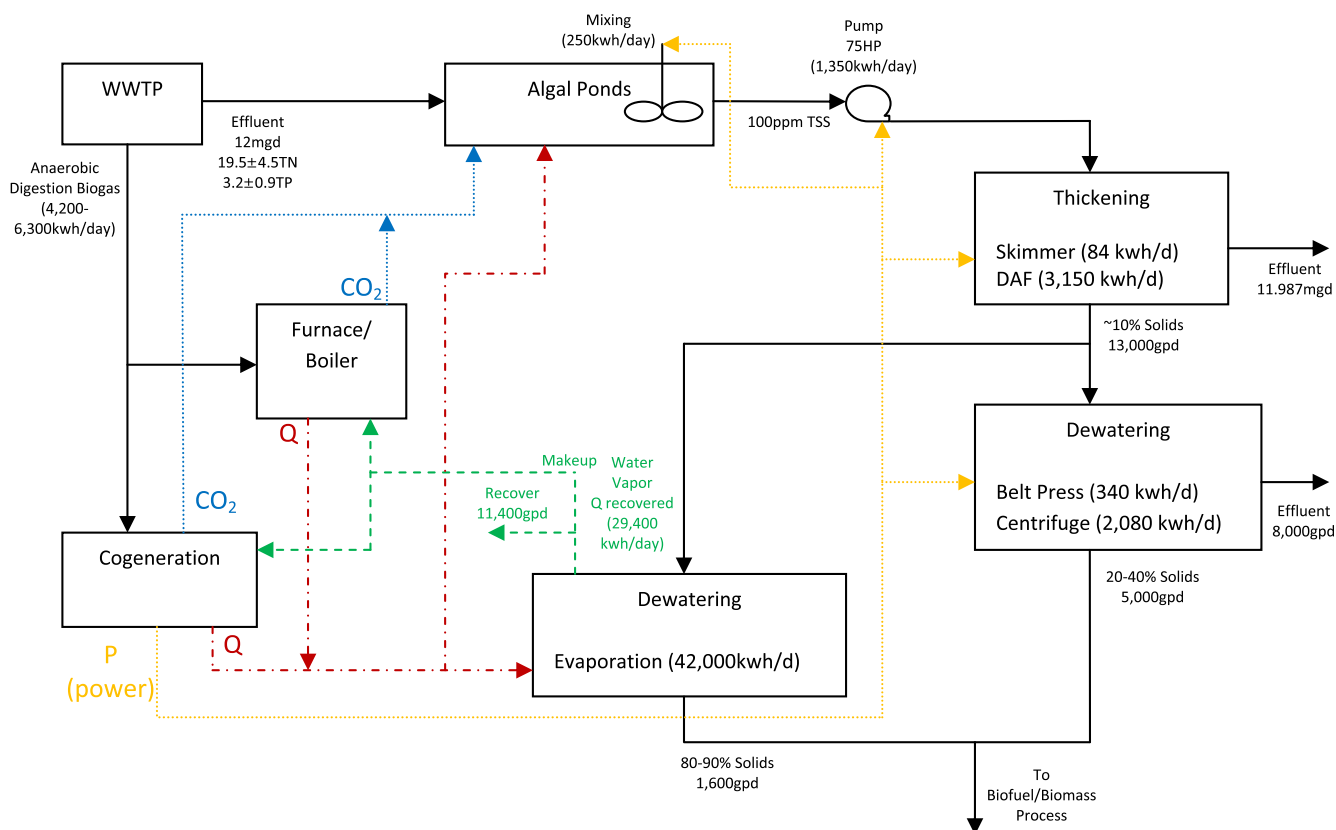


Fig. 2. Flow diagram of coupling algal biomass production with a municipal WWTP treating an average 12 MGD.

for this system is similar to the 5.7 GJ ton^{-1} biodiesel [6] and 7.2 GJ ton^{-1} biodiesel [10] calculated for other large scale designs, but it is larger than the 0.8 GJ ton^{-1} biodiesel estimated when a $25 \text{ g m}^{-2} \text{ d}^{-1}$ dry mass productivity is assumed with 50% lipid content [7].

