Life Cycle Assessment of the Microalgae Biofuel Value Chain

A critical review of existing studies

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***Abstract*—Innovation towards a scalable and viable microalgae industry for renewable and sustainable bioenergy is greatly assisted by the application of life cycle assessment as a benchmarking tool to guide the process. This work examines existing studies in the field that have attempted to assess either the environmental impact and/or commercial viability of the microalgae value chain. Existing literature tends to omit established conventions of life cycle assessment practice, and/or lacks a common approach to boundary definition, functional units and impact assessment that would enable more effective comparison of options. A move towards a 'level playing field' methodology would enable strategic prioritization of research efforts to emerge that could lead to more rapid development of preferred products, cultivation and harvesting technologies, and downstream processing pathways.**

Keywords: microalgae, life cycle assessment, life cycle impact assessment, value chain, techno-economic assessment

I. Introduction

Life cycle assessment (LCA) is a tool within the broad discipline of life cycle management (LCM), "a business management approach that can be used by all types of businesses (and other organizations) to improve their products and thus the sustainability performance of their companies and associated value chains" [1]. LCA is commonly used as a means to benchmark and compare designs, processes and systems, with a view to continuous improvement. Based on standardized methods published by the International Standards Organization (ISO 14040/14044 [2006]), it can provide valuable insight into the overall efficiency and impact of discrete energy and material flows that are relevant to processing and manufacture of a product across its various life cycle stages, and for assessing the aggregated impact of these as a whole.

The benefits of conducting LCA include the ability to;

1. identify and hone in on environmental and economic risks or 'hotspots' within a products' life cycle.
2. gain an understanding of both the upstream and downstream implications of various design choices.
3. inform and guide decision-making as part of an innovation program.
4. communicate more effectively and credibly regarding environmental claims.
5. benchmark, report and track on progress over time.
6. apply a common life cycle impact assessment (LCIA) method to effectively compare the overall product, system or process 'footprint' with its relevant alternatives.

A common criticism of LCA studies based on the last point above, including those relating to biofuels, is that they often have no collective basis for real comparison of results and are not based on a shared set of assumptions or assessment methods [2, 3]. As such, LCAs are sometimes criticized of being manipulated to justify environmental claims, or to retrospectively produce favorable or biased results of products. Likewise, many published LCA studies often present little more than an energy and greenhouse gas (GHG) audit, or life cycle inventory (LCI) only, with no impact assessment methodology applied at all. As such, the relative impact of various identified or documented flows of energy or materials at a macro-scale can be either absent, obscured or misrepresented, even where large flows for instance may be immaterial to the overall outcome (or vice-versa).

While this paper presents a selection of published LCA studies relating to microalgae biofuels, it is not the intention of this review to query specific numbers or findings, as such, or to comment on the veracity of results. However, the purpose of reviewing existing studies is to underscore how differences in LCA methodology make it difficult to achieve collective progress towards commercialization of the microalgae biomass value chain in the absence of shared methods for framing of studies and presentation of relevant data, including assessment of environmental impact. As such, the purpose of this investigation is to highlight the many variables inherent across the life cycle, from species selection through to processing and delivery of downstream products, with a view to recommending a more strategic, industry-wide collaborative approach to LCA-driven innovation, based on agreed standards.

The structure of this paper is based firstly on presentation and discussion of the US DOE's microalgae biofuels industry roadmap, followed by a review of existing LCA studies, focus on the various methodological orientations

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taken, discussion of co-products and allocation in LCA, and finally, conclusions and future work.

II. Methodological Challenges in Microalgae LCAs

The following section outlines the industry roadmap and describes the many differences that exist between published studies, research pathways and areas of commercial endeavor that influence LCA modeling and interpretation.

A. *Prospects for a common approach*

The US Department of Energy published a *National Algal Biofuels Technology Roadmap* under the auspices of the Biomass Program in May 2010 [4]. This document sets out the broad parameters within which techno-economic assessment and innovation of the algae biofuel product value chain can and should occur, in order to drive towards full commercialization. It advocates the integration of recognized LCA methods, with a specific focus on leveraging previous biofuel feedstock studies.

Additional aspects considered in the DOE report include the opportunity to leverage GIS technology to identify specific areas suitable for scalable microalgae cultivation, based on availability of non-arable land and proximity to necessary process inputs, infrastructure and markets. The report also reflects on co-location with synergistic industries, such as stationary power generators or wastewater treatment plants, as a means to explore innovation in the sector.

