An energy analysis on the production of torrefied microalgal biomass

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Abstract. Torrefaction is a process for upgrading raw biomass into an energy-dense fuel. In this study, an energy analysis was conducted to assess the energy consumption in the production of torrefied microalgal biomass. The functional unit of one kilogram torrefied biomass and a system boundary of cradle-to-gate was used. This includes the life cycle stages of cultivation, harvesting, drying, and torrefaction. To include the varying method for the upstream processes, four different scenarios of torrefied biomass production are considered. The result of the analysis revealed that across all four scenarios, the torrefaction stage had a minimal contribution of 1-20% as compared with other life cycle stages. However, even with very optimistic assumptions among all scenarios, the result of the study shows a large energy deficit on the system due to the high energy consumption involved in the cultivation method and even in the drying process. To minimize energy consumption during the cultivation stage, solar lighting was highly recommended. The use of a solar-assisted drying was also advisable to lessen the energy consumption for the drying stage.

Keywords: Cumulative Energy Demand, Life Cycle, Microalgae, Torrefaction,

1. Introduction
Biomass is known as one of the most abundant and renewable energy source globally [1]. However, as compared to fossil-based fuels, the physical characteristics of biomass limit its capability to be used in many applications. Raw biomass has a high moisture content, prone to microbial degradation, and has a lower calorific value. To improve its properties, one promising technology is the use of a thermochemical process called torrefaction. Torrefaction is a pre-treatment technology where biomass is heated to 200-300 °C in an inert environment for 10-60 minutes. The primary product of biomass torrefaction is called torrefied biomass, while bio-oil and syngas are its co-product [1].

Microalgae is a unicellular photosynthetic microorganism that are typically found in surface water with the characteristics of having a high carbon fixing efficiency and fast growth rate [2]. For microalgae to solid fuel production using torrefaction, studies by [3] show that it effectively increased its heating value ranges from 15-20 MJ/kg to 27.93 MJ/kg. The obtained value is close to bituminous coal
which is the range of 25 to 35 MJ/kg. However, despite the positive effect of torrefaction on the microalgal biomass, there is some uncertainty about the energy requirement at each production level. According to [4], there is uncertainty about the microalgae to bioenergy product production in terms of its energy consumption. Thus, a need for energy analysis studies for microalgae to bioenergy products should be performed [5-7].

However, as of today, there are no studies about the energy analysis on the torrefied microalgal biomass. To address the gap, this study aims to identify and compare the energy intensity on the production level using the life cycle assessment method. Also, to address the different production scale and cultivation method, four different scenarios were included and the functional unit of 1 kg torrefied microalgal biomass was used. To systematically analyze the data, the study uses the Cumulative Energy Demand method from the commercially available tool SimaPro 8.5.2 developed by Pre-Consultants.

2. Methodology

2.1. Life Cycle Inventory (LCI)

The production of torrefied microalgal biomass used in this study was consists of four scenarios. Scenario 1 is the lab-scale model for torrefied microalgal biomass production where the raw microalgal biomass was cultivated using an open pond. Scenario 2 is the lab-scale model where the microalgal biomass was cultivated using a photobioreactor system. Scenario 3 is the pilot-scale model where microalgal biomass was cultivated using an open pond and lastly, scenario 4 is the pilot-scale model where microalgal biomass was cultivated using a photobioreactor system. To provide a comparative analysis, the lab-scale models were compared using the annual wet biomass productivity of 50 kg/year while the pilot-scale model was 100,000 kg/year. The general system boundary for the production is shown in figure 1.

![Diagram of the system boundary of the production of torrefied microalgal biomass.](image)

**Figure 1.** The system boundary of the production of torrefied microalgal biomass.

2.1.1. Laboratory scale model

The life cycle inventory data for the lab-scale model cultivated using an open pond, Scenario 1, was derived from the different LCA literature for microalgal biomass. The electricity requirements for the cultivation process were obtained from the works of [8], nutrients and energy requirements during the
The drying and torrefaction energy requirement was obtained from the Research Center for Energy Technology and Strategy, National Cheng Kung University, Tainan, Taiwan.

The life cycle inventory data for the lab-scale model cultivated using a photobioreactor system, Scenario 2, were obtained from the Research Center for Energy Technology and Strategy, National Cheng Kung University, Tainan, Taiwan where it is cultured, harvested, and dried while the torrefaction process was done at the Green Energy and Fuel Laboratory, National Cheng Kung University.