2.1.2. Algal harvesting thickening options

Due to the small particle size of algal cells and their typical growth as small colonies or single cells, harvesting of algal biomass is considered a major challenge for the full scale production of algal biodiesel. Many mature technologies, such as centrifugation, have generally been considered too energy intensive [11]. Researchers are studying how to encourage typically disperse cells to naturally flocculate [12], but there are no publications of this type of bio or auto flocculation working at large scale. Therefore, in this analysis, chemical coagulation, flocculation, and pH adjustment will be required as a first step to all the dewatering alternates presented below. Laboratory tests showed that all process units discussed below had a high efficiency for algal separation from the water phase, but pilot scale testing still needs to be performed.

Chemical coagulation of algae can be accomplished with trivalent cations (ferric sulfate and aluminum sulfate), commercial polymers, cationic chitosan, surfactants, and ionic strength and pH adjustment [11,13,14]. Energy required to manufacture the coagulants is not included in this calculation. The chemical feed and skimmer electrical costs for coagulation and flocculation are estimated as 84 kW h d^{-1} based on 1 HP/2500 gpm skimmer with 70% efficiency (FRC Systems International, Cumming, GA). If solids thickening is then performed by gravity separation, this accounts for the total energy consumption of solids thickening. The size and overflow rate of the sedimentation basin will ultimately depend on the settling velocity of algal flocs, and it should be noted

that it is unclear whether the lipid content of algal cells would change due to respiration during the time required for gravity sedimentation.

A second thickening option is chemical coagulation and flocculation, followed by dissolved air flotation (DAF). DAF is often used in wastewater treatment for separation of bacterial biomass, but it has mostly been investigated for liquid solid separation of algae from drinking water reservoirs [15,16]. DAF works by supersaturating air into water under high pressure, which flows to a low pressure vessel, where the gas is released as micron sized bubbles. The bubbles may attach to the surface of cells and carry them to the free surface, forming a concentrated layer of foam like biomass that can be skimmed and separated. With metal coagulation and successful bubble/floc attachment, DAF can achieve 99.8% removal of algae from dilute waters [16]. The majority of the electrical usage for a DAF unit comes from the dissolution of air into water, and power requirements are directly related to water temperature and solids concentration. Power requirements for air dissolution range from 12.5 to 40 HP/1000 gal (FRC Systems International, Cumming, GA). For this analysis, a value of 15 HP/1000 gal with 70% efficiency was assumed due to the relatively dilute nature of the fluid, totaling 3150 kW h d^{-1} . The power requirement for air saturation may be reduced by atmospheric compression with Nikuni or Edur DAF pumps rather than compressed air injection, but there are no available reports of the use of these pumps with algal suspensions.

2.1.3. Algal harvesting dewatering options

After algal biomass has been flocculated and thickened to a 12% solids concentration, the biomass would need to be dewatered prior to either lipid extraction or direct biomass combustion. The necessary extent of biomass dewatering will be dependent on

the exact lipid extraction method, and this is the subject of current research. A method to produce biodiesel from wet algal biomass (20% solids) has recently been demonstrated at the lab scale [17]. Lardon et al. assumed that algal biomass needed to be 90% solids prior to lipid extraction in order to utilize the same technology as soybean lipid extraction [6]. Biomass that is co fired with coal, such as wood chips, typically has a 50–90% solids content [18]. For this study, algal dewatering to 30% solids is considered achievable with centrifugation and belt filter press technologies, while 90% can be expected from direct evaporation. It may be necessary for algal biomass to be dried further prior to combustion or fuel conversion, depending on the exact methodology employed.

In total, the operating energy demands of three dewatering alternatives were compared. The first dewatering unit, a belt filter press, has an average requirement of 5.7 kW m⁻¹ belt width [19]. Based on a 250 cm belt width (Komline Sanderson Model GRS 1), an energy requirement of 340 kW h d⁻¹ is calculated. Others have assumed an energy demand of 400 W h kg⁻¹ dry mass [6], which would provide an energy estimate of 330 kW h d⁻¹, showing excellent agreement. The second dewatering technology, a centrifuge, has been cited as having an energy demand of 2.0 [10] to 10.7 [7] GJ ton⁻¹ of biodiesel. An operating cost guideline for centrifuges is \$1.5–\$34 per dry ton, with a conversion of \$0.07 per kW h [20]. If an operational cost of \$30 per dry ton is assumed, an energy demand of 2080 kW h d⁻¹ is estimated, equating to 15 GJ ton⁻¹ of biodiesel for our system, which may be an over estimate compared to recently reported values.