The DOE roadmap provides a conceptual framework that highlights the importance of LCA as tool that can contribute to commercialization efforts. Notably, the report also observes that in addition to measuring net greenhouse gas (GHG) emissions, LCA “can also assess impacts and tradeoffs associated with utilization intensity for water, energy, nutrients, and other resources.” [4]

Overall, the roadmap presents a critical challenge for LCA, namely that there are multiple cultivation and processing choices that can be made, spanning from species selection, through to cultivation, intermediate constituents, conversion processes and end user products and markets. The inference being that without at least some degree of harmonization of data collection, boundary definition and/or assessment methods, effective comparison, prioritization and innovation across multiple pathways will be extremely difficult.

B. *Review of existing studies*

The existing published works reviewed here are related to microalgae LCA and are divided into three broad categories. The first covers the spectrum from energy, greenhouse gas and mass balance calculations, to high-level ‘scoping’ LCA studies [5-7]. These do not report beyond a limited set of metrics and/or do not appear to apply or present any discrete LCIA method.

The second category of studies appear to be based on more traditional LCA reporting practices that take a more comprehensive approach to LCIA [8-11]. Nevertheless, they do not generally share a common set of goals, system boundaries, assumptions and/or impact assessment methods, and only the overall approach and structure each adopts is similar, at the very highest level (as proscribed by the ISO standard).

The final category sees LCA results and ‘life cycle thinking’ either directly or indirectly implicated through techno-economic assessments (TEAs), that seek to primarily address the commercial feasibility of the process overall [12, 13]. These may or may not include an approach designed to also measure, assess and report on environmental impacts, however their consideration is necessary to appreciate the growing body of work in this area. While a TEA is a fundamentally different proposition to an LCA, it must be based on relevant assumptions of productivity, as well as material and energy flows, that enable a fully costed model to be assembled. As such they do share common data elements with LCA, although the approach to data collection, interpretation and validation may well be quite different.

Since microalgae is posited as a sustainable alternative to fossil sources of material and energy, those concerned primarily with assessing the environmental impact of industrial microalgae production seek at a minimum to ensure that the overall value chain leads to a net carbon reduction [14-16]. Those interested in techno-economic studies seek, in the main, to establish the capital and/or operating cost profile of an end-to-end process, to ensure economic viability of the proposition. Ultimately, integrated assessment from both perspectives is necessary in order to realize the goal of a scalable, ecologically sound, socially responsible and yet commercially viable solution, surely the intent of sustainable development [15, 17-20].

However, reducing capital and operational costs and adequately assessing environmental impact is complex as fully scaled commercial operations are essentially non-existent and lab scale findings must often be relied upon for extrapolation [10]. Cultivation and harvesting technologies for instance are mostly immature and yet to be realized, hence many studies represent, “a prospective LCA of a non existing process” [8], and very few published studies have even gone on to consider human resource demands of operation, such as labor implications [21].

One study seeks to overcome the nascent status of a scaled microalgae industry by suggesting a bulk growth model that will enable more accurate LCA studies to be formulated [22]. This uses a series of mathematical models relating to light intensity, nutrient uptake and lipid accumulation for instance, to predict maximum thresholds of productivity, also applying a sensitivity analysis to develop a level of confidence in results. The approach put forward also makes allowance for differing geographic locations, since this impacts directly on growth and is a key aspect often overlooked in existing microalgae LCA studies. Comparability of algae LCA studies also depends greatly on consideration of a common species, since a biochemical profile is fundamental to achieving productivity goals and downstream refinement into desired end products [23].

