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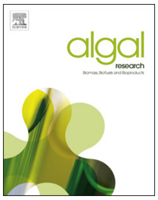

Flare gas recovery for algal protein production

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ABSTRACT

Concern about the sustainable supply of energy and food for future generations has motivated researchers to investigate alternative production pathways. Algal systems represent a promising environmentally favorable production platform for fuel and protein production, however there are many barriers to commercialization, including high energy and intensive fertilizer demands. Meanwhile the volume of flared natural gas around the world has approached 140 billion cubic meters per year. This study investigates the energy return on investment (EROI) of the synergistic integration of flare gas with a microalgae biorefinery. The biorefinery modeled herein includes all sub-processes required for the coincident production of biomass and conversion to biocrude along with a protein-rich feed product. The performance of the biorefinery was estimated by conducting a mass and energy balance for all of the sub-processes. For this design, flare gas is utilized in a combined heat and power plant to generate heat, electricity, and ammonia for use onsite. Using this method, the baseline EROI is 159, which is higher than conventional energy and food production systems. A life-cycle assessment indicates significant emission reductions with a total well to product emission of −786 $gCO_{2\text{-eq}}$ MJ^{-1}. Alternative accounting scenarios and sensitivities are evaluated. Results show the proposed pathway as an opportunity to utilize flare gas for the production of biofuel and protein from algae representing an environmentally beneficial system.

1. Introduction

Recent studies demonstrate that global protein demand is projected to increase by more than 100% by 2050 [1,2]. There are major environmental impacts associated with food production (particularly protein production) and managing these impacts as the population grows is daunting. Research shows that roughly one-third of arable land and up to three-quarters of freshwater is devoted to global food production [3,4]. Increasing demand from a growing global population highlights the need for the development of alternative protein sources. Agricultural production of algal biomass is a promising candidate to fill the anticipated gap between supply and demand with inherent advantages such as high productivity, suitability for non-arable land, and compatibility with low quality water [5], which are among the largest constraints for traditional crop production [6]. However, despite significant investments from government agencies and private companies [7], energy-efficient, economical, and sustainable production of algal bioproducts has yet to be demonstrated [8].

Primary limitations on algal bioproduct systems are associated with high energy and nutrient consumption in the growth phase, large energy demand for product separation in the harvesting phase, and complications associated with processing and drying wet biomass for end use [8–15]. The barriers to realizing energy efficient production of algal bioproducts include electricity demand (predominantly to supply water and carbon dioxide to the algae facility and to mix the growth volumes), heat requirements (primarily for drying biomass), and energy embedded in nutrient requirements (mainly carbon, nitrogen, and phosphorus) [9].

Meanwhile, significant quantities of natural gas (which is a hydrocarbon co-product of oil extraction) are disposed of every day by flaring (i.e., combustion) at production, distribution, and refining sites. It has been estimated that over 140 billion cubic meters (BCM) per year of natural gas was flared in 2012, representing 3.5% of global production [16]. Flaring occurs when excess gas is produced during oil recovery and economical transportation routes are not available to move the gas to market. In 2014, The United States vented and flared roughly 8.5 BCM (300,000 million cubic feet (mmscf)) of natural gas at oil-and-gas production and processing facilities, which is about 1% of total US extraction [17]. Assuming a heating content of 55 MJ/kg (1033 BTU/cf) and an electricity conversion efficiency of 55%, this amount of gas is sufficient to provide electricity to the entire state of Oregon [18].

Despite the apparent waste, the use of flaring helps manage logistical and safety concerns while reducing the overall environmental impact by converting methane with a global warming potential (GWP) of 29 to carbon dioxide (GWP = 1) [19]. In recent years, up to 30% of produced gas in the Bakken field of North Dakota was flared [20]. Recent studies used satellite instrumentation to observe flare sites around the

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world [16,21]. The results revealed thousands of onshore and offshore flare sites associated with production, transportation, refining, and consumption of hydrocarbons. Some of the top flaring countries in the world include Russia, Nigeria, and Iran. As of 2012, the largest flares in the world were located near Punta de Mata, Venezuela with estimated individual flow rates of approximately 1 BCM per year. By comparison, the United States has the largest number of flares of any country, but the vast majority of flare sites burn much less than 0.01 BCM per year (the equivalent of approximately 1 mmscf per day assuming the flare burns continuously throughout the year).

In this study, we propose using flare gas to generate electricity, heat, and nitrogen fertilizer in a novel, integrated pathway to improve the energy efficiency of algal bioproducts (i.e., biocrude and algae meal), increase global protein production, and reduce the negative environmental impacts of oil-and-gas production from flare gas combustion. The integration of algal cultivation systems with flare gas represents a potentially synergistic activity because it would mitigate environmental impacts while producing valuable commodities.