The third dewatering process, evaporation, requires energy to vaporize water. It is possible for this process to utilize biogas generated from an anaerobic digestion system or an energy cogeneration process. The gas from anaerobic digestion can fuel a furnace/boiler system or can be used in an energy cogeneration process (heat engine, microturbine, Stirling engine, and fuel cells). Both of these processes can partially provide the energy necessary for dewatering of the thickened algal solids with evaporation (see Section 2.3.2). The total energy required to vaporize 13,000 gpd containing 10% solids is 42,000 kW h d⁻¹ at 70% efficiency. If 70% of the energy is recovered as steam energy, the net addition of energy required is 12,600 kW h d⁻¹. Evaporation is the most costly dewatering method analyzed from an energy standpoint. Conversely, the potential reduction in% water content (from ~30% for centrifugation or belt filter presses to ~90% for evaporation) can greatly reduce the downstream biofuel or biomass processing costs. In fact, direct combustion of the algal biomass is achievable with 80–90% solids concentration. Therefore, a comparative analysis of the energy revenues from biofuel or biomass combustion was conducted before eliminating evaporation as a viable dewatering strategy.

2.2. Energy revenues

Algal biomass has been proposed as an energy source through lipid extraction and biodiesel production [1], biomass combustion through co firing with coal [21], and as a supplement to methane generation from anaerobic digestion of wastewater treatment generated biosolids [12]. The calorific value of algal biodiesel is estimated as 37.2 MJ/kg [10] with a density of 0.88 g/mL, equaling 32.7 MJ/L. For our Lawrence WWTP pilot system, algal lipid yields averaged 10% of dry mass over a 6 month period, without the addition of CO₂; while 50% lipid content has been shown in the laboratory. With our current system, biodiesel productions of 500 gallons per acre per year are achievable; with CO₂ enrichment (productivity of 25 g m⁻² d⁻¹ with 50% lipid content [7]), this could equal 4300 gal acre⁻¹ yr⁻¹. Energy revenues from biodiesel production would thus range from 4610 kW h d⁻¹ (our system) to 48,000 kW h d⁻¹ [7]. Alternatively, algal biomass has an average calorific value of 21.4 kJ per dry gram (or 9200 BTU per lb) reported

from literature values from multiple *Chlorella* species grown in nitrogen limited and non limited conditions [22] and from mixed algal assemblages [23]. With the average algal production of 12 g m⁻² d⁻¹, and an assumed loss of 70% efficiency, 18,600 kW h d⁻¹ can be recovered from combustion of biomass. The third option, energy recovered from anaerobic digestion of algal biomass, is not considered further in the calculations, although potential synergies are discussed.

2.3. Energy credits for WWTP offsets

2.3.1. Biological nutrient removal

The use of municipal wastewater effluent as a nutrient feed stock for the production of algal solids has environmental and economic benefits. Most life cycle analyses of algal biodiesel production have assumed that N and P would be supplied as fertilizer to the system. One previous analysis considered the environmental benefit of coupling algal production with conventional activated sludge (with nitrification) effluent. In that analysis, the energy required for algal fuel production was reduced from 300 GJ to 24 GJ by the use of wastewater effluent as a nutrient source instead of chemical fertilizers. Avoidance of the energy associated with conventional biological nutrient removal (BNR) accounted for the majority of this energy savings [4].

For the pilot scale algal reactors used as the basis for this analysis, wastewater effluent from a WWTP performing nitrification was used as the nutrient feed. Although this treatment plant does not currently perform BNR, it will likely be required to in the near future. In 2004, the US EPA reported that WWTPs produce 25,796 MGD [24] to 31,100 MGD of wastewater effluent, with less than half of this flow undergoing biological nutrient removal (BNR) [4]. Regulatory agencies have published effluent total nitrogen and phosphorus levels that will require many wastewater treatment plants to significantly upgrade their infrastructure to achieve this level of treatment. Table 1 tabulates proposed and existing goals for total nitrogen (TN) and total phosphorus (TP) effluent concentrations [25]. For this analysis, the equivalent energy required to remove N and P from BNR instead of the algal system is calculated as an energy credit.

