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DOCTORAL DISSERTATION

The development of an integrated environmental techno-economic assessment framework.
How to assess the potential of microalgal-based biorefineries?

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SUMMARY

During the development of a new technology, three main questions need to be answered: 1) "Is the process technologically feasible?"; 2) "Is the process economically profitable?"; 3) "Is the process environmentally sustainable?". The answers on these questions are currently provided by different assessment methodologies at different moments of technology development. This leads to differing system boundaries and a large variation in results.

An example of such a new technology is the concept of microalgal-based biorefineries. Microalgae are small photosynthetic organisms with a large productivity which can grow on degraded lands. They can accumulate large amounts of valuable components. Currently, most algal-related research focusses on the development of energy applications. However, this concept is currently not economically viable and the environmental impact is uncertain as well. Microalgal-based biorefineries can provide a solution as multiple products are valorized from a microalgae feedstock. This corresponds to increased revenues and a decreased environmental impact per product.

However, the results of the economic and environmental assessment of this concept vary as well. This can be explained by the large variation in methodological assumptions and the lack of an integrated assessment methodology. Based on a review of economic and environmental assessment of microalgal-based biorefineries, four recommendations were identified for the development of such an assessment methodology. First, a clear framework with predefined steps is required. Second, the methodology should be adaptable to the appropriate level of technology development. Third, the methodological assumptions should be clearly stated. Fourth, the technological assessment needs to be integrated to create a dynamic model, where a change in one parameter is automatically translated in a change in all output parameters. Based on these four recommendations, the Environmental Techno-Economic Assessment (ETEA) methodology was proposed, which integrates the Life Cycle

Assessment (LCA) methodology in the Techno-Economic Assessment (TEA) methodology.

The development of this methodology was initiated by developing a TEA case study on microalgae biorefineries. Four scenarios were constructed, ranging from a basic scenario, including conventional technologies, to an intermediate scenario, with the inclusion of a medium recycling step, towards an advanced scenario, where more state-of-the art technologies were included. An alternative microalgae biorefinery scenario, with the cultivation of an alternative algae species for an alternative end product was included as well. The inclusion of a membrane for medium recycling proved to be important for an economically viable process. The most important process parameters were the carotenoid content and price.

Afterwards, the LCA methodology was integrated in this model to develop the ETEA methodology. This methodology consists of five steps: 1) market study; 2) process flow diagram and mass and energy balance; 3) economic analysis; 4) environmental analysis; 5) interpretation. The case study consists of three scenarios, based on the basic, intermediate and advanced scenario of the TEA model. An alternative geographical location, being India, was included for each scenario to enable a geographical comparison. According to the results of the ETEA model, the algae biorefinery in India has higher profits, while the algae biorefinery in Belgium has a lower environmental impact.

The ETEA methodology can be used to assess the technological, economic and environmental potential of a new technology. However, in reality multiple technology options are possible. Instead of analyzing each possible scenario separately, a superstructure containing all possible options was constructed. The ETEA methodology was extended with a multi-objective optimization to identify the optimal microalgal-based biorefinery scenario taking both economic and environmental objectives in account. From an economic perspective, the optimal algal-based biorefinery produces feed for aquaculture. The environmentally optimal scenarios produce a combination of carotenoids, fertilizer and energy products.

The ETEA methodology provides a framework to assess a new technology over the entire product lifecycle at each stage of technology development. By providing insights on how a new technology can be improved for multiple objectives, the time-to-market for this new technology can be shortened.

SAMENVATTING

Er zijn drie belangrijke vragen die positief beantwoord moeten worden bij de ontwikkeling van een nieuwe technologie: 1) “Is het proces technologisch haalbaar?”; 2) “Is het proces economisch winstgevend?”; 3) “Heeft het proces een relatief lage milieu-impact?”. Deze vragen worden momenteel beantwoord op basis van allerhande methodologieën op verschillende momenten tijdens de ontwikkeling van de nieuwe technologie. Dit zorgt voor verschillende veronderstellingen en een grote variatie in de resultaten.

Een voorbeeld van een dergelijke nieuwe technologie is het concept van microalgen bioraffinaderijen. Microalgen zijn kleine, fotosynthetiserende organismen met een hoge productiviteit die kunnen groeien op plaatsen die niet geschikt zijn voor landbouw. Microalgen kunnen een hoog aantal waardevolle componenten accumuleren. Momenteel focust het meeste algenonderzoek zich op energie toepassingen. Dit concept is echter nog niet economisch haalbaar en ook de milieu-impact blijft vrij onduidelijk. Microalgen bioraffinaderijen kunnen een oplossing bieden aangezien ze meerdere producten kunnen valoriseren op basis van een microalgen grondstof. Dit zorgt voor hogere opbrengsten en een verlaagde milieu-impact per eindproduct.

De resultaten van economische en milieu-analyses van dit concept variëren echter ook. Dit kan verklaard worden door een grote variatie in methodologische assumpties en het gebrek aan een geïntegreerde methodologie. Vier methodologische aanbevelingen voor de ontwikkeling van een dergelijke methodologie werden geformuleerd aan de hand van een overzicht van bestaande economische en milieu-analyses van microalgen bioraffinaderijen. De eerste aanbeveling is het opstellen van een duidelijk kader met een vooropgesteld stappenplan. De tweede aanbeveling houdt in dat de methodologie aangepast moet zijn aan elk niveau van technologie ontwikkeling. De derde aanbeveling geeft aan dat de methodologische veronderstellingen duidelijk weergegeven moeten worden. Volgens de vierde en laatste aanbeveling moet de technologische analyse geïntegreerd worden in één dynamisch model,

waarbij een verandering in één parameter automatisch resulteert in de aanpassing van alle output indicatoren. Op basis van deze aanbevelingen werd de Milieu- en Techno-Economische Analyse (ETEA) methodologie voorgesteld. Deze methodologie integreert de Levenscyclusanalyse (LCA) in de Techno-economische analyse (TEA).

Voor de ontwikkeling van deze methodologie werd eerst een TEA gevalstudie opgesteld voor microalgen bioraffinaderijen. Vier scenario's werden onderzocht, variërend van een basis scenario met conventionele technologieën, tot een intermediair scenario met de toevoeging van een medium recyclage stap, tot een geavanceerd scenario, met meerdere innovatieve technologieën. Een alternatief microalgen bioraffinaderij scenario, waarbij een alternatieve algensoort gecultiveerd werd voor de productie van een alternatief eindproduct, werd ook onderzocht. De toevoeging van een membraan voor de recyclage van het medium bleek een belangrijke stap te zijn voor een economisch haalbaar proces. De belangrijkste proces parameters waren het carotenoïde gehalte en de carotenoïde prijs.

Na deze gevalstudie werd de LCA methodologie geïntegreerd in het model voor de ontwikkeling van de ETEA methodologie. De methodologie bestaat uit vijf stappen: 1) markt studie; 2) processtroom diagram en massa en energie balans; 3) economische analyse; 4) milieu-analyse; 5) interpretatie. De gevalstudie omvatte drie scenario's die gebaseerd waren op het basis, intermediair en geavanceerd scenario van het TEA model. Een alternatieve locatie, Indië, werd ook toegevoegd voor elk scenario zodat ook een geografische vergelijking mogelijk werd. Volgens de resultaten van dit ETEA model had het optimaal scenario in Indië een hogere economische haalbaarheid, terwijl dit scenario in België een lagere milieu-impact had.

De ETEA methodologie kan gebruikt worden om het technologisch, economisch en milieu-potentieel van een nieuwe technologie te onderzoeken. In realiteit zijn er echter meerdere technologische opties mogelijk voor een bepaald proces. Om te vermijden dat elk mogelijk scenario apart onderzocht moet werden, werd een superstructuur van alle mogelijke scenario's opgesteld. De ETEA methodologie werd uitgebreid met een multi-objectieven optimalisatie (MOO) zodat het optimaal microalgen bioraffinaderij scenario vanuit een economisch en milieu-perspectief geïdentificeerd kon worden. Het economisch optimaal scenario produceert voeder voor aquacultuur. Het optimaal scenario vanuit een milieu-perspectief produceert een combinatie van carotenoïden, meststof en energie producten.

De ETEA methodologie bevat een methodologisch kader om een nieuwe technologie te onderzoeken over de hele levenscyclus van het productsysteem op elk moment tijdens de ontwikkeling. Door inzichten te geven in het verbeteringspotentieel voor meerdere doeleinden, kan de marktintroductie van deze nieuwe technologie versneld worden.

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ETEA	Environmental techno-economic assessment
LCA	Life Cycle Assessment
TEA	Techno-economic assessment
MOO	Multi-objective optimization
PFD	Process flow diagram
TRL	Technology readiness level
GWP	Global warming potential
NPV	Net Present Value
IRR	Internal Rate of Return
MCA	Multi-criteria analysis
LCC	Life cycle costing
PBR	Photobioreactor
DW	Dry weight
IPC®	Integrated Permeate Channel
HDPE	High-density polyethylene
ODP	Ozone depletion potential
IRP	Ionizing radiation potential
PMFP	Particulate matter formation potential
EOFP	Photochemical oxidant formation potential for ecosystems
HOFP	Photochemical oxidant formation potential for humans
TAP	Terrestrial acidification potential
FEP	Freshwater eutrophication potential
HTPc	Human toxicity potential cancer
HTPnc	Human toxicity potential non-cancer
TETP	Terrestrial ecotoxicity potential
FETP	Freshwater ecotoxicity potential
METP	Marine ecotoxicity potential
LOP	Agricultural land occupation potential
WCP	Water consumption potential
SOP	Surplus ore potential

FFP	Fossil fuel potential
HH	Human health
EQ	Ecosystem quality
RS	Resource scarcity
DALY	Disability-adjusted life years
MOMINLP	Multi-Objective Mixed Integer Non-Linear Problem
MILP	Mixed-Integer Linear Problem
ProviApt	Proviron Advanced Photobioreactor Technology
TAG	Triacylglycerol
HTL	Hydrothermal liquefaction
NSGA	Non-dominated Sorting Genetic Algorithm
TSA	Techno-sustainability analysis

Chapter 1.

Introduction

1. Introduction

"Sustainability: enough - for all - forever"
African Delegate to Johannesburg (Rio+10)

A transition to a sustainable society requires the development of technologies with a minimal or positive impact on the environment. In order to reduce the environmental impact of technologies, this impact has to be determined first. By quantifying this environmental impact with the same model as used to determine the economic profits, the costs and gains of adapting the technology are assessed. Assessing the environmental and economic impact of a new technology in an integrated way at an early stage of technology development, makes it easier and cheaper to overcome potential pitfalls compared to adapting a mature technology. This facilitates the development of profitable and sustainable technologies. This dissertation will elaborate an integrated environmental techno-economic assessment (ETEA) methodology for this purpose. This methodology is developed and applied using a case study of microalgal-based biorefineries.

In microalgal-based biorefineries, microalgae are used as a feedstock to valorize a range of products, such as food supplements, fertilizers and/or energy. As these products are based on a biomass, being microalgae, they can be classified as biobased products in contrast to fossil-based products, which are made from fossil resources. Microalgae biorefineries were chosen as a case study due to three main reasons. First, microalgae have a lot of technological and economic potential as a feedstock for numerous applications. Second, a relatively high amount of research has already been conducted in this field which results in a large data availability. Third, although a lot of projects have been finished, a broad commercial implementation of these new technologies has not yet succeeded. Consequently, it is an interesting case to investigate (i) where the largest potential is situated, (ii) why this concept has not been commercialized yet on a broad scale and (iii) how the research can be facilitated to accelerate a broad market implementation. Although the ETEA methodology will be primarily applied to microalgal-based biorefineries, broader applications are possible as well.

This dissertation consists of two main elements, being methodological development and the methodological application on a case study of microalgal-based biorefineries.

1.1. Sustainable technology assessment

1.1.1. Environmental impact reduction strategies

The anthropogenic environmental impact is crossing the planetary boundaries. Without an adequate transition to a more sustainable society, we risk to destabilize the environment on a planetary scale (Steffen et al., 2015). The well-known I=PAT equation indicates that the environmental impact of our society (I) is caused by three factors: 1) the population size (P); 2) the affluence of each person (A) and; 3) the environmental impact of the technologies used by each person at each level of consumption (T) (Chertow, 2001). This highlights three strategies to reduce our environmental impact. The reduction of the population size on short term notice is a highly questionable strategy to obtain this goal, both from an ethical and a practical perspective. Imposing limits on our consumption patterns can be part of the strategy, but is disputable and will face a large amount of opposition. This leaves the reduction of the technological environmental impact as the main target to direct an environmental impact reduction strategy towards.

To reduce the environmental impact of a technology, we need to determine the impact first. However, before we can assess the environmental impact of a technology, we need to assess the technology itself. Without a clear understanding of how the technology works, we cannot quantify or decrease the environmental impact it causes.

1.1.2. Technological assessment

A process design analysis is used to assess a technology. This assessment includes multiple design steps, such as the construction of the process flow diagram (PFD), where all processes and linkages are illustrated, and the calculation of the mass and energy balance. The process design guides the new technology throughout its development by adding more details at each stage (Towler & Sinnott, 2013).

The development of a new technology follows different stages, ranging from the initial idea until market introduction of the mature technology. These stages can be classified according to the Technology Readiness Levels (TRL) as illustrated in Figure 1 (Mankins, 2009).

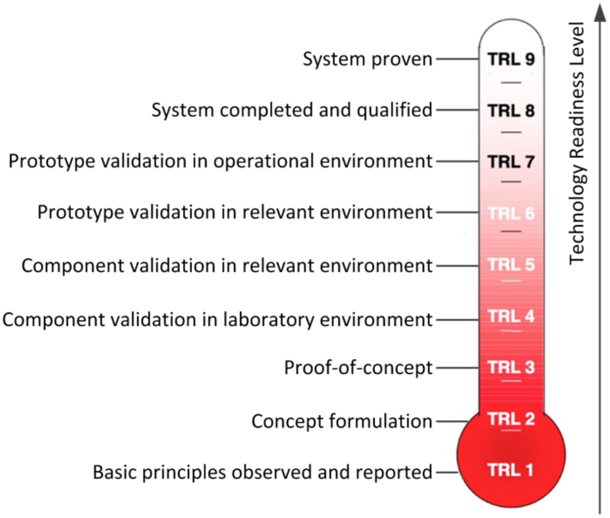

Figure 1. TRL scale (based on Mankins (2009))

Technologies are mainly used to produce end-products for consumers. Therefore, a technology does not stand on its own, but is part of the lifecycle of a product. Alterations in the technology have consequences throughout this life cycle chain and can even increase the overall impact on the environment.

Therefore, it is crucial to take the entire life cycle into account when assessing the impact of a technology.

The typical steps of the product lifecycle are illustrated in Figure 2. This lifecycle starts from the extraction of the raw materials out of the environment. In the second step, which is a typical step for a biobased product, the biomass is produced. Subsequently, the biomass is further processed in the manufacture step. The product is then distributed and used by the consumer. Finally, in the end-of-life phase, the waste is discharged. The lifecycle steps which have preceded a certain process in the chain are designated as upstream processes, while the lifecycle steps after this certain process are called downstream processes. In each step of the lifecycle, different resources can be used and multiple residue products can be generated. The used resources can either directly come from the environment, such as rain water or come from the industry, such as fertilizers. Industrial products have their own upstream lifecycle, which needs to be included as well. Residue products can also directly flow into the environment, such as emissions, or be further processed, in which case their specific downstream lifecycle steps need to be included as well. Inside this lifecycle, multiple recycling loops are possible to limit the required resource extraction from the environment and residue disposal into the environment. This way, the linear lifecycle model can be converted into a circular concept.

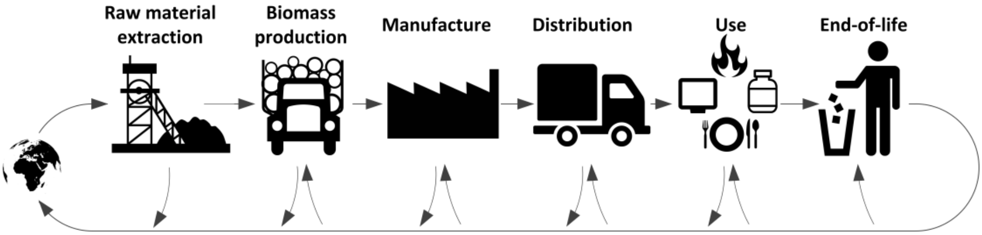

Figure 2. Life cycle stages

The technology assessment model can be used as a starting point for the assessment of the environmental and economic impact of the technology. There are many different sorts of impacts a technology can have on the environment and the economy and these impacts are mostly not straightforward due to complex processes. A clear methodology is therefore required to determine the impact of technologies in a consistent way so technologies can be compared and improved.

1.1.3. Environmental assessment

In general, environmental assessment methodologies focus on the product instead of the technology. This way, rebound effects, where technological alterations to reduce the environmental impacts cause additional environmental impacts upstream or downstream of the process, are taken into account as well.

The most used methodology to determine the environmental impact of products is the Life Cycle Assessment (LCA) methodology. An LCA identifies all emissions and resources of all process steps in the entire life cycle of a product (Guinée et al., 2002). There are two approaches to an LCA, being attributional and consequential. An attributional LCA assesses the environmental impact, which can be attributed to a specific product, within a predefined system. A consequential LCA assesses the consequences in environmental impact in a change of production (M. A. Thomassen, Dalgaard, Heijungs, & de Boer, 2008). The remainder of this dissertation will be focused on attributional LCA. There are four steps in an LCA. In the first step, the ‘Goal and objective’, the main goal of the assessment and the system boundaries are stated. In the second step, the ‘Inventory analysis’, a full inventory is made of the resources and emissions included in the system boundaries. In the third step, the ‘Impact assessment’, each emission and resource of the inventory is multiplied with a corresponding characterization factor for the selected indicator. In the fourth step, the ‘Interpretation’, the results are interpreted, for example by assessing the contribution of each part of the lifecycle. Although by definition an LCA should cover the entire environmental impact over all the life cycle stages, in practice LCAs are often limited to a few environmental impact categories and a specific part of the life cycle (Reap, Roman, Duncan, & Bras, 2008a, 2008b). Different indicator sets exist to measure the environmental impact. A widely used indicator set which covers a broad range of impact categories is the ReCiPe indicator set. This set includes seventeen midpoint categories which contribute to three endpoint categories as illustrated in Figure 3 (Huijbregts et al., 2016).