As a proof-of-principle, we use an energy and mass balance approach to evaluate the energetics and life-cycle emissions of the combined system, recognizing that complete techno-economic (TEA) and additional life-cycle analyses (LCA) are needed in future work to fully characterize the feasibility of the proposed system at commercial scale. The energetics of the production system are evaluated with two metrics: 1) the energy return on investment (EROI) [22] and 2) the energy impact of protein-rich algae meal [23]. The life-cycle analysis determines the net greenhouse gas (GHG) carbon dioxide equivalent (CO_2eq) emissions for the proposed system [24]. By utilizing waste flare gas, this study demonstrates the potential to simultaneously improve the EROI for algal biofuels, reduce the energy intensity of protein meal, reduce emissions, and mitigate the deleterious effects of wasted natural gas. Furthermore, this work conducts a direct comparison of results to previous assessments of traditional fuels, crops, and livestock products in the literature. Discussion includes the potential of the proposed system, environmental impact of integrating flare gas with algae cultivation, and the impact of energy allocation on results for flare gas and co-product electricity.

2. Methods

The analysis was completed using an engineering system model that was constructed in a modular fashion with validated sub-process models as shown in Fig. 1. Sub-process models – flare gas recovery and conversion, biomass production, and biomass processing – were independently validated and integrated into the engineering system model. A single industrial processing facility is modeled that includes the delivery of flare gas from co-located oil-and-gas operations and used to operate a combined heat and power generation plant (CHP) (i.e., cogeneration), ammonia production system, algae cultivation platform, and algae processing system. This design enables convenient electricity distribution for all sub-systems and facilitates the integration of heat recovery from CHP within one site. Carbon is the limiting resource for most algae systems [9,25,26], so the algal cultivation facility was sized to be 10 ha to accommodate all of the carbon dioxide produced from a flare site with a gas flow rate of 2,050 m^3/day (72,000 scfd). Volumetric flow rates at individual domestic flare sites can vary widely from less than 3 m^3/day (100 scfd) to more than 28,000 m^3/day (1,000,000 scfd) [20,27,28]. Volumetric flow rates at international flare sites can exceed 270,000 m^3/day (9,540,000 scfd) [16]. The flare gas flow rate was chosen to represent a single moderately sized flare site or the combination of multiple smaller flare sources that can provide a dependable supply of flare gas.

A summary of the critical input parameters for the integrated model are presented in Table 1 with details on each of the sub-process models presented in the following sections. The engineering system model was used in conjunction with life cycle inventory data to evaluate the environmental impact of the proposed process on the metric of greenhouse gas emissions.

2.1. Flare gas recovery

For the proposed system, repurposed flare gas could be sourced for a single processing facility from multiple nearby wells to ensure a steady supply considering that the flow rates of individual wells vary. The flare gas could also be sourced from a single large facility such as a refinery or

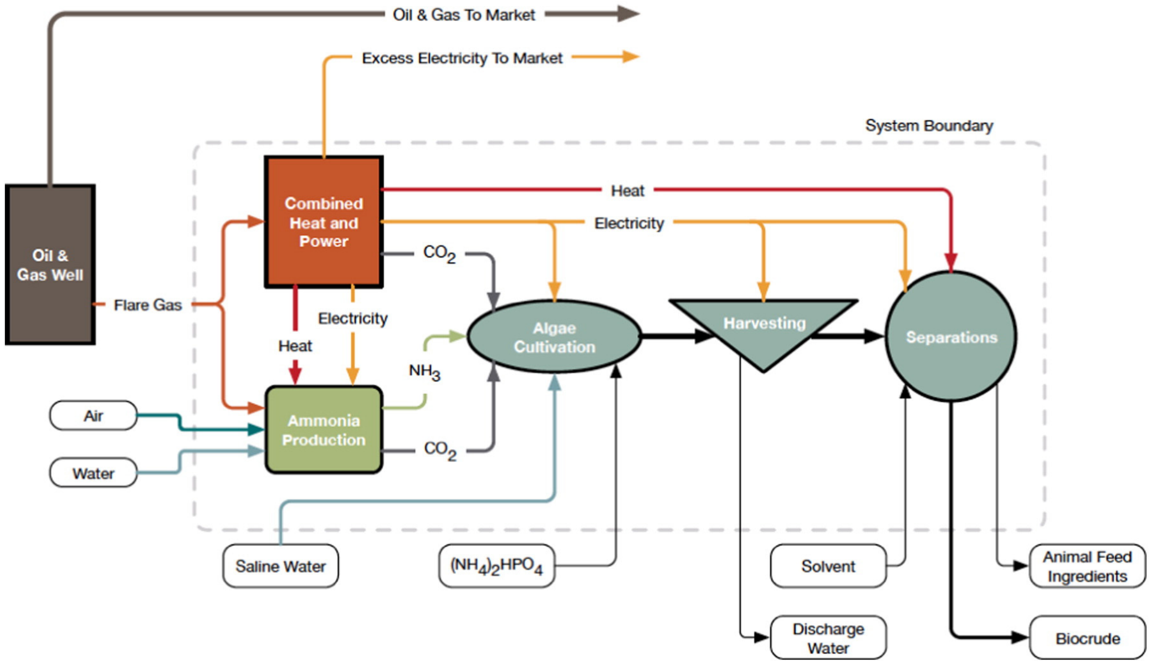

Fig. 1. Baseline process flow diagram for utilizing flare gas to produce protein from algae.