To estimate realistic costs of BNR, nutrient removal and electrical usage data was collected from Johnson County, Kansas before and after the BNR system for the 6 MGD Blue River Main Wastewater Treatment Facility was placed online in October 2006. From September 2008 to September 2010, the average influent nitrogen concentration (measured as total Kjeldahl nitrogen (TKN)) was 31.2 mg/L TKN. The average effluent nitrogen concentration was 1.37 mg/L TKN. Therefore, an average of 95% TKN removal is achieved. The average influent total phosphorus was measured as 4.28 mg/L TP. The average effluent total phosphorus concentration was 1.45 mg/L TP. Therefore, an average of 65% TP removal is achieved. Data from our pilot algal ponds and from the literature shows that open algal ponds may achieve similar rates of nutrient removal. Nutrient removal was measured weekly during the 6 month experiment. A maximum of 61.4% and 90.6% removal of TN and TP, respectively, was achieved. In a separate study, a twin

Table 1
Wastewater effluent nutrient concentration goals [32].

	Nutrient concentration (mg/L)			
	EPA	COE	KDHE	BAT
TN	0.56–2.18	6.0	8.0	3.0
TP	0.020–0.067	1.5	1.5	0.3

EPA's 2001 ecoregional nutrient criteria range (Kansas).
US Army Corp of Engineers (2001).

layer algal system reduced nitrogen and phosphorus nutrient concentrations in wastewater by 90% in 9 days [26].

BNR is an immensely energy intensive process, accounting for 60–80% of energy consumption during wastewater treatment [4]. At the Blue River Main Wastewater Treatment Facility, the energy consumption for the facility averaged 3813 MW h/year in 2004 and 2005. From 2007 to 2009, after BNR began, the average energy consumption increased by 41% to 5376 MW h/year. The BNR system required 761 kW h/mgal, or 2.8 kW h/lb of TKN and TP removed. The additional electrical usage required for adding nutrient removal at several US WWTPs has ranged from 600 to 2600 kW h/mgal [27]. The replacement of a BNR system with an algal system will result in energy offsets of 5725 kW h d⁻¹ (based on the 90% TN and TP removal).

2.3.2. Anaerobic digestion

Many municipal WWTPs, including the City of Lawrence WWTP, operate anaerobic digestion systems as part of their biosolids stabilization process, and these units are capable of producing biogas and heat that can be used by algal production processes. Reported biogas energy productions range from 350 to 525 kW h MGD⁻¹ of treated wastewater, for flows greater than 5 MGD [24]. Approximately 4200–6300 kW h d⁻¹ could be utilized for furnace, boiler, or cogeneration systems. A general guideline for biogas production from anaerobic digestion of secondary solids is 1.0 ft³ capita⁻¹ d⁻¹ per person per day, with a resulting 65% methane concentration [28]. Given a population of 90,000 for Lawrence, KS, combustion of this methane would produce nearly 6800 lb d⁻¹ of CO₂. CO₂ generated from methane combustion could be captured and supplied to algal growth reactors to increase algal productivities. If sparged in the algal pond with a flow of 12 MGD, at standard temperature and pressure, 4.8% CO₂ by volume can be achieved, which exceeds the suggested 2% CO₂ solution [7]. Any additional heat from this system could be recovered and used for further dewatering of algal biomass or heating of the algal ponds, as outlined in Fig. 2. For the current energy analysis, the potential energy credits from biogas combustion and heat recovery have been ignored, since this technology has not been demonstrated for algal ponds. However, this is mature technology and provides opportunity for merging wastewater treatment with CO₂ sequestration as well as nutrient removal.