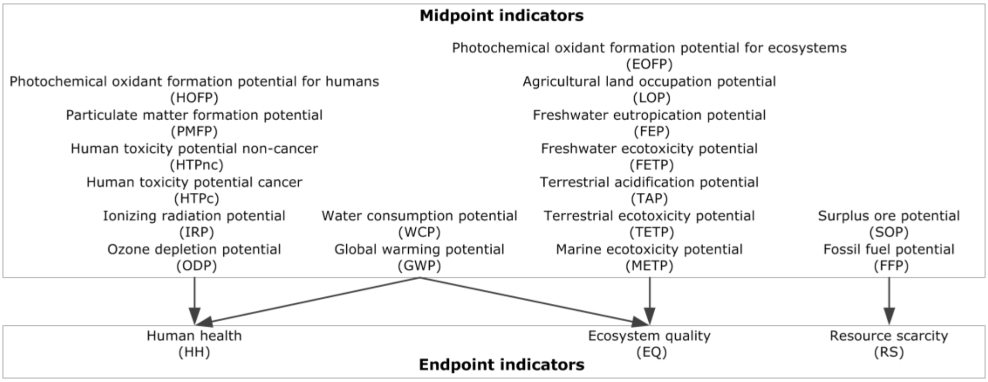

Figure 3. ReCiPe indicators (based on Huijbregts et al. (2016))

Prescriptions on how to perform an LCA are provided by the ISO guidelines (ISO 14040). The environmental impact in an LCA is determined relative to the functional unit. This functional unit describes the primary function of the end product, and indicates how much of this function is included (Guinée et al., 2002). In practice, the functional unit is often based on the mass, energy or cost of the end product. As the functional unit determines one main function of the end product, different co-products with different functions are not automatically included. Hence, the appropriate environmental impact needs to be allocated to each end product (Reap et al., 2008b). The ISO guideline supplies a stepwise procedure to deal with this allocation. The first step of this procedure is to avoid allocation by either dividing the unit process into multiple sub-processes or expanding the system boundaries to include the functions of the co-products. By dividing the process, each sub-process will lead to one end product. In the system boundary expansion approach, the reference process is included as well. The second step of the allocation procedure is to divide the environmental impact over the different co-products, preferably based on a relevant physical characteristic such as energy content or mass, or based on another relevant characteristic such as the economic value.

In general, LCA modelers assume a linear relation between the environmental impact and the production scale and period. The calculation of certain impact categories, such as Global Warming Potential (GWP), can include a time horizon. However, this time horizon does not influence the amount of emissions but only the extent of the impact of these emissions.

The inclusion of the entire life cycle generates the need for a large amount of data. Due to the growing LCA research over the last decades, more and more data becomes available. Large databases such as ecoinvent contain an inventory of the resources and emissions of the majority of process steps of different products (Wernet et al., 2016). Consequently, it has become easier to obtain a relevant estimate of the environmental impact of multiple products and the technologies which are included in their life cycle.

Due to this large data requirement, the environmental impact is often only assessed when the technology is mature. At this point, it is practically complex and costly to make changes to improve the sustainability of the technology. Consequently, environmental assessments are mostly used to assess the environmental impact of an existing technology and not to develop new technologies with a minimal environmental impact. To enable environmental assessments at earlier TRL stages, different streamlining methods, such as the use of proxy data, have been developed to cope with the lack of data availability (Graedel, 1998).

However, even if an environmental assessment methodology to quantify the environmental impact of a technology exists, it may not be used in technology development. A low environmental impact is usually not the main objective in the development of a new technology. Primarily, the technology needs to be profitable and affordable. Even if the technology is developed to have a minimal or positive environmental impact, the technology still needs to be economically viable. A sustainable product should not be a luxury product, only affordable by the lucky few, and a company should be able to survive, making profits in order for the sustainable technology to thrive. An economic assessment is therefore an important part of sustainable technology development.

1.1.4. Economic assessment

The economic assessment of a technology requires a different approach compared to the environmental assessment. Where the environmental assessment focusses on the entire life cycle of the end product, the foreground processes of the economic assessment are usually limited to the technology itself. The other stages of the lifecycle are included in an indirect way as background processes. Upstream costs or revenues are incorporated in the price of the inputs and downstream costs or revenues are incorporated in the product price or waste disposal costs. Another difference is that only the costs and benefits with a market price are included in the assessment. Furthermore, while the environmental assessment, based on the LCA methodology, is usually scale and period independent, the economic assessment will cover a project at a certain production scale over a certain time period. Therefore, the economic assessment takes a project perspective, in contrast to the product perspective of the environmental assessment.

The economic profitability can be assessed by means of an investment analysis. This analysis can include the calculation of investment criteria, such as the Net Present Value (NPV) or the Internal Rate of Return (IRR) (Mercken, 2004). Often the investment analysis is limited to an analysis of only the equipment and operational costs. Although this can provide useful insights into the minimum selling price of the product, no conclusion can be made on the economic feasibility of the project.

The economic profitability is usually assessed in the later TRL stages. Similar to the streamlining models of the environmental assessments, economic assessments have been simplified with rough estimates at earlier stages of process design (Peters, Timmerhaus, & West, 2003).

In conclusion, to develop new technologies, we need to answer three main questions: “Does it work?”, ”What is the environmental impact?”, “Is it profitable?” (Kuppens, 2012). These three questions are often answered independent of each other at different moments of technology development.

1.1.5. Integrated assessment

As technological, environmental and economic assessments use different perspectives to assess a technology, they are often performed independent of each other using separate models, with different assumptions at different TRL stages. Independent assessments neglect the correlations between these different dimensions. To optimize a new technology towards all three dimensions, these dimensions need to be integrated. In such an integrated assessment, a change in a parameter in one dimension automatically affects the output parameters in all dimensions. For example, increasing the process temperature in the model directly influences the total profits and environmental impact. A direct linkage between the process design, the economic impact and the environmental impact is crucial to identify the effect of a different choice in the process design. An integrated model can provide advice on the optimal process design, taking the effects in all dimensions into account. Therefore, the three questions need to be answered in one integrated assessment alongside all TRL stages.

The techno-economic assessment method (TEA), as developed by Kuppens (2012) and Van Dael et al. (2013), provides such an integrated assessment methodology. Their framework consists of four steps. The first step is the market study, where the prices and market volumes are determined. In the second step, the PFD and mass and energy balance are calculated and the different aspects of the process design are analyzed. The third step is the economic analysis, where the NPV is calculated in a dynamic way. In the fourth step, the risk analysis, the most sensitive parameters are identified. The TEA methodology follows an iterative approach, where a go/no-go decision is made after each iteration (Van Dael, Kuppens, Lizin, & Van Passel, 2014).

The TEA methodology does not take into account the environmental impact of a technology yet. An integration with the LCA methodology will improve the methodology and enable a fully-integrated Environmental Techno-Economic Assessment (ETEA).

1.1.6. Multiple criteria decision making

The ETEA methodology has different output indicators in different dimensions for a specific technology scenario. However, how can the optimal scenario be obtained? The different output indicators correspond to multiple criteria which need to be taken into account by the decision maker. This obstructs the identification of the optimal scenario. There are two main approaches to deal with this multiple criteria decision making problem: Multi-criteria analysis (MCA) and Multi-objective optimization (MOO).

The aim of an MCA is to select the best scenario out of a set of known scenarios. MCA assigns weights to the different criteria or objectives in order to obtain one output value (J.-J. Wang, Jing, Zhang, & Zhao, 2009). Both quantitative and qualitative criteria can be used (Cinelli, Coles, & Kirwan, 2014). The use of MOO can result in a set of Pareto-optimal scenarios, instead of one optimal scenario. A Pareto-optimal scenario is a scenario which cannot be improved in one dimension without deteriorating in another scenario (Deb, 2001). After performing a MOO, a MCA can be added to weigh the Pareto-optimal scenarios and obtain one optimal scenario. The aim of the ETEA methodology is to assess new technologies on their technological, economic and environmental feasibility and not to obtain one optimal scenario. Therefore, the MOO is used without MCA to obtain a set of Pareto-optimal scenarios.

In general there are four different groups of methods to handle the multiple objectives in a MOO problem. The first group of methods are *a priori methods*, where the preference for each objective is determined before the optimization. The optimization will result in one optimal scenario. The second group of methods are the *a posteriori* methods, where the preference for each objective is determined after the optimization. The optimization results in multiple optimal scenarios. The third group of methods are the *progressive* methods. The preference is adapted during the optimization and the optimization will result in one optimal scenario. The fourth group of methods are the *no preference* methods. No preference is required and a heuristic is used to find the optimal scenario (for example, the smallest distance to the utopian point). The utopian point is the point where all objectives have their optimal value. Unless all objectives have the same optimum, this point is not a real solution. The opposite of the utopian point is the nadir point, where all objectives have their worst value.

By varying the preferences in certain *a priori* methods, multiple optimal scenarios can be obtained as well and the *a priori* method can be used as an *a posteriori* method (Collette & Siarry, 2003). A frequently used method is the ε-constraint method. In this a *priori* method, one objective is selected as the main objective and the other objectives are transformed into a constraint. Following this constraint, they need to have a better value than their ε-value. The ε-value for each constraint varies between their nadir point and their utopian point. By iterating for multiple ε-values for all objectives and by varying the main objective, multiple optimal scenarios can be found and the method is transformed into an *a posteriori* method (Chiandussi, Codegone, Ferrero, & Varesio, 2012). Using the ε-constraint method, the ETEA methodology can be extended with a MOO. This enables the identification of the optimal scenarios following different objectives, instead of solemnly assessing one scenario at a time.

The MOO-extension is the last part of the integration of the technological, environmental and economic assessments. Using this methodology, a new technology can be optimized alongside its development. To develop and apply the different steps of the ETEA methodology, a case study of microalgal-based biorefineries was used.

1.2. Microalgal-based biorefineries

The age of fossil-fuel-based products makes way for a new era, where biobased materials provide more sustainable building blocks. Biofuels have been developed as an alternative energy carrier to replace conventional fossil fuels. The first generation of biofuels used conventional food crops, such as maize or wheat as a feedstock (R. A. Lee & Lavoie, 2013). However, the market introduction of these fuels had unsought consequences. The use of food crops for energy increased the prices of these food crops, which led to increased food prices worldwide (Hochman, Rajagopal, Timilsina, & Zilberman, 2011). Also, indirect land use change caused additional greenhouse gas emissions, questioning the overall improvement in sustainability of these biofuels compared to fossil fuels (Searchinger et al., 2008). If the sustainability impact of these biofuels would have been thoroughly assessed before market introduction, this potential negative effect might have been prevented. To avoid the food versus fuel debate, biofuel research led to a second generation of biofuels. Feedstocks were food waste, waste oils and perennial crops that were not used for food applications. However, there are still technological problems with this generation of biofuels which prevents their market introduction on a large scale. Microalgae are often considered to be the third generation of biofuels (R. A. Lee & Lavoie, 2013). Their ability to grow throughout the year on degraded land and accumulate large amounts of lipids, makes them an interesting feedstock for fuel (R. E. Lee, 2008). However, there is no consensus over the environmental impact of microalgal-based biofuels and their production costs are still too high to compete with cheap conventional fuels (Quinn & Davis, 2015). Although a large amount of funds has focused on the development of these fuels, the large-scale market introduction of microalgal-fuels has not occurred yet.

A solution to this problem can be found by looking to microalgae from a different perspective. Microalgae can be defined as small photosynthetic organisms which lack typical plant structures such as roots, stems and leaves (R. E. Lee, 2008). As this is a very broad definition, a large amount of different microalgae species exists. Research has estimated this amount to be approximately 77,500 (Guiry, 2012). Of this 77,500 species, four have been widely used, namely for food applications. *Chlorella* and *Spirulina* are mainly produced in Asia and are sold as superfoods, containing proteins and valuable antioxidants. *Dunaliella* and *Haematococcus* can accumulate large amounts of antioxidants, being β-carotene and astaxanthin (Spolaore, Joannis-Cassan, Duran, & Isambert, 2006). Instead of low-value energy products, these algae produce high-value products. The commercialization of these products enables algae growth technologies to become economically viable and reduce costs through learning effects.

The valorization of multiple products out of an algae feedstock will increase the revenues and decrease the relative environmental impact (Chew et al., 2017). In recent years, algal research has therefore increasingly focused on the microalgal-based biorefinery concept as illustrated in Figure 4. Such a concept should follow the cascading principle, prioritizing the production of high-value products, while the residual stream can be used for energy applications (Bastiaens, Van Roy, Thomassen, & Elst, 2017). However, microalgae biorefineries can only be introduced in the market when their technological feasibility, low environmental impact and economic viability are ensured.

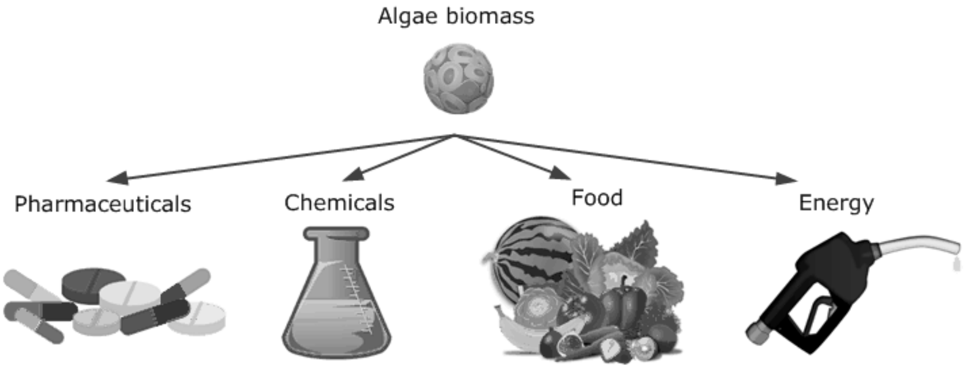

Figure 4. Microalgal-based biorefinery

Microalgal-based biorefineries are a concept, which can be translated in multiple process designs. This concept will be assessed by designing multiple scenarios which can be identified as microalgal-based biorefineries. Such a hypothetical production plant will include multiple technologies, ranging from the cultivation of the algae to the purification of the end products. In this dissertation, the algal-based biorefinery concept is therefore not limited to the refining processes of the end products, but also includes the growth of the microalgae. The hypothetical production plant is assumed to be the n^{th} plant, which means it does not reflect a pioneer plant but it is a part of a hypothetical scenario where similar production plants have already been established and are operating.

The microalgal-based biorefinery scenarios which are chosen as a case study in this dissertation resemble conventional production processes. This conventional production process is then adapted in different scenarios by adding new technologies. By including one new technology in each scenario, the specific impact of including this technology on the entire value chain can be assessed. This way, technologies with different TRLs are used in the case study. The conventional production processes are used on a commercial level and correspond to TRL nine. Therefore, the data underlying these processes is more available and reliable. The new technologies which are added in the different scenarios have lower TRL levels. The data for these processes will therefore be more uncertain. By selecting the conventional production process as the basic process for the scenarios, the uncertainty is mostly restricted to the new technologies, which are of main interest.

The conventional production process for microalgal-based products consists of five main processes. In the first process, the microalgae are cultivated. Afterwards, the microalgae are harvested. The microalgae are dried in the third process. The fourth process includes the extraction of the desired components. In the last step, the obtained fractions are purified. For the cultivation process, two main technologies are used: open ponds and photobioreactors. Open ponds, where the algae are cultivated outdoor in large tanks, are the most commonly used. This technology is relatively cheap and has a low energy consumption (Brennan & Owende, 2010). Photobioreactors are also used for the commercial production of algae (Jorquera, Kiperstok, Sales, Embiruçu, & Ghirardi, 2010). There are different sorts of photobioreactors such as tubular, flat plate or column photobioreactors. The growth conditions in photobioreactors can be more easily monitored and controlled than in open ponds. Moreover, the risk of contamination is lower as well. The biomass productivity is also higher in photobioreactors compared to open pond (Brennan & Owende, 2010). However, photobioreactors are more expensive and the energy consumption is higher as well (Jorquera et al., 2010). As both cultivation systems have their advantages and disadvantages, the selection of the appropriate system relies on the specific application.

Harvesting the algae is often done in a two-step process. In the first step, the algae are thickened to concentrate the algae slurry to approximately 2-7% of total suspended solids. The second step is the dewatering process, where the microalgal slurry is concentrated to 15-25% of total suspended solids. Different harvesting technologies are chemical coagulation, flocculation, gravity sedimentation, flotation, filtration or centrifugation (Barros, Gonçalves, Simões, & Pires, 2015). The appropriate harvesting technology depends on the specific application (Pragya, Pandey, & Sahoo, 2013). An overview of the harvesting technologies with their advantages and disadvantages is provided by Barros et al. (2015).

After the algae are harvested, the slurry needs to be dried for stability, end use, extraction or further processing. Different drying methods such as rotary drying, spraying and solar drying exist. The selection of the drying system depends on the production scale and the purpose. If valuable components need to be preserved, a drying technology needs to be selected which avoids deterioration of these components (Show, Lee, Tay, Lee, & Chang, 2015).

In the extraction phase the desired components need to be extracted from the biomass with a corresponding solvent. If the microalgae have a thick cell wall, these components might not be available for extraction. A cell disruption technology preceding the extraction step can increase the extraction efficiency in this case. A discussion on different disruption technologies is provided by Günerken et al. (2015). After the extraction step, the different components need to be further processed and/or purified.