TABLE I. COMPARISON OF MICROALGAE LCA SYSTEM STUDIES

Study	Features of the study			
	Goal & Scope/ Product Orientation	***System Boundaries***	***Functional Unit***	***LCIA/ Reporting Method***
Batan et. al. [5]	Net energy ratio & GHG of PBR grown *N. salina* biodiesel + co-products	Cultivation-to-consumer; "Strain-to-pump" cf. "well-to-wheel"	Temporal, based on production process over 1 year	GREET 1.8c; displacement of co-products applied
Campbell et. al. [24]	GHG balance of *D. tertiolecta* in open ponds cf. ULS diesel + economic costs; includes people	Pond vs. well-to-tailpipe	CO_2e- of GHG emissions/t /km in an articulated truck	UNFCCC GWPs of GHGs only (100yr)
Chisti [13]	GHG ratio of 1.83:1, based on *P. tricornutum* PBR for elect. & biodiesel cf. bioethanol; incl. economic costs	Cultivation to oil extraction + power generation	MJ/t algal biomass	GHG balance only
Collet et. al. [8]	Biogas production cf. biodiesel from *C. vulgaris* grown in open ponds	Cultivation-to-generator gate; includes 30yrs fixed infrastructure	1 MJ fuel combusted in a gas engine	CML; substitution of co-products applied
Clarens et. al. [14]	Producing energy from algae biomass vs. corn, canola and switchgrass	Cultivation-to-processing gate (delivery of biomass)	317 GJ of biomass-derived energy	Crystal Ball; MJ, m^3 H_2O, CO_2e-, kg PO_4- eq., Ha land
Jorquera et. al. [25]	Net Energy ratio (NER) of *Nannochloropsis* sp. grown in multiple growth systems	Cultivation-to-processing gate (delivery of biomass)	1kt of dry weight	NER only
Lardon et. al. [10]	Expanded boundaries to ascertain broad impact of *C. vulgaris* biodiesel in open ponds cf. diesel	Cradle-to-combustion (fuel), Cradle-to-grave (facility); includes 30yrs fixed infrastructure	1 MJ fuel combusted in a diesel engine	Partial CML: AbD, Ac, Eu, GWP, Ozone, HumTox, MarTox, Land, Rad & Photo
Pfromm et. al. [6]	Mass balance orientation based on chemical engineering tehcniques, held as distinct from LCA 'accounting'	Uses conservation of mass, hence cradle-to-grave, incl. the atmosphere	LHV equivalent of 50m gal of petro-diesel	Balance calculation only - electrical energy, thermal energy, fertilizer, CO_2
Sander & Murthy [26]	Benchmarking algae biodiesel against other transport fuels, highlighting sustainability concerns	Cultivation-to-consumer; ("well-to-pump"), 5% cut-off value	1,000 MJ of energy	Relative mass, energy and economic (RMEE)
Soratana & Landis [11]	Biodiesel from *C. vulgaris* grown in a PBR, using 3 parameters: PBR material, source of CO_2, source of nutrients	Cultivation-to-pump; temporal also (5,10, 20yrs), includes infrastructure	3650kg of algae, grown over 20yrs	TRACI 3.01
Yang et. al. [7]	Water footprint of open pond culturing of *C. vulgaris*	Cultivation-to-finished product	1kg biodiesel	Water & nutrient balance

Critical differences between LCA and TEA studies create challenges in constructing an integrated picture since they each have slightly different conventions and overall orientation. In an LCA, it is common to specifically *exclude* the impact of fixed assets and infrastructure, since experience has shown that it is the environmental impacts related to the operational phase of a product value chain or process that dwarf all else. On the other hand, a financial assessment seeks to encompass all assets and operational costs (including labor), as accurate capital and operating projections are fundamental to building a business case, raising project finance and to calculating tax benefits such as depreciation. In this way, the veracity of LCA data is often far less 'complete' in terms of the precision of actual numbers than the 'line-by-line' accounting approach taken by a TEA. Nevertheless, sensitivity analysis, coupled with LCIA, can reveal credible scientific insights based on LCI results, without the need for absolute certainty on the volume of individual flows, especially where their variance is found to be inconsequential to the final result.

The existing body of work designed to assess the industrial-scale microalgae prospect also seeks to compare and contrast findings from a diverse number of analytical viewpoints (Table 1). For instance, some reports use the intermediary or end products (e.g. FAME, carbon abatement, MJ equivalent) as the basis of comparison [5], whereas others use the cultivation system [13], or perhaps both [27]. There are several trade-offs to be considered in design of the entire system, though it can be generalized that the greater amount spent on capital equipment and infrastructure (such as comparing open pond systems with photobioreactors), the higher the biomass productivity per unit area that can be expected [14, 15, 17, 28, 29]. Hence, a key position many studies attempt to establish is the point at which this trade-off is no longer justified.

A comparison of select studies, further highlighting the fundamental differences in approach to system boundary definition, is presented in Figure 1. All of these positions are equally valid however contribute to general confusion regarding system boundaries, goals, functional units, impact reporting categories and/or methods that would otherwise make fair and transparent, 'level playing field' comparison of value chain options across the innovation landscape possible [5].