3. Results and discussion

The energy gained from the ultimate combustion of either algal biodiesel or dry algal biomass has been calculated with six different biomass thickening and dewatering alternatives. The average algal productivities obtained in our pilot study were used for all calculations, but the energy revenues for biofuel combustion were compared for algae with 10% lipid content (achieved in our pilot without CO₂ addition or nutrient manipulation to induce nitrogen stress) and 50% lipid content. The energy gained from fuel or biomass combustion was added to the calculated energy credit for nutrient removal, and this value represents a potential energy gain for the total process. The difference between the energy that can be gained from the system and the energy cost of algal growth and dewatering represents the maximum energy that may be consumed by other processes (i.e., lipid extraction, fuel conversion, transport, or combustion) for the system to remain energetically favorable. The resulting alternatives are represented in Fig. 3; the estimates from Fig. 3A represent values collected from experimental field data, whereas Fig. 3B demonstrates potential energy gains when a higher algal lipid content is realized.

In all instances, energy losses associated with algal growth and dewatering are less than the potential gains, except for when

evaporation is used as a dewatering system for biofuel combustion. The viable process combination that resulted in the lowest energy surplus (3700 kW h d⁻¹) was the production of biofuel with DAF and centrifuge dewatering. The combination with the greatest energy surplus for biofuel production was chemical flocculation followed by gravity sedimentation and a belt filter press. Since biomass combustion was estimated to yield more than four times the energy of biofuel combustion from our experimental data, the greatest surpluses were always observed with biomass combustion. For comparison, the gravity and belt press combination had a calculated energy surplus of 8600 kW h d⁻¹ with biofuel combustion, and 22,600 kW h d⁻¹ for dry biomass combustion. Also, evaporation remained a viable dewatering process in combination with biomass combustion. When 50% lipid content is assumed for the same biomass productivities, we estimate that more energy can be gained from biofuel combustion, rather than biomass combustion (Fig. 3b) because a 30% loss of efficiency was assumed for biomass combustion. Evaporation remained a viable dewatering technology in conjunction with biofuel combustion, when biomass had a 50% lipid content rather than a 10% lipid content. This model has a number of avenues for process synergies that were omitted from this energy analysis, but which could boost biomass productivity and make the system more viable. Specifically, if CO₂ is recovered from methane combustion and added to the algal ponds, biomass productivity should increase while lowering greenhouse gas emissions from a WWTP. Heat can also be recovered to offset the cost for evaporation of algal biomass.

In order to demonstrate the relative contribution of individual processes on this energy balance, the two most energetically favorable options for each combustion path are presented in Fig. 4. Only the scenario with 10% lipid content of algal biomass is presented in this Figure, since it was the case demonstrated in the field experiment. The energy credit provided from offsetting the cost of BNR at a WWTP accounts for 24–55% of the total energy gained in the systems, which is consistent with other estimates [4]. This demonstrates the large potential for coupling algal biomass production facilities with municipal WWTP, and this should be pursued by the energy and water sectors working together [29]. If we ignore any energy credit for BNR, all biofuel and biomass alternatives remain viable, except for biofuel production that incorporates DAF thickening or evaporation. Therefore, this technology should not be considered for future designs, but rather, research should focus on ensuring that chemical flocculation and gravity sedimentation has no adverse effects on downstream fuel processing.

Since energy losses associated with full scale extraction of algal lipids are largely unknown, a range of values from the literature have been collected and are compared in Table 2. The estimates for energy consumption from lipid extraction and algal fuel production range from 4.4 to 31.5 GJ ton⁻¹ biodiesel, and there is a great amount of uncertainty in the specific process that can be applied at large scale. Research is currently being conducted on methods to efficiently lyse algal cells, on appropriate solvent to water ratios for extraction (in order to minimize the necessary extent of dewatering), and on the specific extraction technology that is most economical at scale. Despite the uncertainty in these values, the estimated energy requirements were applied to the experimental productivity and lipid content values achieved in this field experiment, and the energy losses due to extraction were added to losses due to algal growth, chemical flocculation, gravity sedimentation, and belt press filtration to produce Fig. 5. Since the energy losses from extraction vary greatly depending on the source, three separate analyses are presented. For all three, the total energy loss of algal cultivation to biodiesel is estimated to be less than the energy content of the produced biodiesel in our WWTP pilot system. The maximum energy losses, including extraction and fuel conversion, were estimated as 2800 kW h d⁻¹, while the energy content