An algal-based biorefinery can produce multiple products. Multiple market studies provide extensive discussion on the potential of these products. Subhadra and Edwards (2011), for example, provide information on market prices, volumes and trends of different products such as algal meal. Discussions on the commercialization opportunities of microalgae-based carotenoids can be found in Guedes, Amaro, and Malcata (2011). A broad discussion on market opportunities for microalgae-based products in the EU was provided by Vigani et al. (2015) and the report of Enzing et al. (2014). As these studies extensively discuss the market opportunities of the different algal-based products, no additional market study will be included in this dissertation.

2. Main research question

Currently, the potential of new technologies is assessed using technological, economic and environmental assessments. In general, these assessments are performed independent of each other, using different assumptions, at different stages of technology development. This leads to multiple problems. The first problem is that the environmental impact of a new technology is usually only assessed when the technology is close to market introduction. This way, the goal of the environmental assessment is primarily to inform about the environmental impact instead of to optimize the technology towards a minimal environmental impact. The second problem is that general conclusions about the potential of new technologies are hard to draw when different assumptions are made by separate assessments. These separate assessments are often done by different people at different research institutions which does not lead to transparency. The third problem is that separate assessments are more costly and time consuming than one integrated assessment. In an integrated assessment, the technological assessment forms the backbone for both the economic and environmental assessment. In this case, the process only needs to be modelled once. An integrated technological, economic and environmental assessment can therefore pose a solution to these problems.

The aim of this dissertation is to develop a framework to assess the technological, environmental and economic potential of new technologies in an integrated way. The main research question which will be answered is:

How can the technological, environmental and economic potential of new technologies be assessed in an integrated way?

In order to develop the framework and answer this main research question, the question has been divided in four different subquestions. Microalgal-based biorefineries are used as an example of a new technology in the different subquestions.

3. Subquestions

Subquestion 1: Can an existing methodology be used to assess the integrated technological, environmental and economic potential of microalgal-based biorefineries?

To develop a new integrated methodology, a thorough understanding of the currently used methodologies with their assets and pitfalls is required. Chapter 2 reviews the current literature and analyses the methodological differences between the studies. Based on this review, recommendations are formulated for the new methodology.

Subquestion 2: What is the techno-economic potential of an algal-based biorefinery concept?

In chapter 3, the existing techno-economic assessment method is used to assess four algal-based biorefinery concepts. This chapter introduces a generic design for the case study and a basic for the development of the environmental techno-economic assessment.

Subquestion 3: How can the environmental assessment be integrated in the techno-economic assessment (TEA) methodology?

The new methodology is developed in chapter 4, based on the recommendations of chapter 2 and the case study of chapter 3. The TEA, as used in chapter 3, is extended to include an environmental assessment and different streamlining models are used to cope with data scarcity. A comparison between Belgium and India is made to include the geographical considerations in the methodology.

Subquestion 4: How can the technological, economic and environmental potential of algal-based biorefineries be optimized?

The new methodology is extended with a multi-objective optimization (MOO) in chapter 5. Optimal algal-based biorefinery designs, from a technological, economic and environmental perspective, are identified.

Each of the subquestions forms a part of the methodology as illustrated in Figure 5. Subquestion 1 assesses current methodologies to come up with the overarching framework. Subquestion 2 develops the TEA for microalgae biorefineries. Subquestion 3 integrates the environmental assessment in this model and Subquestion 4 extends the model further with a MOO. This figure will be used in the remainder of this dissertation.

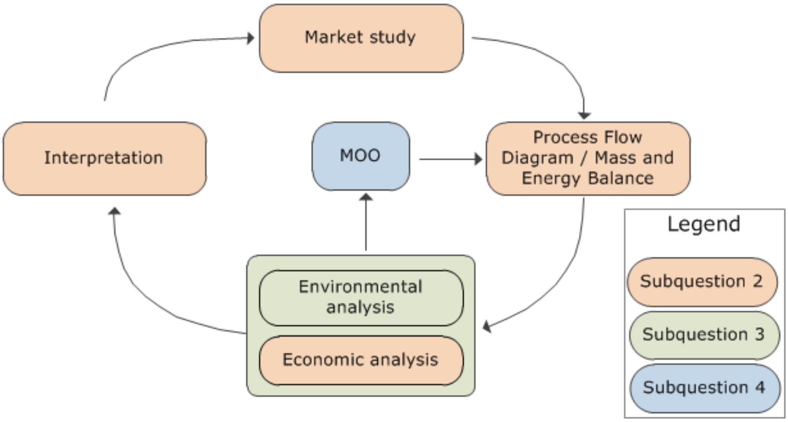

Figure 5. Subquestions in the ETEA methodology

Chapter 2.

Current assessment methodologies[*]

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[*] *Parts of this section have been published in:*
Thomassen, G., Van Dael, M., Lemmens, B., Van Passel, S. (2017) A review of the sustainability of algal-based biorefineries: Towards an integrated assessment framework. Renewable and Sustainable Energy Reviews 68, p. 876-887.

In this chapter, current assessment methodologies, from both an environmental and economic perspective, are analyzed. Based on the good practices of these current assessments, a framework for the ETEA methodology is proposed.

Abstract

Algal-based bioenergy products have faced multiple economic and environmental problems. To counter these problems, algal-based biorefineries have been proposed as a promising solution. Multiple environmental and economic assessments have analyzed this concept. However, a wide variation in results was reported. This study performs a review to evaluate the methodological reasons behind this variation. Based on this review, four main challenges for a sustainability assessment were identified: 1) the use of a clear framework; 2) the adaptation of the methodology to all stages of technological maturity; 3) the use of harmonized assumptions; 4) the integration of the technological process. A generic methodology, based on the integration of a techno-economic assessment methodology and a streamlined lifecycle assessment was proposed. This environmental techno-economic assessment can be performed following an iterative approach during each stage of technology development. In this way, crucial technological parameters can be directly identified and evaluated during the maturation of the technology. The use of this assessment methodology can therefore act as guidance to decrease the time-to-market for innovative and sustainable technologies.

1. Introduction

Algal-based biorefineries have been proposed as a promising approach to enhance the microalgae industry. The valorization of multiple co-products could improve the economic viability of microalgal-based biofuels (Zhu, 2015). However, further investigations concerning the economic feasibility and the environmental impact are required (Yen et al., 2013). Multiple studies have performed economic or environmental assessments in order to accurately quantify these impacts. The main objective of this chapter is to propose a new methodology, which can harmonize the different assessments from a methodological point of view. Such a harmonized assessment enables the comparison of the different proposed production processes to permit a clear view on the commercialization potential of microalgae-based biorefineries.

Compared to other bioenergy feedstocks, microalgae have a large biomass productivity and high lipid content (Ahmad, Yasin, Derek, & Lim, 2011). Therefore, the application of microalgae biofuels has gained a lot of attention during the last decades (J. Singh & Gu, 2010; Suali & Sarbatly, 2012). However, several economic and environmental constraints concerning its commercialization have been identified; examples are the high production costs compared to fossil fuels and the high water consumption during cultivation (Cheng & Timilsina, 2011; Chisti, 2013). Moreover, the production of biofuels in general has become controversial, for instance due to the food-versus-fuel debate and indirect land-use change emissions. If the biofuel industry cannot ensure that its environmental impact is significantly lower than that of the fossil fuels it substitutes, the main reason of existence for this industry is at risk (Koh & Ghazoul, 2008).

A solution to these environmental and economic problems of biofuels could be the supplementary valorization of other biochemical components from the microalgae biomass (Zhu, 2015). This algal-based biorefinery perspective has been suggested by multiple authors and has been the subject of multiple research projects in the last years (Chen et al., 2009; Y. Li, Horsman, Wu, Lan, & Dubois-Calero, 2008). Also other biomass feedstocks have been discussed for the application of a biorefinery concept (Ghatak, 2011). The algal-based biorefinery should follow the cascading principle, which prioritizes the production of high-value products before energy products (European Parliament, 2013). The sustainability of this concept has been examined by multiple studies, in order to prevent the problems that slowed down the research and development of algal biofuels. Multiple authors have emphasized the need for harmonization efforts as the results of these economic and environmental assessments are widely varying (Collet, Hélias, Lardon, Steyer, & Bernard, 2015; Quinn & Davis, 2015). Such a harmonization study was performed by Sun et al. (2011) in order to decrease the variability in production costs between 12 economic studies. The authors concluded that the variety could be attributed to disparate assumptions and uncertainties in economic and process inputs. The differences in process inputs have been reviewed by multiple studies, such as Williams and Laurens (2010). However, only a few papers, such as Collet, Hélias, Lardon, Steyer, and Bernard (2015), reviewed the disparate methodological assumptions in depth. Moreover, most of these reviews were limited to one dimension of sustainability. Harmonization efforts between a techno-economic and environmental assessment of algal-based biofuels have been undertaken in order to enable the study of tensions and tradeoffs between the different sustainability dimensions (ANL; NREL; PNNL, 2012). However, an in-depth review, including the integration of these different dimensions, is still lacking.

This chapter fills this gap by reviewing the methodologies used to assess the sustainability of algal-based biorefineries. The different methodological choices and assumptions are discussed in order to identify the main methodological reasons for the varying results. This review generates four main challenges for a harmonized and integrated methodology. Based on these challenges, a generic integrated assessment of the sustainability of algal-based biorefineries is proposed. This strategy was illustrated in Figure 6.

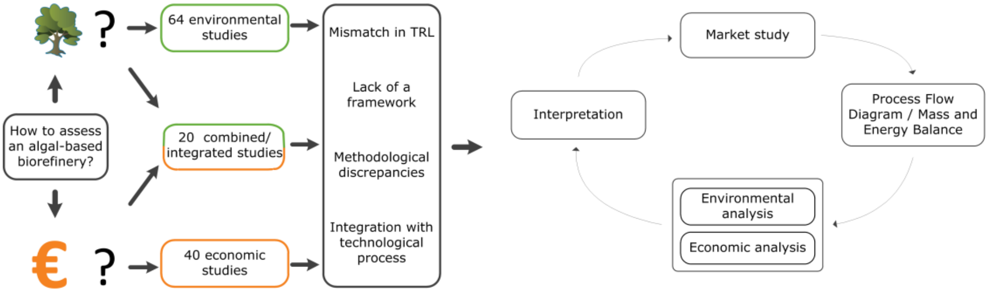

Figure 6. Graphical abstract of this chapter

2. Methodology

This review covers quantitative sustainability assessments from an environmental, an economic and a combined perspective. No papers were encountered which examined the social aspects of algal-based biorefineries; therefore, this dimension could not be included. The assessments included in this review originate from scientific peer-reviewed articles found in different scientific databases (EBSCOHOST and Google Scholar).

Sixty-four environmental assessments, forty economic assessments and twenty assessments, which combined or integrated both dimensions, were included. The methodology used for the assessments was reviewed in detail, focusing on the framework of the methodology itself, the scope of the assessments, the inclusion of uncertainties, the assumptions and the static or dynamic character of the technological process, which was assessed. Based on the differences between the different assessment methodologies on all these categories, four main challenges with which the different studies have to deal with are identified. Three of these challenges are directly related to the differences between the different studies within one sustainability dimension. The fourth challenge is linked to the harmonization and integration efforts between the different sustainability dimensions.

The reviewed papers cover a period of six years, from January 2009 to January 2015. All papers have a general biorefinery perspective. A general biorefinery was previously defined as “a facility (or a network of facilities) that integrates biomass conversion processes to produce fuels, power and chemicals from biomass” (Cherubini, 2010; Demirbas, 2011). Therefore, by definition a biorefinery adopts a multi-product perspective based on biomass. This review will focus on the sustainability assessments of microalgal-based facilities which produce more than one product, but is not restricted to the combination of energy and materials. Therefore, an assessment, covering a production plant which only produces fuel, power or chemical products was also included. As these studies encounter the same problems as algal-based biorefineries which do produce a combination of energy and materials, this broader perspective on the algal-based biorefinery concept was adopted. Outputs, which were considered to be waste, were not defined as a product.

More technologically oriented reviews of sustainability assessments can be found in the studies of Quinn and Davis (2015), Benemann, Woertz, and Lundquist (2012) and Collet, Hélias, Lardon, Steyer, and Bernard (2015). Therefore, this review will focus on methodological differences and only briefly discusses technological aspects. However, the lack of a detailed engineering design and system analysis has been identified as a crucial problem to sustainability assessment methodologies (Benemann et al., 2012). The degree of integration of the technological process is therefore included in this review. Three levels of integration are identified: (1) no technological assessment, (2) combined technological and environmental/economic assessment, and (3) integrated technological and environmental/economic assessment. If there is no technological assessment combined or integrated in the assessment, the technological input parameters are based on the literature of different processes. No common technological process from feedstock to end-product is defined. If the technological assessment is combined, the analysis of a process chain from feedstock to end-product is included. In this case, the environmental or economic assessment is performed in an independent manner. Outputs from the technological assessment are used as static values in the environmental or economic assessment. If the technological assessment is integrated, the environmental or economic assessment is directly linked to dynamic process parameters. A change in process parameters will have a direct influence on the environmental or economic feasibility. The classification of the different studies in accordance with these three categories was made based on the content of the respective paper.

3. Results

The methodological variation in the reviewed environmental assessments is displayed in Table 1 and Table 2.

Table 1. Overview of environmental assessment literature. Part 1

Ref[a]	Fw[b]	App.[c]	SB[d]	Sp.[e]	T.[f]	W.[g]	FU[i]	All[j]	SA[k]
(1)	LCA		Cr*-Gr*	C	I,E	X	M	S,Ec	P
(2)	LCA		Cr*-Gr*	C	I,E	X	M	S,Ec	P
(3)	LCA		Cr*-Gr*	C	E		En^{l}	S, En^{l}	
(4)	LCA	Att	Cr-Gr*	R	I,E	X	M,En^{h}	Ec	P
(5)	LCA		Cr-Gr*	R			M	En^{h}	P
(6)	LCA		Cr-Gr*	C	I		En^{l}	S	
(7)	LCA		Cr-Gr*	R	I		En^{l}	En^{l}	P
(8)	LCA		Cr-Gr	C		X	En	M,En	P
(9)	LCA		Cr-Gr	R	P		M	S,Ec	P
(10)	LCA		Cr-Gr	C		X	En^{h}	En^{h},S	P
(11)	LCA		Cr-Ga	R	P,I		F		P
(12)	LCA		Cr*-Ga	R	E	X	En^{h}	Ec	F
(13)	LCA		Cr*-Gr	C	E		En^{h}	S	F
(14)	LCA		Ga-Ga	R			En^{h}	M	
(15)	LCA		Cr-Ga	C		X	En	S	P
(16)	LCA		Ga-Ga	C	I,E	X	V		P
(17)	LCA		Cr-Ga	C		X	M	S	
(18)			Cr*-Gr*	C	I,E		En^{l}	En^{l}	F
(19)			Cr*-Gr*	R	I,E	X	F	S	P
(20)			Cr*-Gr	C	I,E	X	En^{l}	En^{l}	F
(21)		Att	Cr*-Gr	C	I,E		En^{l}	En^{l}	P
(22)			Cr*-Gr	C	E	X	F	S	F
(23)			Cr*-Gr		E		En^{l}	En^{l}	F
(24)			Cr-Gr	S	E	X	En^{l}	S	P
(25)			Cr-Gr*	R			F	M/En	F
(26)			Cr-Gr*	R		X	V	Nc	P
(27)			Cr-Gr*				En^{l}	En^{l}	F
(28)			Cr-Gr				En^{l}	Hy^{l}	P
(29)			Cr-Gr*	C	E	X	M		
(30)			Cr-Gr	R			En^{l}	En^{l}	P
(31)			Cr-Gr	C			En^{l}	En^{l}	F
(32)			Cr*-Ga				M	M	
(33)			Cr*-Ga	R	I,E		F	S	F
(34)			Cr*-Ga	R	E		En^{l}	S	P
(35)			Cr*-Ga	R			P	S	P
(36)			Cr*-Ga		E		M	En^{h}	P
(37)			Cr*-Gr*	R	E		En^{h}	En^{h}	
(38)			Cr-Ga	S			En^{l}	S/En^{l}	P
(39)			Cr-Ga				M	S	P

(40)	Cr-Ga	R	I		En	S/Ec	P
(41)	Cr-Ga				M	S	
(42)	Cr-Ga	S			V	S	F
(43)	Cr-Ga	R	E		En^l	S,En,Ec	P
(44)	Cr-Ga	S	I		M,Ec,En^l	Ec,M	P
(45)	Ga-Ga	R			T	S	P
(46)	Cr-Ga		I,E	X	M	S,Ec	
(47)	Cr-Ga	R		X	T	S	P
(48)	Cr-Ga	C			M	M	
(49)	Ga-Gr	C		X	M	NC	P
(50)	Ga-Gr	S	I		En	S	
(51)	Ga-Gr	C	E		En		P
(52)	Ga-Ga	C	E	X	M		
(53)	Ga-Ga	C			En^l	Ec	P
(54)	Ga-Ga	R			En^l		
(55)	Ga-Ga		I,E	X	T		
(56)	Ga-Ga	C	I		V	En,S	
(57)	Ga-Ga	C	I,E	X	V		
(58)	Ga-Ga			X		Ex	
(59)	Ga-Ga			X		Ex	
(60)	Ga-Ga				V		
(61)	Ga-Ga				V		
(62)	Ga-Ga				V		P
(63)	Ga-Ga	R		X	T		
(64)	Ga-Ga				En		P

[a]**Ref** = Reference, see Table 6; [b] **Fw =** Framework. LCA: Life Cycle Assessment; [c] **App.** = Approach. Att: Attributional; [d] **SB** = System boundaries. Cr: Cradle; Cr*: Cradle (+ infrastructure); Ga: Gate; Ga*: Gate (+ Infrastructure), Gr: Grave; Gr*: Grave (+ coproducts); [e] **Sp.** = Spatial scale. C: Country-specific; R: Region-specific; S: Site-specific; [f] **T.** = Time horizon. I: Defined for the impact (GWP); E: Defined for the equipment; P: Defined for the project; [g] **W.** = Inclusion of waste streams; [i] **FU** = Functional unit. En: Energy; M: Mass; T: Time; F: Functional; V: Volume; Ex: Exergy; Ec: Economic; Hy: Hybrid; l: Lower heating value; h: Higher heating value; [j] **All** = Allocation. S: Substitution; M: Partitioning based on mass; Ec: Partitioning based on economic value; En: Partitioning based on energy; Nc: Not clear l: Lower heating value; h: Higher heating value; [k] **SA** = Sensitivity assessment. F : Full sensitivity analysis; P : Partial sensitivity analysis.