C. *Functional units, comparability, inclusions and exclusions*

A study comparing the life cycle impact of cultivating microalgae in open ponds versus photo bioreactors (PBR) proposes a focus on net energy ratio (NER) as a functional unit, wherein the construction process and materials used, in addition to process energy, are collectively taken into account when making inferences about their relative suitability and efficiency [28]. However, the environmental impact of their respective operational lives, in this case mostly related to the energy used in pumping, mixing and CO_2 delivery, as well as possible impacts associated with process nutrients, will far outweigh these calculations relating to infrastructure [9], hence this metric appears questionable.

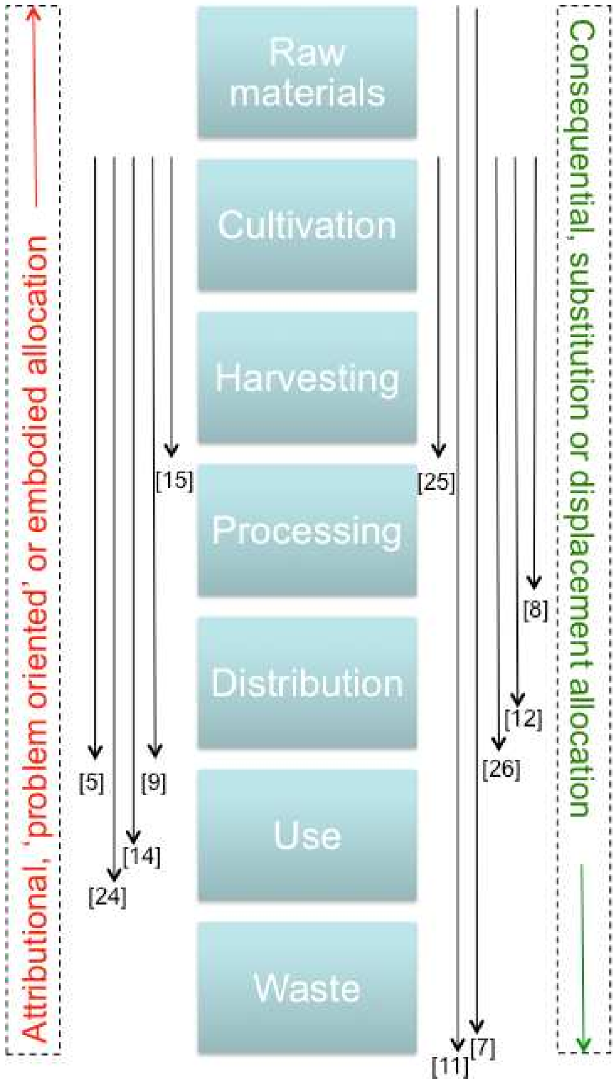

Figure 1. Examples of contrasting system boundary definitions in microalgae biofuel LCAs and related system studies (ref. Table 1)

Another illustrative work targets LCA of algae biodiesel, suggesting through this analytical approach that for every 1kg of algal biodiesel produced, approximately 1.4kg of co-products are generated [26]. This study is notable for several reasons. Firstly, it adopts the RMEE method wherein data relating to specific unit processes is assembled prior to the selection of system boundaries with the intent of avoiding arbitrary exclusion of certain items. The functional unit chosen relates to 1000 MJ of energy, based on a 'well-to-pump' system boundary. Mass, energy and economic value ratios are calculated for each input, with a cut-off ratio of 5% chosen as the sole basis to exclude items. This has the effect of neglecting the imbalance that often exists in relation to the type and volume of certain flows and applying a sensitivity filter *before* any impact characterization is undertaken carries this risk. That is, the environmental impact of certain industrial chemicals for instance are often disproportionate to the volume of their flows, hence this LCA approach could overlook such inventory items that would otherwise be captured under the terms of a more comprehensive study.

Another 'problem oriented' study coupled wastewater treatment and high rate algae ponds together to solve both an environmental and commercial problem. This is proposed as an example of the means to close the competitive price gap between the cost of biofuel production and incumbent fossil fuels [30]. In addition to removing nutrient from the water (a useful process input for algae growth), the capital and operating cost of a conventional wastewater treatment plant can be redirected to algae ponds and process water is better utilized overall.

Of particular relevance to realizing full-scale commercialization of algae biomass, biofuels and bioproducts is the establishment of a 'level playing field' approach to synthesis and interpretation of LCI results, that enable them to be interpreted in a meaningful way. This is essential in order for such studies to be comparable across the industry itself, regardless of the desired output product/s [31].