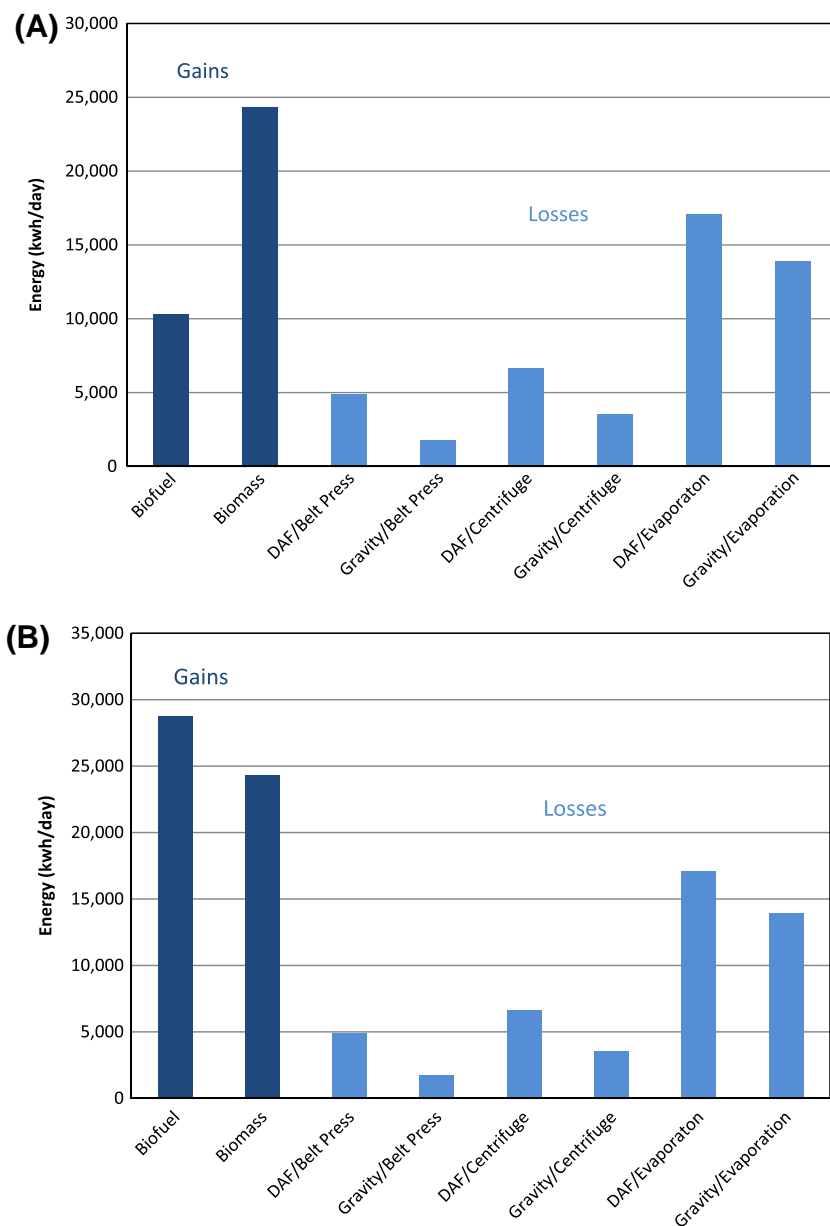


Fig. 3. Comparative algal dewatering energy gains and losses for biofuel and biomass production from municipal wastewater. An average algal productivity of $12 \text{ g m}^{-2} \text{ d}^{-1}$ was obtained over a 6 month open pond pilot study. Energy yields associated with this biomass productivity with a 10% lipid content (A) and a 50% lipid content (B) are shown.

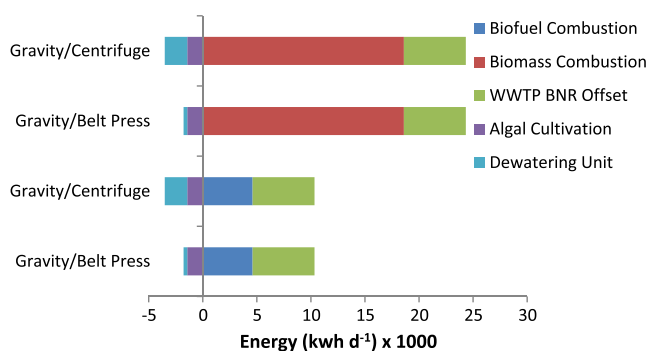


Fig. 4. Total energy losses for the growth and harvesting of algal biomass by two alternate processes are shown with the potential energy gains associated with either biofuel or biomass combustion. The energy offset for WWTP biological nutrient removal is also included.

of biodiesel produced was 4600 kW h d^{-1} , without any energy credits from offsetting BNR.