Table 2. Overview of environmental assessment literature. Part 2

Ref[a]	**Imp.**[b]					**Int**[c]	**Ref**[a]	**Imp.**[b]					**Int**[c]
	CC	En	W	Eu	OI			CC	En	W	Eu	OI	
(1)	X	F^{l}	X			Int	(33)	X	X		X		Int
(2)	X	F^{l}	X			Int	(34)	X	F$^{l/h}$				Int
(3)	X	F^{l}		X	X	Comb	(35)	X					Int
(4)	X	F^{h}	X	X	X	Comb	(36)		F^{h}			X	Int
(5)	X	X^{h}				Comb	(37)		X^{h}	X		X	Int
(6)	X	F^{l}				Comb	(38)			X		X	Int
(7)	X					Int	(39)	X	F^{l}	X			Int
(8)	X	F		X	X	Comb	(40)	X	X	X			Comb
(9)	X	F^{l}			X	Comb	(41)	X	X^{h}		X		Comb
(10)	X	X^{h}	X		X	Comb	(42)	X	X^{l}	X		X	Int
(11)	X	F^{l}		X	X	Int	(43)	X	X^{l}				Int
(12)	X	X^{h}	X	X	X	Int	(44)	X	X^{l}				Int
(13)	X	F^{h}				Int	(45)	X				X	Comb
(14)	X	X^{h}				Comb	(46)	X					Int
(15)	X	X	X		X	Int	(47)	X					Int
(16)	X					Int	(48)			X			Int
(17)	X					Comb	(49)	X	X		X	X	Comb
(18)	X	F^{l}				Int	(50)	X	X				Comb
(19)	X	X^{l}	X	X		Int	(51)	X	F				Comb
(20)	X	F^{l}				Int	(52)	X	X			X	Comb
(21)	X	X^{l}	X	X	X	Comb	(53)	X	X^{l}				Comb
(22)	X	X^{l}	X	X		Int	(54)	X				X	
(23)	X			X	X	Int	(55)	X					Int
(24)	X	F^{l}	X			Int	(56)	X					
(25)	X	X^{l}	X			Int	(57)	X					Int
(26)	X	X^{l}				Int	(58)		Ex				Int
(27)	X	F^{l}				Int	(59)		Ex				Int
(28)	X	F^{l}			X	Int	(60)		X	X			Int
(29)	X	X^{h}				Int	(61)		X	X			Int
(30)	X	X^{l}				Int	(62)		X	X			Int
(31)	X					Int	(63)		X^{h}	X			Int
(32)	X	X	X	X	X		(64)			X			

[a]**Ref** = Reference, see Table 6; [b]**Imp** = Impact category. CC: Climate change; En: Energy; W: Water; Eu: Eutrophication; OI: Other indicator; X: Total energy; F: Fossil energy; Ex: Exergy; l: Lower heating value; h: Higher heating value; [c]**Int** = Integration of technological assessment. Int: Integrated technological and environmental assessment. Comb: Combined technological and environmental assessment.

The main assessed environmental impacts for algal-based biorefineries are the energy consumption and the greenhouse gas emissions. The majority of the studies conclude that microalgae have lower greenhouse gas emissions compared to conventional fuels (Benemann et al., 2012). However, the exact greenhouse gas emissions reported vary widely (Quinn & Davis, 2015). The recycling of nutrients, water and energy has been suggested to reduce the resource and energy consumption (Chowdhury, Viamajala, & Gerlach, 2012; Quinn, Smith, Downes, & Quinn, 2014; C. Rösch, Skarka, & Wegerer, 2012). Other technologies with the same purpose that were included in the studies are the use of wet extraction methods and the use of brackish, saline or wastewater (Azadi et al., 2014; Resurreccion, Colosi, White, & Clarens, 2012). However, due to the high methodological variation of the environmental assessments, it is not possible to draw a generic conclusion over the environmental impacts of algal-based biorefineries.

The economic feasibility of algal-based biorefineries is mainly dependent on the production costs of the algal biomass (Chisti, 2013). The largest contribution originates from the supply of resources, such as nutrients, CO_2 and water; labor and overhead costs, and the construction and operation of the cultivation and harvesting system (Chen et al., 2009; Klein-Marcuschamer et al., 2013; J. N. Rogers et al., 2014). Subsidies and taxes also play an important role (Gallagher, 2011). In general, the use of photobioreactors is much more expensive than the use of open raceway ponds (Resurreccion et al., 2012; Richardson, Johnson, & Outlaw, 2012). Most studies remain focused on biofuels and do not fully incorporate the economic potential of the coproducts. Economies of scope due to the commercialization of coproducts may enable an increase in revenues, and therefore an increase of the overall economic feasibility (Gong & You, 2015). However, in accordance with the environmental assessment, no general conclusion can be made yet concerning the economic viability of algal-based biorefineries. The methodological variation of the reviewed economic assessments is displayed in Table 3 and Table 4.

Table 3. Overview of economic assessment literature. Part 1

Ref[a]	Goal[b]	FU[c]	W.[d]	Loc.[e]	Depr (yrs.)[f]	Ind[g]	Time (yrs.)[h]	Disc (%)[i]	SA[j]	T/S[k]
	RA									
(64)		T					1			
	CA									
(54)		En	X	R	15,50	X	13	2,5,8	P	
(65)		M		R	10	X	1	8.5	F	
(29)		T	X	C	20	X	1			
(62)		V				X			P	
(56)		P		C	Ns	X		7	F	T
	LCC									
(66)		En[l]	X	R	10,20	X	1	Ns	P	
(22)		F	X	R	11	X	30	5,10,15	F	T
(33)		P		R	7	X	20	5,10,15	P	T
	FA									
(67)		P	X		5%	X	10	10	F	T
(68)		P		R	16	X	20	10	P	T,S
	EA									
(53)		M		C						
(69)		T		C	10	X	1		P	
(11)		F		R	Ns		1		P	S
(49)				C						
(61)		V			Ns	X			P	
(60)		T			Ns	X				
(70)		P		C	Ns	X	35	3.5	P	T
(71)		P	X	R	Ns	X	30	7,15	F	T
(51)		P		C	10	X	10	7.5	F	T
(72)		P			20		20	9.95	P	S
	TEA									
(55)		T	X		20	X	20	12	P	
(46)		T,V	X	C	20	X	20	10		
(35)		V		R	Ns	X	1		P	T
(73)		V		S		X	30		P	
(74)		V		S					P	
(75)		V	X	R	7	X	20	10	P	T

(63)	V	X	R	10,20	X	10,20		P	
(57)	V	X	C	20	X	20	10		
(76)	V		R						
(77)	V	X	C	7,20	X	30	10	F	T
(78)	V	X	S	7	X	30	10	P	T
(79)	V		C	25	X	25	10	P	
(80)	V	X	C	7	X	20,30	10	P	T
(16)	P		C	Ns	X	Ns	Ns	P	T
(81)	P	X		20	X	20,30	5,10		S
(52)	T	X	C	10	X	10	16		T
(82)	P		C	RBM	X	15	15		S,T
(83)	P								
(84)	P,M		C	5%	X	30,5			T

[a] **Ref** = Reference number: see Table 6; [b] **Goal.** RA: Revenue assessment; CA: Cost assessment; LCC: Life Cycle Costing; EA: Economic assessment; FA: Financial assessment; TEA: Techno-economic assessment; [c] **FU** = Functional unit. En: Energy; M: Mass; T: Time; P: Project; F: Functional; V: Volume; l: Lower heating value; [d] **W. =** Inclusion of waste streams; [e] **Loc. =** Location definition. C: Country scale; R: Regional scale; S: Selection of a specific location; [f] **Depr (yrs.) =** Depreciation period in years. RBM: Reducing balance method; Ns: Period is not specified; [g] **Ind** = Indirect costs (labor, overhead, …). Ns: Not specified; [h] **Time (yrs.) =** Time span in years. Ns: Not specified.

[i] **Disc** (%) = Discounting factor in %. Ns: Not specified; [j] **SA** = Sensitivity assessment. F : Full sensitivity analysis; P : Partial sensitivity analysis.; [k] **T/S** = Taxes and subsidies. T: Tax included; S: Subsidy included.

Based on Table 1, Table 2, Table 3 and Table 4, the variation in results between the different impacts assessment studies can be explained by three main reasons related to the assessment methodology: (1) the framework methodology, (2) a mismatch in the Technology Readiness Level (TRL) of the technology and the required TRL for the methodology, and (3) methodological discrepancies.

Table 4. Overview of economic assessment literature. Part 2

Ref[a]	**Sc (P)**[b]	**Sc (T)**[c]	**Imp**[d]	**Int**[e]	**Ref**[a]	**Sc (P)**[b]	**Sc (T)**[c]	**Imp**[d]	**Int**[e]
(64)			Rev		(72)	1	IR	IC	Int
(54)	1		IC		(55)	0.3-0.8	Inx	Pr	Int
(65)	1		Pr	Int	(46)	0.4-1	Inx	Pr	Int
(29)	1	IR	Pr	Comb	(35)	1		Pr	Int
(62)	1		Cost	Comb	(73)	1		Cost	Int
(56)	0.6-0.8	Inx	IC		(74)	1		Cost	Comb
(66)	0.8-0.9	IR	Cost	Int	(75)	1	Ns	Pr	Comb
(22)	1	IR	Pr	Int	(63)	1		Cost	Int
(33)	Nc		IC	Int	(57)	0.6-1	Inx	Pr	Int
(67)	1	IR	IC	Int	(76)	1	Inx	Pr	Comb
(68)	1	IR	IC		(77)	0.6	Ns	IC	Int
(53)	1		Cost	Comb	(78)	0.6	Inx	IC	Comb
(69)	1	IR	Pr	Int	(79)	1	Inx	Cost	Comb
(11)	Reg	Inx	Pr	Int	(80)	1		IC	Int
(49)	1		Pr	Comb	(16)	0.3-0.8	Inx	IC	Int
(61)	1	Ns	Pr	Int	(81)	1	IR	IC	Comb
(60)	1	Ns	Pr	Int	(52)	1	IR	IC	Comb
(70)	1	Inx	IC	Comb	(82)	0.7-0.9		IC	Int
(71)	1	Ns	IC	Int	(83)	1		IC	Int
(51)	1		IC	Int	(84)	0.8	IR	IC	Int

[a] **Ref** = Reference number: see Table 6; [b] **Sc(P)** = Sizing factor for the scale of the process. Nc: Not clear; [c] **Sc(T)** = Temporal scale. Inx: Index; IR: Inflation rate; Ns: Not specified; [d] **Imp** = Impact category. Rev: Revenue; Pr: Profit; IC: Investment criteria (for example: net present value, internal rate of return); [e] **Int** = Integration of technological assessment. Int : Integrated technological and environmental assessment. Comb: Combined technological and environmental assessment.

3.1. Framework methodology

The lack of a generic framework or the inconsistent following of its predefined guidelines is identified as the first reason for the assessments to render varying results.

Most of the environmental studies aimed at performing an LCA. An LCA is defined as "the compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle" (ISO

14040). The life cycle starts from the extraction of resources, moving through the production of materials, the process itself, the use of the product, and ends with the reuse, recycle or disposal phase (Guinée et al., 2002). Although there is no single method to perform an LCA, clear guidelines were stated in the ISO LCA standards to enable a harmonized generic framework based on the four predefined steps (ISO 14040). These four steps enable the clear illustration of the methodological strategy. An example of this asset can be found in the study by Weinberg, Kaltschmitt, and Wilhelm (2012). These four main steps were only encountered in 18 of the 48 environmental studies which aimed to perform an LCA. Although ignoring this framework does not necessarily mean that the environmental study is of a lesser quality, the advantage of a generic harmonized framework provided by the LCA is lost.

Three economic studies aimed at a Life Cycle Costing (LCC) for their assessment. A LCC captures all costs endured during the life cycle of a product; it can include external costs such as environmental costs and social costs. Upstream financial costs are automatically included in the price of inputs, so upstream activities do not need to be considered (Hoogmartens, Van Passel, Van Acker, & Dubois, 2014). Therefore, an LCC shares the same scope and timeframe as an LCA, so the LCA framework can also be used by the LCCs. However, only Meyer and Weiss (2014) followed the predefined steps of the LCA framework. No other economic studies used a generic framework for their assessment.

3.2. Technology Readiness Level (TRL)

The second reason for the varying results is related to the early TRL of algal-based biorefineries. The TRL scale is a classification scale for the maturity of a specific technology (Mankins, 2009). As there are currently no commercial algal-based biorefineries, this technology is in an early TRL stage, where data for the entire process is not yet available. Therefore, the assessments have a prospective nature, rather than a retrospective one.

Most environmental assessments aim at analyzing the total environmental impact of a product during all life cycle phases. For that reason, a complete range of environmental impacts needs to be included for all processes, inputs and outputs during the entire life cycle. Such large amount of data is only available in a late TRL stage. Therefore, a mismatch exists between the TRL level needed for the methodologies and the TRL level of the technology under assessment. The reviewed studies solve this mismatch by streamlining their assessment methodology to reduce the data requirement. Three different streamline approaches have been followed: (1) excluding certain life cycle phases, (2) reducing the number of environmental impact categories, and (3) using surrogate data.

The first streamline strategy used by most studies is the exclusion of certain life cycle phases. Thus, most studies do not cover a complete cradle-to-grave perspective. The use and disposal stage is excluded by the cradle-to-gate assessments; gate-to-grave assessments exclude the environmental impact of certain inputs. However, as most studies do not treat all inputs or products in the same way, a subdivision (cradle/cradle* and grave/grave*) was made in Table 1 and Table 2. Studies with a 'cradle' perspective include the environmental impact of certain inputs, such as fertilizers, but exclude the environmental impact of other inputs, such as construction materials. Therefore, a 'cradle*' perspective is only assigned to studies that include the environmental impact of all inputs. A 'grave*' perspective includes the disposal and use phase of all coproducts, where a 'grave' perspective only includes the main product. The disposal of waste should also be considered within the system boundaries. However, the waste streams are often not taken into account, or a recycling efficiency of 100 percent is assumed. A good example of a cradle*-to-grave* system boundary can be found in the study by Stephenson et al. (2010). Some studies use criteria to exclude processes which are considered less relevant (e.g. Sills et al. (2013)). However, the relevant inputs and processes can only be determined if their environmental impact has already been assessed (Finnveden et al., 2009; Graedel, 1998; Grierson & Strezov, 2012). For example, the often-neglected infrastructure emissions can be a significant contribution to the overall environmental impact (Canter, Davis, Urgun-Demirtas, & Frank, 2014). Hence, this first streamline strategy is not valid, as important contributions to the overall environmental impact will be neglected by the exclusion of certain life cycle phases (Graedel, 1998).

The second streamline strategy is the reduction of the environmental impacts included in the assessment. The study by Resurreccion et al. (2012) used this streamline strategy and referred to their study as a 'partial LCA.' Due to the low TRL level of algal-based biorefineries, at this point it is not clear how the environment will be affected and which environmental impact categories will be relevant. Consequently, the choice of impact categories varied widely over the reviewed studies. Although most studies were limited to one or two impact categories, some authors, such as Collet et al. (2011), for instance, included a broader range. Climate impacts and resource depletion were frequently used impact categories. Resource depletion can include a wide range of resources, such as minerals, fossil fuels, water, soil, and biotic resources. Most of the reviewed studies consider fossil fuels and water consumption; however, some studies based on energy use do not make the specifications towards fossil fuels. Other impact categories, which were considered less frequently, were eutrophication, acidification, eco-toxicity, human toxicity, photochemical smog, ozone depletion, ionizing radiation and air emissions. Although only a few studies included these impact categories, the impact of algal-based biorefineries in these categories could be substantial (Grierson, Strezov, & Bengtsson, 2013). Therefore, the exclusion of relevant environmental impacts can lead to incorrect or irrelevant conclusions (Guinée et al., 2002).

The third streamlining methodology to cope with the low TRL was the use of surrogate data. Surrogate data originates from a similar process where more accurate data is readily available. An example is the use of the soy transesterification process as a proxy for the transesterification of algal biomass (Batan, Quinn, & Bradley, 2013; Passell et al., 2013). According to Graedel (1998), who conducted a survey among multiple LCA practitioners, this streamline methodology is the only valid methodology included.

Although an environmental assessment methodology can be streamlined to adapt to earlier TRL stages, this streamlining should not be interpreted as the exclusion of relevant life cycle phases or impact categories. For that reason, the TRL mismatch between the technology and the methodology leads to streamline methodologies which alter the system boundaries of the assessment and the impacts considered.