A comparative study of microalgae systems modeled 20 different cultivation scenarios, with a view to evaluation of 3 key parameters, namely chosen material for PBR construction, source of nutrients and source of CO_2 [11]. A further temporal dimension was added to this analysis to view the impacts of various scenarios in terms of length of operation of 3 alternate timescales. The LCIA method used here was based on the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI), from which 9 impact reporting categories were selected and reported against. The functional unit in this case benchmarks all LCIA results against the ability of a standardized PBR design to deliver a calculated yield of algae biomass over time (essentially based on productivity potential), with a view to downstream conversion to biodiesel. The standardization of reactor design in this work provides a useful anchor point, and leads to the observation that choice of PBR materials has a significant impact in relation to several environmental metrics, where this capital infrastructure is included in the model.

Production of algal biodiesel is assessed in a UK-based study, wherein the avoided impacts, or 'reference systems' are also modeled in order to establish the quantum of benefit [32]. LCIA is based here on a recognized, consistent reporting method, EDIP 2003, which adds gravitas and a degree of comparability to the results. In the case of liquid fuel substitutes, extending system boundaries to include combustion is necessary given that in this case, algal biofuel properties will differ when compared directly with their fossil alternatives [10, 29].

D. *Co-products and the challenge of impact allocation*

Since microalgae systems present an opportunity to remediate wastewater streams, address the emissions intensity of stationary power generators and heavy industry, as well as offset fossil resource consumption, this prospect offers potential environmental advantages when considered from an attributional LCA perspective, albeit from one that addresses multiple problems simultaneously [14]. This has important and possibly controversial implications for allocation of environmental impacts and suggests that more of a 'consequential' LCA orientation would neatly sidestep the inherited burden of the upstream processes (such as coal-fired power) that feed into it.

Attributional LCA by definition only really assists with answering a question based on the environmental impact of a burden at any given moment in time, largely based on average production practices. This is useful for simplified benchmarking and certification of environmental performance however fails to recognize the positive flow-on effects that a value-adding solution such as microalgae might deliver over time. Consequential LCA takes on a much larger scope by effectively trying to model scenarios over decades, including coupled flow-on effects and marginal changes, however adds significant additional complexity to the process.

Some published algae LCA studies that take an attributional approach conclude that algal biofuels are likely to perform poorly when compared with terrestrial biofuels from an environmental perspective. This is mainly reflected in the results for CO_2 and nutrients, hence the clear preference towards wastewater and emissions intensive-coupled growth systems as drivers of industrial microalgae commercialization [14, 16, 33]. Further, since water is also identified as a critical limiting factor for many potential algae cultivation sites, exploitation of wastewater for growth of freshwater algae species is likely to be essential to achieve any significant scale of production [34].

A thoughtful discussion of allocation methods in a study of algal biodiesel suggests direct substitution (consequential allocation) as the preferred approach, before concluding that byproducts and their impacts (where they only substitute existing waste byproducts of other processes, such as heat) should be avoided [32]. The reflection is that economic allocation is the simplest and best method to apply, in this case an approach to LCA that is in line with the demand cycles of the open market, albeit perhaps in conflict with the more optimistic, future-oriented view that a consequential orientation would deliver, in terms of assessing long terms impacts related to sustainable development.

Of critical interest to allocation in the microalgae context is the extent to which the downstream cultivation of microalgae (where CO_2 from an adjacent power station is utilized for growth) is considered an inherited environmental burden to the overall process. An undesirable outcome may result through application of an attributional LCA method, where burden is passed on and distributed proportionately down a value chain, whereas a consequential approach may lead to a more favourable assessment over time.

III. CONCLUSION AND FUTURE WORK

It is clear that LCA can be a valuable tool for innovating across the microalgae value chain with a view to full commercialization. However, there needs to be greater methodological consistency between LCA studies to guide this effort. In the case of algal biomass, allocation is a key methodological issue that needs to be strictly consistent in relation to assessment of all technologies and pathways, as this enables more balanced decision making to be made based on both utilization of wastes and generation of co-products. Future work should address the issue of harmonization of agreed system boundaries and LCIA methods, collectively benefitting the industry and enabling it to benchmark and report on multiple value chain options with greater confidence and comparability, based on a 'level playing field' approach. This effort should draw on the experience of other industries in establishing a common approach, in particular those that have already developed such LCA-driven methods, such as the Building Products Innovation Council (Australia) and The Sustainability Consortium for benchmarking of consumer products.

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