Despite the relatively low biomass productivity and lipid content achieved in this field experiment, the energy balance shows great promise for coupling nutrient removal with algal biomass or biofuel production. Furthermore, in a nitrogen limiting system such as this one, a theoretical maximum algal yield can be estimated if all nitrogen available in wastewater effluent in the US were converted to algal biomass. Using the average total nitrogen of wastewater effluent for this study (19.5 mg N/L), an algal cell stoichiometric Redfield expression of $\text{C}_{106}\text{H}_{263}\text{O}_{110}\text{N}_{16}\text{P}_1$ [30], and a total wastewater effluent flowrate of 25,800 MGD in the US [24], an estimated maximum 31,800 tons of algae could be produced per day. With an energy content of 21.4 kJ/g , $172 \times 10^6 \text{ kW h d}^{-1}$ ($62,700 \times 10^6 \text{ kW h yr}^{-1}$) of energy could be generated from these systems. While this theoretical maximum production is only a small percentage of the total US energy

Table 2

Comparison of estimates for energy and heat requirements of biodiesel production from microalgae.

	Units GJ ton ⁻¹ biodiesel	This study (10% lipid content)	Batan et al. [7]	Lardon et al. [6]	Stephenson et al. [10] ^a
Cultivation		9.7	0.8	5.7	7.2
Flocculation		3.0			0.5
Centrifugation		15.0	10.7	–	2.0
Belt filter press		12.2	–	11.9	–
Oil extraction					
Electricity		–	21.8 ^b	3.9	0.3
Heat		–	–	10.2	2.3
Lipid conversion					
Electricity		–	9.7	–	0.2
Heat		–	–	0.9	1.6

^a Values for this reference taken from Table 3 in Ref. [10].

^b Value calculated from reported energy requirements of 52,149 kW h ha⁻¹ with oil yields of 43,009 L ha⁻¹; biodiesel density assumed to be 0.88 g mL⁻¹.

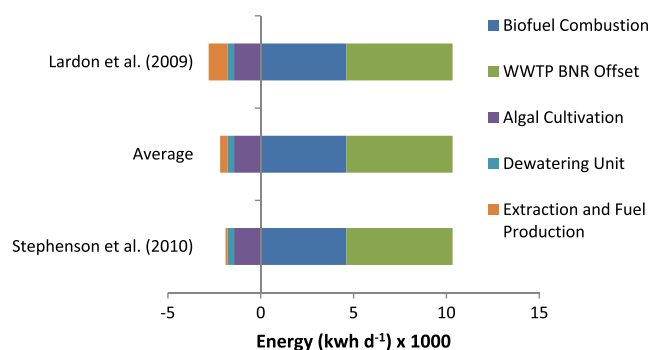


Fig. 5. Total energy losses and gains for the production of algal biodiesel with flocculation, gravity sedimentation, and belt press dewatering. Three estimates for the energy losses associated with lipid extraction and oil conversion are compared (sources outlined in Table 2), assuming the lipid productivity of this field experiment instead of the reported values.

consumption, it compares favorably with other energy recovery systems currently in place at wastewater treatment plants. A recent study estimated that if all wastewater treatment plants in the US utilized biogas produced from anaerobic digestion, nearly 5000×10^6 kW h yr⁻¹ would be produced [31].

4. Conclusions

The results show that biofuel production is energetically favorable for open pond reactors utilizing wastewater as a nutrient source, even without an energy credit for nutrient removal. The energy content of algal biomass was also considered as an alternate to lipid extraction and biodiesel production. Direct combustion of algal biomass may be a more viable energy source than biofuel production, especially when the lipid content of dry biomass (10% in this field experiment) is lower than the high values reported in lab scale reactors (50–60%). In addition to nutrient removal, there are several processes in WWTP that can be coupled to algal biomass production to improve the energy balance, and to lessen the environmental footprint of WWTP, particularly CO₂ and heat recovery from biogas combustion.

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