The economic studies assess an algal-based biorefinery on a hypothetical commercial scale. A large amount of data is needed to incorporate all relevant economic costs and revenues. However, this large amount of data is currently not available for algal-based biorefineries. Therefore, some economic assessments adapt their goal to only calculate the costs or revenues of the project. Another approach is to exclude some costs or revenues like infrastructure, waste disposal and indirect costs (for example: labor, overhead). A third approach to cope with the low data availability is the use of cost data from the literature or proxy data (Richardson, Outlaw, & Allison, 2010). Literature data corresponds to a specific year; as prices and costs are not constant over the years, this time setting needs to be incorporated. Most studies make use of inflation rates or specific price indices (such as CEPCI). However, some studies ignore this time problem. Literature data also corresponds to a specific capacity or scale. Sizing factors (*n*) are used by some studies to scale the equipment and infrastructure cost relative to their capacity (Gong & You, 2014b; Taylor et al., 2013). However, most economic studies do not incorporate economies of scale and use a linear sizing factor.

3.3. Methodological discrepancies

The third reason is related to varying methodological choices. For environmental assessment, these choices concern the approach of the LCA, the functional unit, impact allocation and temporal and spatial scale. There are two broad strategies to approach an LCA: an attributional or a consequential approach. An attributional approach focuses on the evaluation of the direct environmental flows which can be attributed to the process (Kendall & Yuan, 2013). The main objective of an attributional LCA will be the assessment of a product. The consequential approach takes the consequences, both direct and indirect, of the process on the entire environmental system into account (Ekvall & Weidema, 2004). However, the assessment of these consequences induces a high level of uncertainty in the model, as it is dependent on underlying economic prediction models. An example of such a consequential impact is the assessment of the Land Use Change (Kendall & Yuan, 2013). Therefore, the consequential LCA is more appropriate for policy decisions (Collet et al., 2015). As both approaches have a different objective and consequently will follow different strategies, the identification of the followed strategy is important. However, the LCA approach was only mentioned in the study by Grierson et al. (2013) and in the study by Resurreccion et al. (2012).

The functional unit enables a comparison of the environmental impacts over different products or processes (Cherubini et al., 2009; Guinée et al., 2002). As an LCA aims at the environmental assessment of a product, most studies use a product-based functional unit. This functional unit can be expressed in terms of mass, energy content, volume or functionality of the end product. An energy-based functional unit can also be considered as functionality-based. If the energy content is used, both the lower heating value and the higher heating value have been used by the studies. Some studies use a time-based functional unit, where the environmental impact of a project is averaged over a certain period of time. Therefore, a time-based functional unit is based on the project instead of on the product. As it is not clear which functional unit is the most appropriate, the choice for a specific functional unit is entirely based on the author's perspectives.

By definition, an algal-based biorefinery is comprised of multiple end-products. Therefore, the environmental impact should not be allocated to one end-product, but divided over the different end-products. The ISO guidelines provide three hierarchical allocation approaches (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010; ISO 14040): subdivision, substitution and partitioning. (1) Subdivision divides the overall process in mono-functional single-operation unit processes. This way, allocation can be avoided. However, from an algal-based biorefinery perspective, the subdivision into single processes is not possible. (2) Substitution replaces the coproducts with similar products from other production processes. This method is also known as the displacement or system expansion method. It can be used as an application of a consequential LCA, as it is not limited to the main direct effects of the process or products, but includes the substitution of conventional technologies (Ekvall & Weidema, 2004). However, the identification and quantification of these conventional technologies can be a major challenge for this allocation method (Michael Wang, Huo, & Arora, 2011). (3) Partitioning allocates the impacts over the products based on an allocation criterion. This allocation criterion is usually based on mass, energy content, functionality or price of the products (Michael Wang et al., 2011). The Renewable Energy Directive (RED) advises to use the energy content as an allocation criterion (European Commission, 2009a). However, allocation based on energy content is only valuable when the algal-based biorefinery solely consists of energy products. The exergy content also includes flows of matter, and has for that reason been suggested as an alternative partitioning criteria (Maes et al., 2015). Cherubini, Strømman, and Ulgiati (2011) suggested a hybrid allocation measure combining both substitution and partitioning. This method was tested and further elaborated by Sandin, Røyne, Berlin, Peters, and Svanström (2015). However, a hybrid method is less transparent and objective compared to pure partitioning. The reviewed studies used both substitution and partitioning. Different allocation criteria were used for the partitioning. Similar to the choice of a functional unit, the choice of an allocation methodology can have a large influence on the results (Cherubini et al., 2011; Sandin et al., 2015; Zaimes & Khanna, 2014).

As stated by McKone et al. (2011), the temporal and spatial scale can be of major influence. The effects of the temporal scale were included in the environmental assessment studies in three different ways: (1) the definition of a time horizon for the Global Warming Potential (GWP) indicator, (2) the definition of a lifetime for the facility and/or equipment, and (3) the definition of a time horizon for the entire project. The second approach was mostly used to incorporate the environmental impacts from the infrastructure. The spatial scale has a large influence on technological parameters, like the biomass productivity; moreover, it is also an important consideration when waste materials such as wastewater or flue gas are included as an input to the process. Most studies only defined the country of their hypothetical production plant, as this defines the electricity composition used for the energy supply. However, a few studies (e.g. Vasudevan et al. (2012)) did include detailed assessments of appropriate locations (Batan et al., 2013; Vasudevan et al., 2012).

For economic assessments, the methodological choices are related to the definition of the life span, depreciation period, discount rate, functional unit and spatial scale. Due to the annual variation of costs, revenues and profits, the economic profitability of an algal-based biorefinery needs to be defined over the entire life span of the project. The definition of this life span varied over the different studies. The depreciation period of certain equipment defines the period until this equipment loses its value. However, most studies use one depreciation period for all sorts of equipment, and the length of this depreciation period also varied. To incorporate the opportunity cost of money, future costs or revenues can be discounted. However, the used discount rate also varied among the studies. Resurreccion et al. (2012) included three different assumptions for this discount rate to assess its impact on the overall profitability of the project.

The functional unit, in accordance with the environmental assessments, defines on which level the economic profitability is displayed. Most studies that calculate investment criteria use the entire project as a functional unit. However, some of these studies specify the economic profitability per ton, gallon or MJ biodiesel. The studies, which only calculate the costs or revenues, have a larger variety in functional units.

In accordance with the environmental impact, the specific location of the algal-based biorefinery can also have a large impact on the profitability of the project. Both technological parameters (for example, biomass productivity) and economic parameters (for example, specific taxes or rent costs) are dependent on the location. Some studies, like the study by R. E. Davis et al. (2014), include a detailed resource assessment to specify a suitable location for the algal-based biorefinery. Other studies define the specific location for their production plant on a country or regional level, or exclude the definition of a spatial scale.

3.4. Integration of different dimensions

3.4.1. Integration of the technological process

The economic profitability or environmental impact of an algal-based biorefinery depends on the specific technological process underlying it. Most studies include a technological assessment to define this process and calculate the input and output flows. However, some studies do not include this technological assessment and are restricted to an environmental or economic assessment. Studies defined as combined in this review do include a technological assessment; however, they do not completely integrate this technological assessment. An integrated technological and economic/environmental assessment performs one assessment where the technological parameters are directly linked to the environmental/economic output parameters. Such an integrated approach allows for safeguarding environmental and economic feasibility during the maturation of the technology. The integration of the environmental and economic assessment into one assessment has also been recommended by different studies (Benemann et al., 2012; Quinn & Davis, 2015). The adaptation of certain technological parameters may highly improve economic profits. However, this same adaptation can be disastrous for the environmental impact. An approach that integrates all three dimensions will directly translate the effect of an improved technological parameter on the environmental and economic feasibility during each TRL stage.

An important asset of an integrated approach is the possibility to assess the sensitivity and uncertainty of all input parameters for all technological, economic and environmental output parameters. Two different types of sensitivity analyses are defined in this review: (1) a partial sensitivity analysis and (2) a full sensitivity analysis. A partial sensitivity analysis is limited to the inclusion of a few alternative values for the assumed key parameters, while a full sensitivity analysis includes a continuous range of variation over all input parameters. Such a full sensitivity analysis is only feasible when a dynamic connection exists between the different dimensions.

Of the 64 environmental assessments, 42 performed an integrated technological and environmental assessment. The environmental impact parameters were directly linked to the technological process. Most environmental impact categories in this review are normalized to a certain technological input or output flow (for example: m^3 water consumption, kg CO_2-equivalents, kg CFC-11-equivalents and kg SO_2-equivalents). Therefore, these impacts can be directly calculated in the technological assessment. If more environmental impacts are included, or if the environmental impacts are weighted and aggregated to certain indicators, the focus shifts more towards the environmental part of the assessment. Eighteen of the environmental studies were classified as combined technological and environmental assessments. A detailed technological assessment was often included. The output from this technological part was then used as static input data in the environmental assessment. The dynamic linkage between both dimensions was missing.

Nineteen economic studies specifically aimed at performing a TEA. However, seven of these studies only combined the technological and economic assessments, as they did not display a clear dynamic connection between the technological and economic assessments. Therefore, they were not classified as integrated technological and economic assessments. Some of these TEAs did not include a full economic assessment, being limited to a cost assessment. Only two studies specified what a TEA meant and what it should include. According to Coleman et al. (2014), a TEA aims at “identifying and understanding key costs and subsequent technology constraints that potentially affect the commercialization and success” and enables a “measure of performance relative to cost among various technologies and design scenarios.” Although these definitions mention the link between the technological and economic dimensions, the integrated aspect is not emphasized, as they are limited to specific scenarios. Moreover, as only the costs are considered, a complete economic assessment is not performed. According to Davis et al. (2014), a TEA is “an engineering costing method that determines selling prices to evaluate and quantify economic implications for technology options”. They also referred to a methodology developed by Aden and Foust (2009), which focuses on an integrated assessment by means of a process flow diagram and mass and energy balance. The economic viability is assessed with a cash flow analysis based on the specifics of the process. A sensitivity analysis is included to enable the assessment of the effect of varying parameters on the economic output parameters. As this methodology does integrate the technological and economic assessments, it can be considered a valid integrated technological and economic assessment.

Van Dael, Kuppens, et al. (2014) created a framework methodology for the execution of a TEA that extended this definition, adding a market study as the first step for their framework methodology. The market provides information concerning the competitors, customers, market sizes, expected costs and revenues, and market trends. Therefore, it is an important aspect of the economic part of the TEA. None of the studies classified as an integrated technological and economic assessment in this review included a market study.

3.4.2. Integration of environmental and economic assessments

Sustainability is based on the integration of the three different dimensions. Most of the assessments only covered one dimension of sustainability. However, some studies did include both environmental and economic assessments. These studies are displayed in Table 5. Most of these studies combined two separate assessments, performed in a sequential order. By separating the two assessments, the connections between the two dimensions get lost. An integrated assessment would be able to use common system boundaries and assumptions to arrive at a general conclusion over the sustainability of algal-based biorefineries. If the ISO guidelines had been followed, such framework could have been provided by the two studies which aimed at LCA-LCC studies.

Table 5. Overview of combined assessment literature

	Ref[b]	**FU**[c]		**Imp**[d]		**SA**[e]		**Int**[f]		
		Env	**Ec**	**Env**	**Ec**	**Env**	**Ec**	**T-En**	**T-Ec**	**En-Ec**
Opt[a]										
X	(57)	V	V	CC	Pr	G		Int	Int	Int
X	(55)	T	T	CC	Pr		L	Int	Int	Int
X	(46)	M	T,V	CC	Pr			Int	Int	Int
X	(11)	F	F	CC,En,Eu,OI	Pr	L	L	Int	Int	Int
X	(16)	V	P	CC	IC	L	L	Int	Int	Int
X	(62)	V	V	En,W	Cost	L	L	Int	Comb	Comb
X	(60)	V	T	En,W	Pr			Int	Int	Comb
X	(61)	V	V	En,W	Pr		L	Int	Int	Comb
	(35)	P	V	CC	Pr	L	L	Int	Int	Comb
	(22)	F	F	CC,En,W,Eu	Pr	G	G	Int	Int	Comb
	(33)	F	F	CC,En,W,Eu	IC	G	G	Int	Int	Comb
	(64)	En	T	W	Rev	L				Comb
	(63)	T	V	En,W	Cost		L	Int	Int	Comb
	(51)	En	P	CC,En	IC	L	G	Comb	Int	Comb
	(29)	M	T	CC,En	Pr			Int	Comb	Comb
	(53)	En[l]	M	CC,En	Cost	L		Comb	Comb	Comb
	(49)	M		CC,En,Eu,OI	Pr	L		Comb	Comb	Comb
	(52)	M	T	CC,En,OI	IC		L	Comb	Comb	Comb
	(56)	V		CC	IC	G	L			Comb
	(54)	En[l]	En[l]	CC,OI	IC		L			Int

[a] **Opt** = Optimization study; [b] **Ref** = Reference number: see Table 6; [c] **FU** = Functional unit. Env: Environmental; Ec: Economic. En: Energy; M: Mass; V: Volume; F: Functionality; T: Time; P: Project; l: Lower heating value; [d] **Imp** = Impact category. Env: Environmental; Ec: Economic. CC: Climate change; En: Energy consumption; W: Water consumption; Eu: Eutrophication; OI: Other impact categories; Pr: Profit; IC: Investment criteria; Rev: Revenue; [e] **SA** = F: Full sensitivity analysis; P : Partial sensitivity analysis; [f] **Int** = Integration of technological – economic – environmental assessments. T-En: Technological and Environmental assessments; T-Ec: Technological and Economic assessments. En-Ec: Environmental and Economic assessments. Int: Integrated assessments; Comb: Combined assessments.

Kovacevic and Wesseler (2010) determined a total cost by internalizing both the external environmental and social costs. Therefore, this study could be considered an integrated economic-environmental assessment. However, the technological dimension was not integrated.

Optimization studies program different technological configurations to optimize technological and economic and/or environmental impacts. Therefore, they use the technological framework as a 'backbone' for their environmental and economic assessments. Although they all lacked a full sensitivity assessment, they displayed a clear dynamic connection between the different dimensions. Therefore, they were classified as integrated technological and environmental/economic assessments. In general, the optimization studies use the same boundaries for their environmental and economic assessment. Only three of these optimization studies extended their integrated methodology to a common functional unit. Five of the optimization studies used multi-objective optimization to maximize profits and minimize environmental impacts; therefore, they did not simply combine the environmental and economic assessments, but used the optimization methodology to construct a dynamic connection between these dimensions.

4. Environmental TEA (ETEA)

An environmental and economic assessment of an algal-based biorefinery faces four challenges, as identified in this review. Based on these four challenges, we propose a framework methodology based on the TEA framework proposed by Van Dael, Kuppens, et al. (2014), extended with an environmental assessment that is based on the LCA methodology. This ETEA is illustrated in Figure 7 and deals with these four challenges in the following way:

A clear framework was provided. The ETEA framework consists of five clear steps, combining both the steps from the original TEA framework and the LCA framework:
(1) **Market study**. During the market study, the market perspectives – related to prices, competitive products and market trends, for example – are identified. Based on this market study, the main objectives and methodological

assumptions can be identified. This step therefore combines the original market study from the TEA framework with the scope and goal definition step of LCA.

(2) **Definition of the process flow diagram and mass and energy balance**. This step links the data in the different dimensions to the process design. Although retrieved from the TEA framework, it is equal to the life cycle inventory step of LCA.

(3) **Environmental assessment.** The environmental assessment determines all relevant environmental impacts of the project. The assessment is performed by using dynamic technological process parameters, which are obtained from the process flow diagram and from the mass and energy balances. Therefore, it is a literal translation of the life cycle impact assessment step of LCA.

(4) **Economic assessment.** This step assesses the economic feasibility of the project based on the dynamic technological process parameters. The system boundaries are the same as those used in the environmental assessment. This step is adopted from the TEA framework. The third and fourth step could be grouped together as the impact assessment step, where the third step focusses on the environmental impact and the fourth step focusses on the economic impact assessment.

(5) **Interpretation step.** The interpretation step facilitates the interpretation and analysis of results. A risk assessment is included to identify the probability distribution of the output parameters. This risk assessment includes a sensitivity analysis that analyzes the variation of output parameters when input parameters are varied. As the technological assessment is truly integrated, a full sensitivity analysis that varies all parameters (that is, technological, economic and environmental) is possible. This step was adopted from the LCA framework. However, the risk assessment as included in the TEA framework is a crucial analysis in this fifth step.

A main characteristic of the ETEA, which was a common property of the LCA and TEA framework as well, is the iterative approach (Aden & Foust, 2009; European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010; Van Dael, Kuppens, et al., 2014). However, none of the reviewed studies used multiple iterations for their assessments. An early iteration can consider a mere black-box model, and can make use of valid streamline technologies, such as the adoption of proxy data, to adapt the methodology to an early TRL. Later iterations can increase the level of detail for the process parameters that were identified as important. The further the technology evolves, the more detailed the assessment will be. In the market study of the first iteration, a range of relevant environmental impact categories needs to be defined. For microalgae, the studies of Efroymson and Dale (2015) and Christine Rösch and Maga (2012) were performed with this objective. An early iteration should include a broad range with rough estimates of the environmental impacts. Later iterations can focus on refining the environmental impact for the important impact categories as identified by the environmental results and sensitivity analysis. Therefore, the ETEA methodology would allow assessing the sustainability of the entire value chain of a technology at each TRL stage.

Technological, environmental and economic assumptions should be clearly stated, when performing an ETEA. A harmonized functional unit and allocation methodology will enable a comparison of the results over different studies and a generic conclusion regarding the sustainability of algal-based biorefineries. As suggested by Collet et al. (2015), the variation in results due to a different assumption should also be added to the assessment.