2.1.3. Pilot-scale model
To project the impact of the pilot-scale model, the LCI for the raw materials for Scenario 3 and 4 were adapted from [5, 10], cultivation and harvesting from [11], and rotary drum drying from [12]. Due to the limited data for the energy consumption of the torrefaction process, especially for the pilot-scale torrefaction plant, the pilot-scale torrefaction data from [13] was used for the torrefaction data from this study. The data for the pilot-scale torrefaction was also compared with the study of [14].

2.2. Torrefaction
The torrefaction experimentation is performed at the Green Energy and Fuel Laboratory, National Cheng Kung University, Tainan, Taiwan. Pure nitrogen (99.99%), fixed at 300 ml/min, is used to provide the inert environment. The reactor is composed of a glass tube, a power controller, a tube furnace, and a circulating bath. For temperature measurement, an embedded K-type thermocouple was used.

3. Results and Discussion
The Cumulative Energy Demand from SimaPro 8.5.2 includes the non-renewable resources namely fossil fuel, nuclear, and biomass while the renewable sources are wind, solar, water, and geothermal. Fossil fuel include the use of hard coal, crude oil, lignite, natural gas, peat, and coal mining off-gas. The non-renewable resources such as nuclear energy includes the use of uranium, while non-renewable biomass uses wood and primary forest biomass.

![Energy Consumption (%)](#)

**Figure 2.** The cumulative energy demand for torrefied microalgae biomass

The resulted energy analysis for torrefied microalgae biomass, as shown in figure 2, shows that among all the sources of energy, non-renewable fossil fuel has the highest contribution by 75 to 79%. It is then followed by the use of non-renewable nuclear energy by 16-23%, and the remaining percentage for renewable water, wind, solar, geothermal, and biomass.
Figure 3. The energy consumption of the four scenarios

As shown in figure 3, among all scenarios, scenario 2 has the highest energy consumption with a total requirement of 3,343 MJ energy. It is then followed by scenario 4 > scenario 3 > scenario 1 with 1,355 MJ, 537 MJ, and 507 MJ energy respectively.

To identify the hotspot, the process contribution for the four scenarios were shown in figure 4. The analysis revealed that regardless of the production scale, the type of cultivation type has a significant impact in terms of its energy consumption. As noticed, figures 3a and 3c show that when the cultivation is done using an open pond method, the drying process consumes the highest amount of energy. It is contrary to the result of figures 3b and 3d where the cultivation method using a photobioreactor shows to be more energy extensive as compared to the drying process.

Upon scrutinizing the data, 82% of the high energy requirement for scenario 2 came from the cultivation method wherein it uses an artificial light source operated 24hrs/day. Meanwhile, the energy consumption for scenario 4 was lessen by 40% as compared to scenario 2 since the cultivation was done outdoor. However, a high amount of energy was still needed to maintain the condition of the photobioreactor type cultivation method. Similar to scenario 2, the cultivation method still has the highest contribution by 76%. For scenario 1 and 3, since all the open pond models were cultivated outdoor, a minimal amount of energy was used. In this case, the drying process contributes 55% for scenario 3 and 69% for scenario 1.

Moreover, among all scenarios, the harvesting and the torrefaction process consume a lower amount of energy as compared to the other processes. In this study, after the torrefaction experimentation, the calorific value of the raw microalgal biomass increased up to 27.93 MJ/kg. This indicates that torrefaction effectively increased the microalgal biomass’ energy content while consuming a lower amount of energy. The torrefaction process only contributes by 3-20% to its total energy consumption for scenario 1 and 2 and <1% for scenario 3 and 4. However, even with the inclusion of the torrefaction process to increase its energy content, the higher energy consumption during the upstream process contradicts this significance.
4. Conclusion

The resulting energy requirement considering the different production scale and cultivation method from lowest to highest follows the order of scenario 1 < scenario 3 < scenario 4 < scenario 2. Regardless of the production scale, the cultivation type has a significant impact when comparing each process. The energy analysis revealed that when the cultivation method is done using a photobioreactor type, 76% to 82% of the total energy requirement is only for the cultivation process. The energy requirement is high as compared to 10% to 38% for the open pond cultivation method.

On the other hand, even with a lower energy requirement, the torrefaction process effectively increased the energy content of the microalgal biomass by 40% up to 50%. Across all scenarios, the torrefaction process consumes a lower amount of energy by just 1% to 20%. However, the high energy requirement during the upstream process negates this advantage. The total energy requirement during the whole production resulted to be higher as compared to the produced energy, making the energy output lower as compared to the energy input.

To minimize energy consumption during the cultivation process, solar lighting is highly recommended. The use of a solar-assisted drying is also advisable to lessen the energy consumption for the drying process.
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