The manner in which the technological process was integrated in the reviewed papers was highly variable. The genuinely integrated methodologies translated the integration of the technological process by means of mass and energy balance and a detailed process flow diagram adapted to the current TRL level. This strategy was included in both the LCA framework and the TEA framework and therefore adopted in the ETEA as well. As both methodologies share a ‘technological backbone’, the ETEA therefore includes common system boundaries on process, temporal and geographical scales

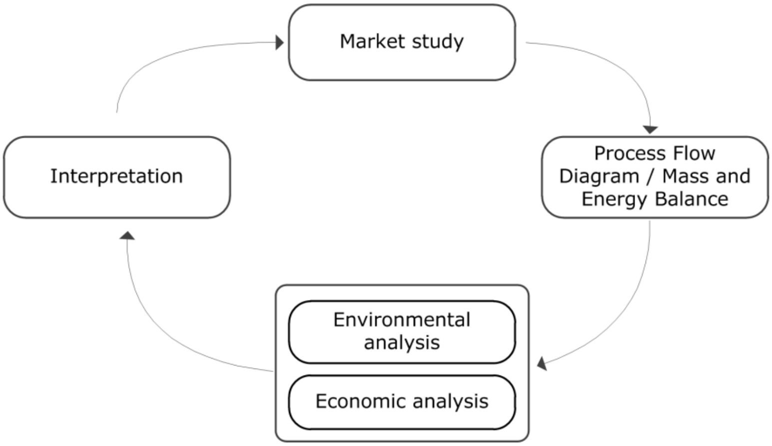

Figure 7. Environmental Techno-Economic Assessment

5. Conclusions

The varying results in sustainability assessments are due to (1) the lack of a generic integrated framework, (2) a mismatch between the TRL of the technology and the assessment used, and (3) methodological differences. These three reasons are translated into three challenges related to the harmonization of assessment results covering one sustainability assessment dimension. These three challenges are extended with a fourth challenge related to the harmonization of assessments over different sustainability dimensions: (4) the integration of a common technological process, directly linked to the economic and environmental assessment.

Based on these four challenges, we suggest an integrated framework methodology, the ETEA, based on the TEA framework and extended with an environmental assessment. The iterative character of the methodology will facilitate the adaptation to different TRL stages. Clear and harmonized assumptions are crucial to enable a generic assessment of the sustainability of algal-based biorefineries. Good practices – as encountered in the different articles reviewed – should be adopted in order to avoid the different flaws found in the current sustainability assessments.

Further research can apply this proposed framework to specific algal-based biorefinery cases. The current methodology does not specify the appropriate environmental impact categories. These categories are case specific and can therefore not be defined in a generic assessment methodology. Further research is required to identify the most appropriate environmental impact categories for algal-based biorefineries. Finally, most sustainability assessments have only focused on the economic and/or environmental dimension. However, the social impact of an algal-based biorefinery should also be included in a full sustainability assessment. The integration of such an assessment methodology in the current proposed assessment framework is therefore an interesting track for further research.

Table 6. Legend references

Number	Reference
1	Adesanya, Cadena, Scott, and Smith (2014)
2	Stephenson et al. (2010)
3	Collet et al. (2011)
4	Grierson et al. (2013)
5	Ponnusamy, Reddy, Muppaneni, Downes, and Deng (2014)
6	Handler, Shonnard, Kalnes, and Lupton (2014)
7	Weinberg et al. (2012)
8	Hou, Zhang, Yuan, and Zheng (2011)
9	Yanfen, Zehao, and Xiaoqian (2012)
10	Passell et al. (2013)
11	Gutiérrez-Arriaga, Serna-González, Ponce-Ortega, and El-Halwagi (2014)
12	Brentner, Eckelman, and Zimmerman (2011)
13	Sills et al. (2013)
14	Khoo, Koh, Shaik, and Sharratt (2013)
15	Sander and Murthy (2010)
16	Gebreslassie, Waymire, and You (2013)
17	O'Connell, Savelski, and Slater (2013)
18	Azadi et al. (2014)
19	Mu et al. (2014)
20	Shirvani, Yan, Inderwildi, Edwards, and King (2011)

21	Collet et al. (2014)
22	Resurreccion et al. (2012)
23	Soratana, Khanna, and Landis (2013)
24	Vasudevan et al. (2012)
25	Clarens, Nassau, Resurreccion, White, and Colosi (2011)
26	X. Liu et al. (2013)
27	Frank, Elgowainy, Han, and Wang (2013)
28	Frank, Han, Palou-Rivera, Elgowainy, and Wang (2012)
29	Ventura, Yang, Lee, Lee, and Jahng (2013)
30	Woertz et al. (2014)
31	Holma et al. (2013)
32	Draaisma et al. (2013)
33	Y. Zhang, White, and Colosi (2013)
34	Gao, Yu, and Wu (2013)
35	Rickman, Pellegrino, Hock, Shaw, and Freeman (2013)
36	L. Xu, Brilman, Withag, Brem, and Kersten (2011)
37	Gerbens-Leenes, Xu, de Vries, and Hoekstra (2014)
38	Batan et al. (2013)
39	Chowdhury et al. (2012)
40	Yuan, Kendall, and Zhang (2015)
41	Soh et al. (2014)
42	Baliga and Powers (2010)
43	Batan, Quinn, Willson, and Bradley (2010)
44	Pacheco et al. (2015)
45	Andersson, Broberg Viklund, Hackl, Karlsson, and Berntsson (2014)
46	Gong and You (2015)
47	Brune, Lundquist, and Benemann (2009)
48	T. Zhang, Xie, and Huang (2014)
49	Liang, Xu, and Zhang (2013)
50	Quinn et al. (2014)
51	T. M. Mata, Mendes, Caetano, and Martins (2014)
52	Moncada, Tamayo, and Cardona (2014)
53	Ferreira et al. (2013)
54	Kovacevic and Wesseler (2010)
55	Gong and You (2014b)
56	Agusdinata, Zhao, Ileleji, and DeLaurentis (2011)

57	Gong and You (2014a)
58	Peralta-Ruiz, González-Delgado, and Kafarov (2013)
59	Peralta, Sanchez, and Kafarov (2010)
60	Martín and Grossmann (2012)
61	Martín and Grossmann (2014)
62	Severson, Martín, and Grossmann (2013)
63	J. N. Rogers et al. (2014)
64	Subhadra and Edwards (2011)
65	Richardson et al. (2010)
66	Meyer and Weiss (2014)
67	Richardson et al. (2012)
68	Gallagher (2011)
69	Williams and Laurens (2010)
70	Tabernero, Martín del Valle, and Galán (2012)
71	Stephens et al. (2010)
72	Amanor-Boadu, Pfromm, and Nelson (2014)
73	Coleman et al. (2014)
74	Pienkos and Darzins (2009)
75	Davis, Aden, and Pienkos (2011)
76	Harun et al. (2011)
77	Ou, Thilakaratne, Brown, and Wright (2015)
78	R. E. Davis et al. (2014)
79	Klein-Marcuschamer et al. (2013)
80	Thilakaratne, Wright, and Brown (2014)
81	Zamalloa, Vulsteke, Albrecht, and Verstraete (2011)
82	Taylor et al. (2013)
83	Pokoo-Aikins, Nadim, El-Halwagi, and Mahalec (2009)
84	Brownbridge et al. (2014)

Chapter 3.

Techno-Economic Assessment[*]

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In this chapter, the existing TEA methodology, as illustrated in Figure 8, is used to assess multiple microalgal-based biorefinery project scenarios. In each of these project scenarios, a hypothetical production plant is simulated and assessed over a specific evaluation period.

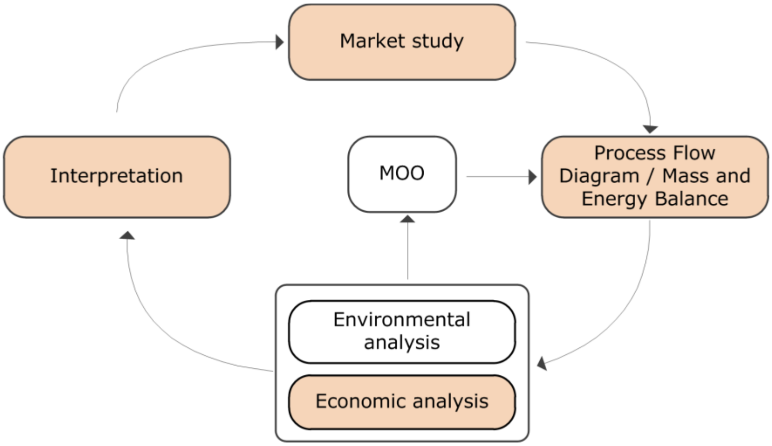

Figure 8. The TEA methodology

Abstract

Economic and technological assessments have identified difficulties with the commercialization of bulk products from microalgae, like biofuels. To overcome these problems, a multi-product algal-based biorefinery has been proposed. This paper performs a TEA of such a biorefinery. Four production pathways, ranging from a base case with commercial technologies to an improved case with innovative technologies, are analyzed. All region-specific parameters were adapted to Belgian conditions. Three scenarios result in techno-economically viable production plants. The most profitable scenario is the scenario which uses a specialized membrane for medium recycling and an open pond algae cultivation. Although the inclusion of a photobioreactor decreases the culture medium costs, the higher investment costs result in lower economic profits. The carotenoid content and price are identified as critical parameters. Furthermore, the economies of scale assumption for the photobioreactor is critical for the feasibility of this cultivation technology. The TEA is an important methodology to

guide and evaluate further improvements in research and shorten the time-to-market for innovative technologies in this field.

1. Introduction

A preliminary economic assessment of a biorefinery concept was performed by Abdo et al. (2016), focusing on the production of biofuels, cake and glycerol. Another study by J. N. Rogers et al. (2014) assessed a biorefinery which produced crude oil and a feed supplement. Beal et al. (2015) combined a techno-economic assessment and a life cycle assessment of ten different biofuel scenarios on a scale of 100 ha. Besides biofuel, other products such as biocrude, ethanol and animal feed were produced as well. Consistent with most of the assessments in literature, these studies all focus on biofuel as the primary product. However, according to the cascading principle (emphasized by the European Parliament (2013)), priority should be given to high-value products. Pacheco et al. (2015) performed an assessment of an algal-based biorefinery producing high-value pigments and hydrogen. Although their study included an extensive environmental assessment, the economic dimension was only briefly discussed by a short overview of product prices and the energy costs. Another study, which did not primarily focus on bioenergy products, was performed by Chauton, Reitan, Norsker, Tveterås, and Kleivdal (2015). They concluded that the production of omega-3 fatty acids from microalgae for aquaculture could become economically feasible in the near future. However, this study only valorized one product stream and was therefore not considered as a biorefinery assessment.

This chapter will elaborate an early assessment of the overall feasibility of an algal-based biorefinery concept. Instead of developing a new scenario with applications, which have not been valorized yet, this paper starts from a conventional scenario, resembling current microalgae production of *Dunaliella salina* for the valorization of β-carotene. Although this process has been commercialized, no TEA studies were found in literature. This study extends this production process by valorizing an additional product, fertilizer, and therefore assesses the technological feasibility and economic viability of a biorefinery case focused on the production of high-value products. Starting from this conventional scenario, three other scenarios were assessed as well, including more innovative technologies. This enables a comparison and the determination of the specific advantages and disadvantages of these new technologies. *Dunaliella salina* for β-carotene production was selected as a case study for two main reasons. The first reason is that the production process is already on a commercial level. This way, the data for the main processes is relatively reliable and available. Moreover, the algal-based biorefinery scenario can be considered as a realistic case. The second reason is that the production process can be easily adapted towards a biorefinery. The purification of β-carotene leaves the residual biomass as a potential co-product. After purification, this can be sold as a fertilizer. *Chlorella* and *Spirulina* are also produced on a commercial level. However, as the entire biomass is sold as a product, this case is more difficult to adapt towards a biorefinery. The commercialization of a biorefinery as assessed in this study, may catalyze the market introduction of microalgae-based biofuels, by stimulating research on more cost-effective technologies for microalgae production.

2. Methodology

Most of the techno-economic studies in the literature do not follow a clear framework or guidelines. However, a transparent assessment methodology enables the harmonization of different studies and the comparison of different algal-based biorefinery concepts. Therefore, this assessment follows a framework methodology which has already been successfully implemented in earlier techno-economic studies, for example by Kuppens et al. (2015) and Van Dael, Márquez, et al. (2014). This TEA framework consists of four steps (Van Dael, Kuppens, et al., 2014):

1) Market study. During this first step, the market perspectives and external factors influencing the commercialization of a product are

examined. As mentioned in the introduction of this dissertation, this step will not be elaborated here.

2) The process flow diagram and mass and energy balance. This step forms the technological 'backbone' of the assessment. An Excel-based spreadsheet model was constructed and used throughout the entire techno-economic assessment.

3) The economic assessment. The economic feasibility is determined based on the integrated technological process by calculating economic investment criteria like the net present value (NPV).

4) The sensitivity assessment. This step examines the impact of a variation of the input parameters on the economic output parameters (Morio, 2011). A Monte Carlo risk analysis was used as this is a powerful and flexible way to assess the influence of risk and uncertainty on the results. In a Monte Carlo analysis, random values are generated for each variable based on an assigned distribution. After assigning the distributions, multiple potential scenarios are generated. Based on these scenarios, the relative contribution of the input variables to the uncertainty of the model's output variables can be determined. For all variables a triangular distribution was assumed as this is the most commonly used distribution for modeling expert opinion (Vose, 1997). A minimum and maximum value of -10% and +10% was selected for each variable (Van Dael et al., 2013). This fraction of 10% has to be the same for all variables and does not represent the uncertainty of that parameter (Homma & Saltelli, 1996). The Crystal Ball extension was used to perform Monte Carlo simulations (10,000 trials). The crucial parameters should be investigated in more detail in later iterations of the TEA, which justifies the chosen distribution and range (Van Dael et al., 2013).

The assumptions, calculations and process data used to develop the technological process flow diagram and mass and energy balance can be found in Table A1.1 in Appendix 1. Table A1.2 of Appendix 1 contains all information on the cost of the equipment, the lifetime of the equipment, the operational costs, the revenues, and the financial assumptions such as loan interests and taxes. All references and information sources are provided as well. This data was mainly based on literature and calculations and was discussed with experts in the field.

3. Case study

This paper evaluates four different scenarios. The first scenario is the basic scenario which consists of conventional technologies. In the second scenario, the intermediate scenario, a membrane is added to enable medium recycle. The third scenario is a more advanced scenario, in which a photobioreactor (PBR) is used for the cultivation stage instead of an open pond. These three scenarios are based on the cultivation of *Dunaliella salina* as a feedstock for the biorefinery. In the fourth scenario a different microalgal-based biorefinery concept is analyzed. *Haematococcus pluvialis* is cultivated in a process similar to the advanced scenario, in order to compare this scenario with an alternative case.

In the basic scenarios, all included technologies are applied on a commercial scale and correspond to a TRL of nine. The membrane which is added in the intermediate, advanced and alternative scenario is a new technology. The application of this technology is currently on a demo scale and the data used for this technology is primary data corresponding approximately to TRL five. Therefore, the whole analysis will be performed at TRL five. The assessment of the inclusion of the membrane in the algal-based biorefinery is the main technological novelty of these case studies.

The four scenarios each produce 170 tonnes of dry weight (DW) biomass per year to enable a comparison of the different scenarios. As the microalgal biomass is an intermediate product, this choice enables a comparison of both cultivation and downstream processes. Each scenario assumes optimal growth conditions as found in the literature. All scenarios produce two products: a high value carotenoid and a fertilizer, consisting of the residual biomass. The algal-based biorefinery is operated for 256 days per year. The other days cannot be used for cultivation due to inappropriate climate conditions and maintenance requirements.

All the scenarios use two stages for cultivation. The first stage maximizes biomass production. During the second stage, stress conditions are induced to maximize carotenoid production. Most studies in the literature use a linear or exponential growth assumption. However, this would assume that the microalgae would grow infinitely. Y. Xu and Boeing (2014) have therefore discussed a logistic growth model. This study uses the sigmoidal growth curve as defined in equation 1:

$$N(t) = \frac{K}{1 + (\frac{K}{N_0} - 1) \times e^{-rt}} \qquad (1)$$

In this equation, K is the maximum biomass concentration, N(t) is the biomass concentration at time t, r is the maximum specific growth rate and N_0 is the initial biomass concentration. The growth parameters and corresponding growth curves are displayed in Figure A1.1 and Table A1.3 of Appendix 1.

Algae cultivation depends on region-specific parameters, such as temperature, evaporation, precipitation and solar irradiation. As the current study uses Belgian conditions as a reference, this was incorporated in the cultivation parameters.

3.1. Basic scenario

The first scenario cultivates *Dunaliella salina* as a feedstock to produce β-carotene and fertilizer. *Dunaliella salina* was one of the first microalgae used for commercial applications (Spolaore et al., 2006). Therefore, this scenario resembles the corresponding commercial production process. However, in the commercial production process only β-carotene is produced. In this first scenario this production process will be extended with the purification of the residual biomass for fertilizer application. The process flow diagram and mass and energy balance of this first scenario are illustrated in Figure 9.

3.1.1. First stage cultivation

The start-up of the production plant required inoculum for the initial concentration. This inoculum was produced on site. The amount of initial inoculum depends on the cultivation volume and the initial biomass concentration.

The cultivation stage was based on the pilot culture study of Tafreshi and Shariati (2006). They cultivated three strains of *Dunaliella salina* for β-carotene production in open paddlewheel ponds. As the average yearly temperature in Iran (19°C) is much higher compared to Belgium (11°C), additional heating was required (Jones et al., 2012; Osborn & Jones, 2014). The ponds were heated to 20°C. Supplementary heating by radiation and solar energy was assumed to increase this temperature to 25°C. Temperature losses of 30% per day were included and compensated for by additional heating. As the precipitation rate in Belgium is higher than the evaporation rate, no additional water compensation due to evaporation was included. Another important region-specific parameter is the solar irradiation (Norsker, Barbosa, Vermuë, & Wijffels, 2011). The solar irradiation is relatively low in Belgium: 1,040 $kWh \cdot m^{-2}$ compared to 2,100 $kWh \cdot m^{-2}$ in Iran (SolarGIS). Therefore, a correction factor for the growth function was included based on the ratio of solar irradiation of Belgium and the country where the cultivation study was performed.

The initial concentration of biomass in the first cultivation stage was set at 0.06 $g \cdot l^{-1}$ (Prieto, Pedro Cañavate, & García-González, 2011). This corresponds to a concentration of 38 $g\ DW \cdot m^{-2}$ after the first stage. A specific growth rate of 0.12 day^{-1} was used, incorporating the correction factor for the Belgian climate. According to the study of Tafreshi and Shariati (2006), the growth rate of *Dunaliella salina* starts to decline after approximately 16 days. This period was therefore used as the cultivation time. The biomass production corresponds to a linear biomass productivity of 1.8 $g \cdot m^{-2} \cdot day^{-1}$ or 0.012 $g \cdot l^{-1} \cdot day^{-1}$. An overview of microalgae biomass productivities was reported by Brennan and Owende (2010) and Teresa M. Mata, Martins, and Caetano (2010). The value calculated in this study corresponds to the lower range of productivities. As most microalgae cultivation experiments are performed in warmer climate conditions, this biomass productivity was considered as a valid estimate, given Belgian climate conditions.

The following nutrients were supplied during the first cultivation stage: NaCl (2 M), KNO_3 (5 mM), $MgSO_4$ (2 mM), KH_2PO_4 (0.1 mM) and $FeCl_3.6H_20$ (0.01 mM) (Tafreshi & Shariati, 2006). Instead of the use of $NaHCO_3$ as only carbon source, this study added CO_2 as well. The use of CO_2 as an input for microalgae cultivation has been frequently discussed, for example by Wang, Li, Wu, and Lan (2008). It has also been included in multiple techno-economic studies on microalgae cultivation for biofuels, such as in Pokoo-Aikins, Nadim, El-Halwagi, and Mahalec (2009). The $NaHCO_3$ and CO_2 consumption was therefore based on the study of García-González et al. (2003). On Figure 9, the $NaHCO_3$ consumption is part of the total nutrient consumption. The CO_2 supply is given separately. Freshwater was used in the cultivation stage to ensure that the quality of the end products is safeguarded. For the same reason, CO_2 was supplied from a commercial source. The energy consumption of the CO_2 supply originated from the injection of CO_2 and the mixing. An automatic preparation unit was included to prepare the cultivation medium.

The cultivation ponds for this first stage covered an area of 24 hectares and had a depth of 15 cm (Tafreshi & Shariati, 2006). This corresponded to a pond volume of 35,549 m³. After the first cultivation stage, a certain amount of biomass remained in the first pond. This amount equaled the initial inoculum amount. Therefore, no additional inoculum production was required.

3.1.2. Second stage cultivation

In the second stage of cultivation, stress conditions were induced based on a limitation of nitrogen and a higher NaCl concentration (2.5 M) (Tafreshi & Shariati, 2006). KNO_3 was supplied in a minor concentration (1 mM). The other nutrients were added in the same concentrations as in the first stage. Based on the results of Prieto, Pedro Cañavate, and García-González (2011) who examined the β-carotene content relative to the solar irradiation, a DW β-carotene concentration of 9.78% was assumed. The maximum specific growth rate was assumed to be two thirds of its first stage value. This equaled a biomass productivity of 1.08 $g\cdot m^{-2}\cdot day^{-1}$ and 0.009 $g\cdot l^{-1}\cdot day^{-1}$. The ponds for the second stage had a depth of 12 cm and covered a total area of 22 hectares (Tafreshi & Shariati, 2006). The required pond volume in this second stage equaled 26,895 m^3.

3.1.3. Harvesting

A centrifuge was used to harvest the microalgae. During this step, the biomass concentration was increased from 0.37 $g\ DW\cdot l^{-1}$ to 120 $g\ DW\cdot l^{-1}$ (Patel et al., 2012). The centrifuge was assumed to have a biomass recovery rate of 97% and an energy consumption of 1.4 $kWh\cdot m^{-3}$ culture medium (Milledge & Heaven, 2011). The wastewater resulting from the centrifuge was not treated on the production plant itself, but was sent to a wastewater treatment plant.

3.1.4. Washing

Due to the high salinity level during cultivation, a high amount of salt remained in the biomass flow after centrifugation (0.12 $kg\cdot l^{-1}$). A washing step was therefore required. New water is added with a ratio of 30 to the total volume to ensure a salt concentration in the end products under 3%. After the water addition, the biomass flow was centrifuged until a biomass concentration of 120 $g\ DW\cdot l^{-1}$ was restored.

3.1.5. Drying

A drying step increased the solid concentration of the biomass flow to 934 $g\cdot l^{-1}$. The technological specifications for the drying step were based on the study of Leach, Oliveira, and Morais (1998). To calculate the total energy consumption of this spray dryer, a factor of 2.9 was used to account for the heat exchanger energy transition efficiency. This calculation was based on the course “Sproeidrogen” by Technotrans BV in 2001. The total electrical energy consumption equaled 5.1 MJ per kg of removed water. *Dunaliella salina* lacks a rigid cell wall (Oren, 2005). The cells were therefore disrupted during spray drying and centrifugation and no additional cell disruption was required.

3.1.6. Extraction

The lipid fraction of the microalgae was extracted by the use of hexane. This process was based on the study of Cerón et al. (2008), where lutein was extracted from microalgae biomass. Six extraction steps were included, using a ratio of 1:1 of hexane to sample volume. The extraction efficiency of β-carotene was assumed to be 95% and the extraction time was 60 minutes per step (C. C. Hu, J. T. Lin, F. J. Lu, F. P. Chou, & D. J. Yang, 2008). The bead mill and alkaline treatment used by Cerón et al. (2008) were assumed not to be necessary, due to the fragile cell wall of *Dunaliella salina* which breaks during the drying and centrifuge step and due to the relatively high carotenoid content (Oren, 2005). The energy consumption was assumed to be the same as for the paddle wheel mixing in the open ponds, $3.72\ W \cdot m^{-3}$.

3.1.7. Filtration

The filtration step separated the liquid fraction, which contained the lipids dissolved in the hexane, from the solid fraction, which contained the residual biomass. No energy consumption was required in this step.

3.1.8. Evaporation

The solid fraction went to an evaporation step to recycle the hexane. The remaining fraction was sold as fertilizer. To calculate the energy consumption, a correction factor for the heat transfer efficiency was included. This factor was equal to the correction factor used in the drying step.

3.1.9. Vacuum distillation

The liquid fraction from the filtration step contained the carotenoids and the hexane. This hexane was distilled in a vacuum distillation to obtain a relatively pure stream of carotenoids. The calculation of the energy consumption used the same heat transfer efficiency factor as the drying and evaporation step. The carotenoids had a residual fraction of 1 mg of hexane per kg carotenoid, corresponding to the legal limit of hexane as a solvent for food or feed (European Commission, 2009b). To obtain this high distillation efficiency, the vacuum distillation was performed in three steps.

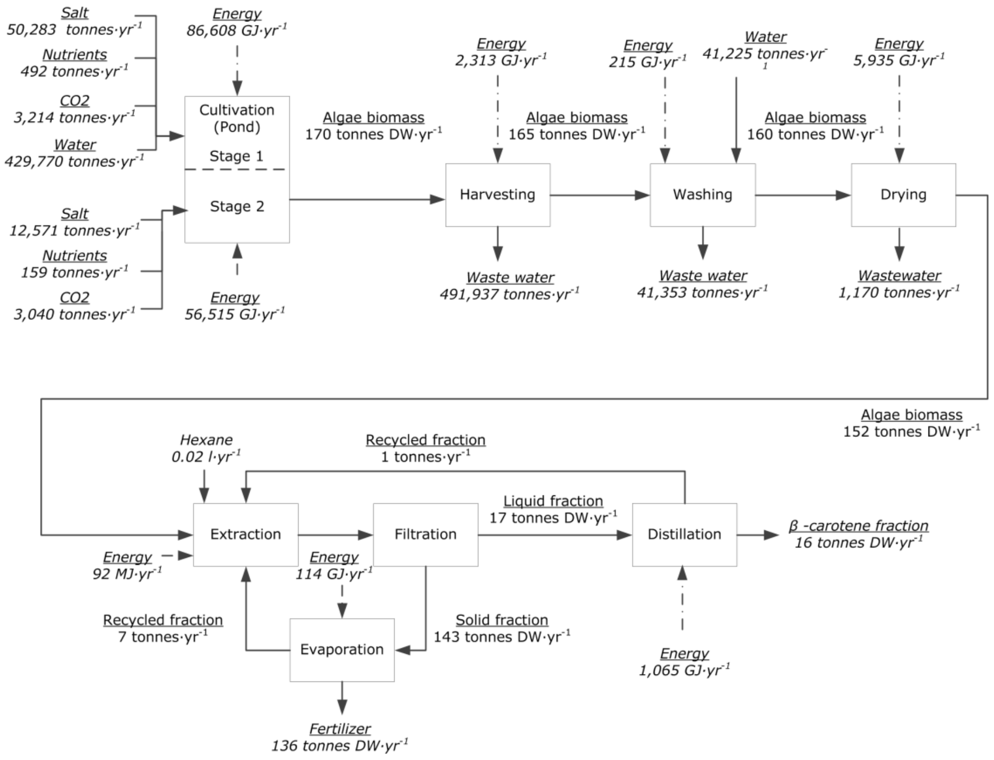

Figure 9. Basic scenario

3.2. Intermediate scenario

The second scenario cultivated the same species of microalgae. Therefore, the same cultivation parameters, such as nutrient and salt concentration were used. To harvest the microalgae, a filtration step was added using the integrated permeate channel membrane (IPC®). This backwashable membrane was developed at VITO and consists of three dimensional fabric spacers which form a membrane envelope. De Baerdemaeker et al. (2013) compared the performance of this backwashable submerged membrane to other membranes. Technological specifications can therefore be found in their benchmark study. The IPC® membrane concentrated the biomass to a concentration of 10 g·l^{-1}. The membrane filtered out bacteria and contaminations and enabled the recycling of water and salt. The amount of salt and water which needed to be supplied during the first cultivation stage was therefore lower compared to the basic scenario. The recycling ratio was limited by the difference in salt concentrations between the two cultivation stages. The residual water left the process to a wastewater treatment plant. After this membrane filtration, the downstream processes remained the same as in the basic scenario. The process flow diagram for this intermediate scenario is illustrated in Figure 10.

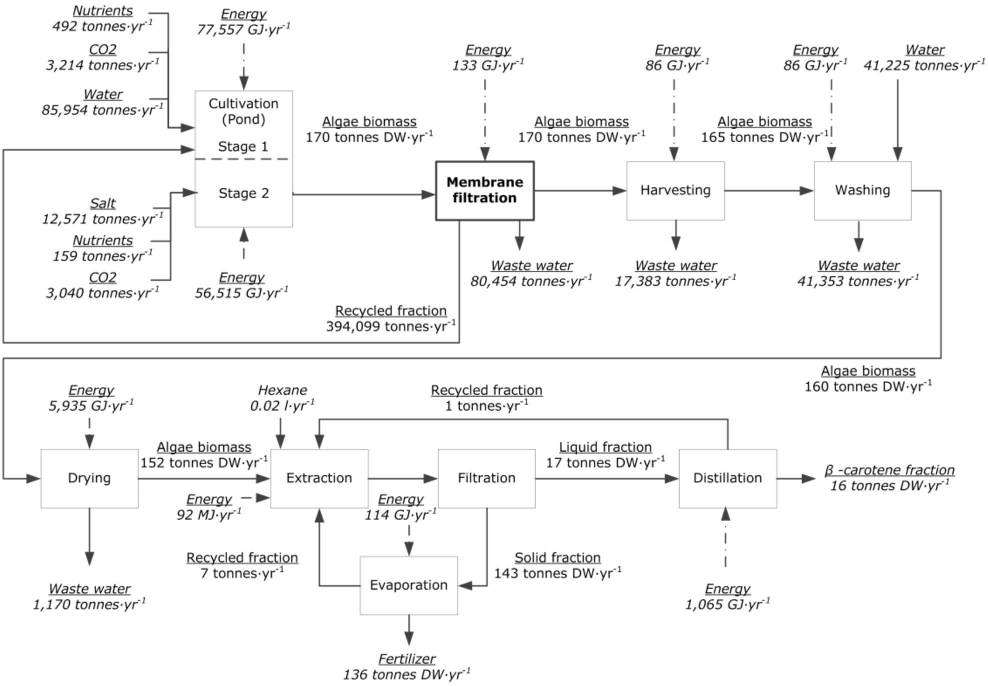

Figure 10. Intermediate scenario

3.3. Advanced scenario

The third scenario used a PBR to cultivate *Dunaliella salina.* This PBR enables a higher biomass productivity and facilitates a more strict control of cultivation conditions (Prieto et al., 2011). Less area is needed for the cultivation compared to open ponds. However, a PBR is more expensive and less durable than an open pond (Teresa M. Mata et al., 2010).

The two-stage system from the previous scenarios was preserved in this scenario. The growth curve was based on the study of Prieto, Pedro Cañavate, and García-González (2011). An initial biomass concentration of 0.23 $g \cdot l^{-1}$ and a maximum biomass concentration of 2 $g \cdot l^{-1}$ were assumed. As the study of Prieto et al. (2011) was performed in Cadiz, the difference in solar irradiation with Belgium is smaller. According to the growth curve of Prieto et al. (2011), biomass productivity leaves the exponential stage after the fifth day of cultivation. This period was therefore adopted as the cultivation period. A maximum specific growth rate of 0.25 day^{-1} was assumed, incorporating the correction factor for the Belgian climate. This corresponds with a biomass accumulation of 0.80 $g \cdot l^{-1} \cdot day^{-1}$, which was approximately the biomass productivity from the study of García-González, Moreno, Manzano, Florencio, and Guerrero (2005). This productivity was again in the low range of the productivities mentioned in the literature (Brennan & Owende, 2010). The nutrients were added in the same volumes as for the open ponds. The CO_2 was added in the same rate per m². As a smaller surface was required, this resulted in a lower CO_2 consumption. This lower CO_2 supply was motivated by the lower amount of CO_2 that escapes into the atmosphere. The reactor volume was 5,098 m³ in this first stage, which equals 14% of the pond volume in the previous scenarios.

The β-carotene accumulation in the second stage remained constant compared to the open pond cultivation. The energy consumption was assumed to be the same as for the first stage of this scenario. The reactor volume was 3,232 m³. The other processes included in this scenario were the same as used in the intermediate scenario. The process design of this advanced scenario is illustrated in Figure 11.

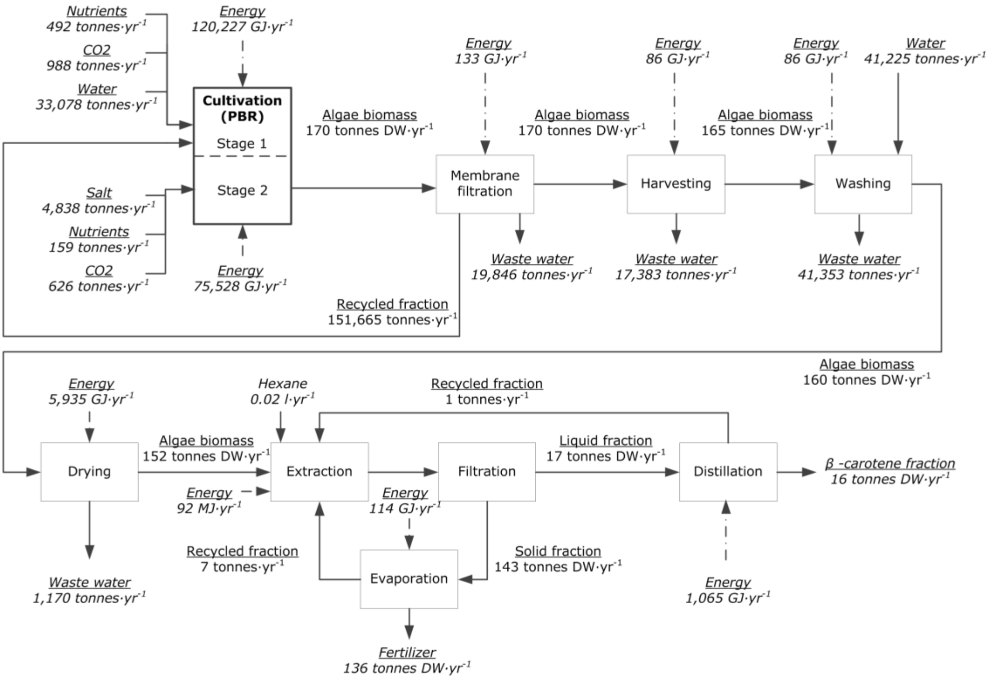

Figure 11. Advanced scenario

3.4. Alternative scenario

The fourth scenario uses an alternative microalgae, *Haematococcus pluvialis,* to produce astaxanthin and fertilizer. The production of astaxanthin from this microalga has already been commercialized. Therefore, it is an interesting case for comparison with the previous scenarios. As there is a large variety in characteristics between the different microalgae species, this comparison gives an idea of the variation in technological and economic feasibility. *Haematococcus pluvialis* is a freshwater alga, which produces haematocysts to accumulate astaxanthin in stress conditions (Del Campo, García-González, & Guerrero, 2007). Therefore, it does not require any addition of salt. This microalga is very sensitive to extreme conditions, which marks the PBR as the most suitable cultivation method (Del Campo et al., 2007). The maximum biomass concentration was assumed to be 4.1 g DW·l^{-1} based on the studies of J. Wang, Sommerfeld, Lu, and Hu (2013) and Aflalo, Meshulam, Zarka, and Boussiba (2007). The maximum specific growth rate was assumed to be 0.14 day^{-1}, based on Olaizola (2000) and the correction factor. According to J. Wang et al. (2013), the optimal biomass concentration for astaxanthin accumulation is 0.8 g DW·l^{-1}. To reach this concentration at the end of the first cultivation stage, the initial biomass concentration was assumed to be 0.45 g DW·l^{-1}. This resulted in a productivity of 0.073 g·l^{-1}·day^{-1}, which is slightly higher than the productivity measured by Olaizola (2000) (0.036-0.052 g·l^{-1}·day^{-1}), but much lower than the biomass productivities found by García-Malea Lopez et al. (2006) (0.41 g·l^{-1}·day^{-1}) and Aflalo et al. (2007) (0.37 g·l^{-1}·day^{-1} – 0.8 g·l^{-1}·day^{-1}). The optimal growth temperature for *Haematococcus pluvialis* is 27 °C (Evens, Niedz, & Kirkpatrick, 2007). As the total biomass production remained the same as in the previous scenario, the same amount of nutrients was added. The reactor volume in this first cultivation stage was 6,440 m³, which is 26 % higher compared to the advanced scenario. The second stage of cultivation had a specific growth rate of 0.09 day^{-1}. Astaxanthin accumulated to 2.9% of total dry weight, according to the results of Olaizola (2000). A reactor volume of 2,874 m³ was used.

As the recycling ratio of the IPC® membrane in this scenario is not restricted by the salt concentration, a maximum recycling ratio of 97% was assumed. *Haematococcus pluvialis* is less fragile than *Dunaliella salina.* The cell walls are therefore not broken during the drying and centrifugation step which necessitates a disruption step (Mendes-Pinto, Raposo, Bowen, Young, & Morais, 2001). As no salt was added to the cultivation step, no washing step was required. The other downstream processes remained the same as in the previous scenarios. Figure 12 illustrates the process design of this alternative scenario.

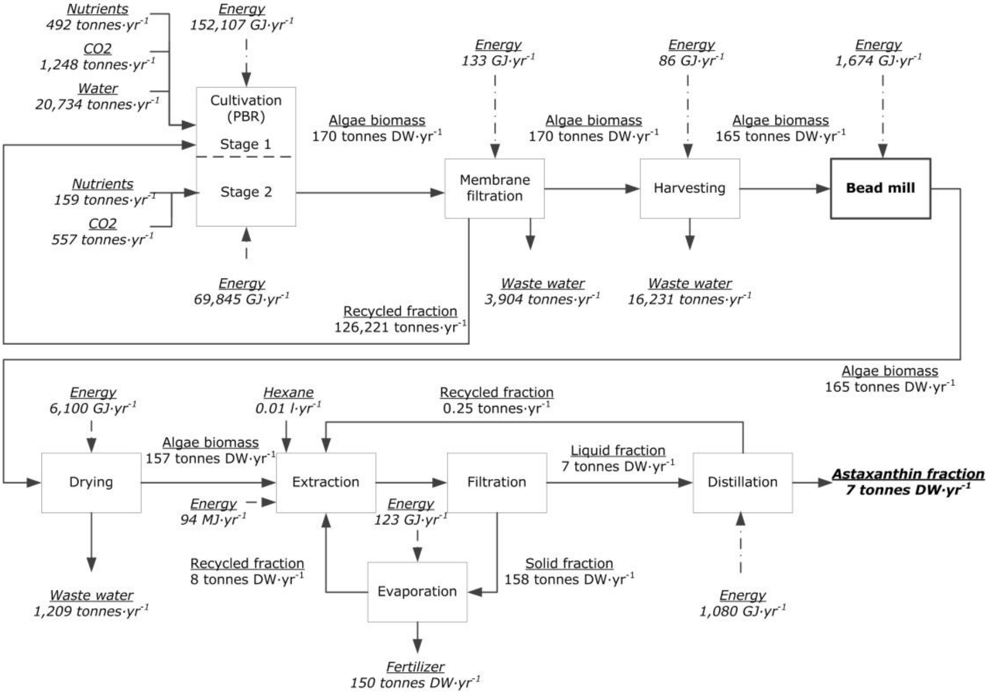

Figure 12. Alternative scenario

3.5. Economic assumptions

The investment costs for the open pond cultivation included high-density polyethylene (HDPE) liners, landscaping, paddlewheels and mixers. The PBR installation consisted of a reactor and an air blower. Both cultivation installations also included an inoculum production system, a medium preparation unit, a CO_2 supply unit and a heat exchanger unit, including a circulation pump. For the scenarios cultivating *Dunaliella salina,* a titanium heat exchanger was required as the high salt concentration could induce corrosion. For *Haematococcus pluvialis* cultivation, a cheaper heat exchanger of incoloy was used. Downstream investment costs included the IPC® membrane, centrifuges, spray dryer, bead mill, filter, evaporator and distiller. For the evaporator, the same investment cost as for the distiller was used. For the extraction and washing stage, a tank and mixer were included. For these equipment costs, additional direct and indirect costs were added according to Peters, Timmerhaus, and West (2003).

These additional costs were also added for the IPC® membrane. For the equipment costs which originated from literature the relative direct and indirect cost of the study itself were used. The other installation costs were based on vendor prices, where the direct and indirect costs were assumed to already be included. For the entire installation a site preparation cost of 10% of total investment cost was added. The pumping requirements on the production site were based on the estimate of Rogers et al. (2014), who analyzed a similar production process.

Operational costs included the costs for the personnel, electricity and heating, water, nutrients, salt, CO_2 and hexane. As the wastewater is not treated on the plant itself, the disposal costs are included. These costs are based on the average prices for the region of Flanders in Belgium.

In the current study, an average β-carotene price of € 1,183 per kg is assumed (Brennan & Owende, 2010). The astaxanthin price is an estimate of 2013, which was retrieved from Pacheco et al. (2015): € 5,113 per kg.

For region-specific costs, such as taxes, the specific rates for Belgium were used. The evaluation period was 10 years. For the installations with a shorter lifetime than the evaluation period, reinvestment was taken into account. To incorporate the effect of time on the economic parameters, the CEPCI index was used where necessary. The reference year was set at 2014. No cost data older than 2010 were used in the model. Scale effects were included based on the prices of the equipment on different scales. If only one price estimate was given, the scale effect was based on the typical exponents given by Peters et al. (2003). For equipment where no typical exponent was available, the six tenth rule was used. However, if the scale difference was more than a factor ten, an exponential scale factor of 0.8 was used. This exception was also made for the cultivation stage. The cultivation installation will require multiple units of the same scale, which necessitates a higher scale factor (Taylor et al., 2013). Revenues originate from the sales of fertilizers, β-carotene and/or astaxanthin.

4. Results

4.1. Mass and energy balance and economic assessment

4.1.1. Basic scenario

Table 7 illustrates the summary of the mass and energy balance for the four different scenarios. The basic scenario requires a large amount of water and salt to obtain optimal cultivation conditions. This subsequently results in a large amount of wastewater. The 1,700 tonnes of DW biomass which are produced during the entire project lifetime (10 years), are converted into 141 tonnes β-carotene and 1,476 tonnes of fertilizer. The largest energy requirement is the heating during cultivation.

Table 7. Summary of the mass and energy balance of the four scenarios

	Unit	Basic	Intermediate	Advanced	Alternative
Input					
Water	m^3	4,718,608	1,301,961	747,486	213,372
Salt	Tonnes	629,552	129,867	48,974	0
Nutrients	Tonnes	6,516	6,516	6,516	6,516
CO_2	Tonnes	62,544	62,544	16,140	18,047
Hexane	Liter	955	955	955	970
Electricity	GJ	132,270	111,383	1,997,281	2,239,657
Heat	GJ	1,400,535	1,310,600	37,918	49,884
Land use	ha	69	69	18	20
Output					
Fertilizer	Tonnes	1,476	1,476	1,476	1,583
β-carotene	Tonnes	141	141	141	0
Astaxanthin	Tonnes	0	0	0	43
Wastewater	m^3	5,012,339	1,364,891	773,052	216,353
Emissions	Tonnes	61,303	61,303	14,899	16,806

Table 8 illustrates the main economic results for the four scenarios. As the operational costs can vary over the different years, their value for the first year is given. Investment costs are the lowest for the basic scenario. The main investment costs are the costs for the open ponds, land, the dryer and the centrifuges. The main operational costs are the salt and water consumption and the personnel costs. The first scenario has a positive NPV and can therefore be considered economically viable.

Table 8. Economic results of the four scenarios

	Basic	Intermediate	Advanced	Alternative
Investment costs (EUR)	11,223,432	10,748,522	43,139,268	46,145,468
Operational costs (EUR·year^{-1})	13,251,766	7,937,365	13,256,883	13,733,721
Revenues (EUR·year^{-1})	16,746,464	16,746,464	16,746,464	22,119,970
Net Present Value (EUR)	8,694,773	36,961,710	-13,779,353	8,337,917

4.1.2. Intermediate scenario

The intermediate scenario includes a membrane to recycle the water to the cultivation stage. This recycling reduces the water and salt consumption during cultivation fivefold compared to the basic scenario. Consequently, the amount of wastewater is much lower. Electricity consumption is lower for this second scenario as the centrifuge uses more energy than the IPC® membrane. The heating requirement is reduced by 6%. This is due to the high temperature of the recycled water which reduces the overall heating during cultivation. The downstream processes after drying remain the same, as a constant amount of biomass is produced and the water content after the centrifuge is constant for all scenarios. The inputs to cultivation also remain constant, as no additional nutrients or CO_2 are recycled. The total production plant occupies 69 hectares.

The intermediate scenario has the highest NPV of all four scenarios. The investment costs decrease by 4% compared to the basic scenario. The addition of the IPC® membrane increases the investment costs. However, a smaller centrifuge can be included in this scenario as less water needs to be removed. This results in small decrease in the investment costs. The operational costs are reduced by 40% compared to the basic scenario. This is explained by the recycling of medium, which lowers the salt and water requirements. Another reason is the lower energy requirement during cultivation. The most influencing operational costs are the CO_2 and salt cost. The revenues remain the same compared to the basic scenario.

4.1.3. Advanced scenario

The use of a PBR reduces the water and salt consumption during cultivation by 85% compared to the basic scenario. The energy consumption during cultivation is higher due to the large mixing requirements. The heating requirements are reduced due to the lower water volume. The nutrient consumption remains constant as the same biomass amount is produced. However, less CO_2 is required as the uptake in a PBR is more efficient. The amount of fertilizer and β-carotene produced remains constant as well. Less wastewater is produced as a lower volume of water is required in the cultivation stages due to a higher biomass concentration and productivity. The total production plant area is 18 hectares.

The advanced scenario is the only scenario which has a negative NPV. Therefore, it is not considered economically viable. The investment costs increase by 284% compared to the intermediate scenario. This can be explained by the inclusion of a PBR, which is responsible for 89% of the total equipment cost. The membrane costs are reduced as a smaller volume needs to be filtered. This scenario has higher operational costs than the intermediate scenario, due to the energy consumption during cultivation. Maintenance and personnel costs are also important components of the total operation costs. The total revenues remain the same compared to the previous scenarios.

4.1.4. Alternative scenario

The fourth scenario cultivates the freshwater algae *Haematococcus pluvialis*. Therefore, no salt is required. The cultivation stage requires more water as this algae has a lower productivity compared to the advanced scenario. The total water consumption however, will be lower as no washing step is included. The water recycling ratio is higher as well, as this ratio is limited by the amount of salt. The addition of the bead mill and the larger water volume increases the electricity consumption compared to the advanced scenario. The heating requirement is higher than in the advanced scenario due to the higher cultivation temperature. CO_2 consumption increases compared to the advanced scenario as a larger area is required. Due to the constant biomass production, the nutrient consumption remains the same. The total production plant area is 20 hectares, which is lower than for the first two scenarios but higher compared to the advanced scenario.

The alternative scenario has a positive NPV, which is lower than the NPV for the first two scenarios. The investment costs are the highest of all scenarios, due to the costs of the PBR and the lower productivity. Therefore, a larger capacity for the PBRs is required. The inclusion of a bead mill further increases the investment costs, although the PBR is still the largest contributor to the investment costs. Moreover, the operational costs are also higher than in the advanced scenario. The energy costs are higher, due to a higher cultivation volume, more heating and the bead mill electricity consumption. This compensates for the lower salt and water consumption. The amount of revenues for the alternative scenario with *Haematococcus pluvialis* is 32% higher than the advanced scenario. Although *Haematococcus pluvialis* contains a lower amount of astaxanthin than the β-carotene content of *Dunaliella salina,* the price for astaxanthin is much higher.

4.2. Sensitivity assessment

The sensitivity assessment identifies the parameters which have a large impact on the variance of the NPV. The critical parameters that contribute more than 5% to the variance of the NPV are summarized in Table 9 for all four scenarios.

The most crucial parameters for the basic scenario are the β-carotene content and price. The yield of β-carotene in the process is relatively low. However, the high price of β-carotene renders the project economically viable. The other important parameters are related to all the processes where part of this β-carotene can be removed in a waste stream. The higher the recovery of these processes, the higher the economic profitability. The intermediate scenario has the same critical parameters as the basic scenario. In the advanced scenario, the sizing factor of the PBR is of main importance. The cost of this PBR was based on the study by Acién, Fernández, Magán, and Molina (2012), which linearly upscaled a PBR of 3 m³. Due to this small unit scale, a large amount of units are required. Moreover, the total PBR cost was the main component of the total investment cost and therefore paramount to the overall economic viability. The measure to include scale advantages of the PBR will therefore have a large impact on the overall economic profitability. In the alternative scenario, the scaling factor of the PBR is also important. However, the impact of the carotenoid content and price is larger compared to the advanced scenario.

The carotenoid price is identified as one the most critical parameters for an economic profitable process. However, this price is highly uncertain as future market trends may have a large influence. The lowest carotenoid price for which the process has a positive NPV for the different scenarios, keeping all other parameters constant, is € 1,059 per kg β-carotene (basic scenario), € 657 per kg β-carotene (intermediate scenario), € 1,379 per kg β-carotene (advanced scenario) and € 4,725 per kg astaxanthin (alternative scenario).

Table 9. Relative contribution of the critical parameters to the variance in NPV

Variable	Basic	Intermediate	Advanced	Alternative
Carotenoid content (%)	+18.4%	+17.1%	+5.3%	+7.1%
Price antioxidant (EUR tonne^{-1})	+17.5%	+16.7%	+5.4%	+6.9%
Extraction efficiency (%)	+10.7%	+10.1%		
Drying carotenoid recovery (%)	+10.5%	+10.8%		
Washing (centrifuge) efficiency (%)	+8.3%	+7.9%		
Centrifuge efficiency (%)	+8.3%	+7.9%		
PBR scaling factor			-51.9%	-51.1%

5. Discussion

This study performs a TEA of four different algal-based biorefineries. The NPV was positive for three of the four scenarios, although all four scenarios had higher yearly revenues than yearly costs. The cultivation of *Dunaliella salina* currently occurs in open ponds. The use of PBRs instead of these ponds is not yet economically viable as was assessed in the advanced scenario. However, PBRs are commercially viable for the cultivation of *Haematococcus pluvialis* for astaxanthin.

Although the current assumed production scale is not sufficient to obtain four economically viable scenarios, scale advantages exist. Each scenario can therefore be characterized by a minimum viable production scale. This minimum biomass production scale for a positive NPV in the advanced scenario is 596 tonnes DW per year. This corresponds to a land use of 63 hectares. As the other scenarios have a positive NPV, a lower scale may also be economically viable. For the basic scenario, a minimum biomass production scale of 75 tonnes DW per year is identified. The intermediate scenario, which had the largest NPV in this TEA, requires a scale of 25 tonnes DW per year. The alternative scenario needs a minimum production scale of 105 tonnes DW per year to be economically viable.

For the assessment of the techno-economic potential of algal-based biorefineries multiple assumptions have been made. Therefore, the results are only valid under the current assumptions. An important assumption is the energy consumption of the spray dryer. In the current model, this energy came from electricity. If we would assume a gas-based spray dryer instead, the operational costs would decrease with one to five percent.

The goal of the sensitivity analysis included in this assessment is to identify the crucial parameters which variation affects most the output parameters. This is categorized as a local sensitivity analysis. In contrast to such a local sensitivity analysis, a global sensitivity analysis takes into account the uncertainty of the input parameters as well. The goal of a global sensitivity analysis is therefore to identify the crucial parameters whose uncertainty affects most the output parameters (Homma & Saltelli, 1996). If the probability distribution of the input parameters is unknown, but a worst-case value, a most-likely value and a best-case value can be identified, a triangular distribution can be used (Vose, 1997). By including the uncertainty on the input parameters, the range of uncertainty of the output parameters can be estimated as well. This is categorized as an uncertainty analysis (Saltelli et al., 2008). However, to obtain the probability distribution of the output parameters, more specific probability distributions of the input variables need to be defined.

There are multiple other studies which assessed the techno-economic potential of a microalgae business case, with widely varying results. This variety is for example due to different process pathways, which convolutes the comparison (Quinn & Davis, 2015). If the revenues and taxes are omitted from the calculations of the current study, a biomass production cost of € 65 per kg (basic scenario), € 40 per kg (intermediate scenario), € 82 per kg (advanced scenario) and € 86 per kg (alternative scenario) was calculated. This is higher than for example the biomass calculation costs calculated by Norsker et al. (2011), which range between € 4.15 and € 5.96 per kg. Their study focused on the production of biofuels and could therefore use a microalgae species with a higher productivity. The biorefinery which was assessed in the current study produces high-value products such as food additives, which are accumulated in specific microalgae species. This makes the production process more expensive.

Three main challenges for the implementation of an algal-based biorefinery focused on high-value products in Belgium can be identified.

The first challenge which needs to be taken into account is the relatively small market volume of the different products. According to Spolaore et al. (2006), β-carotene and astaxanthin have a market volume of respectively 1,200 tonnes per year and 300 tonnes per year. A large production scale can therefore saturate the market and drastically reduce the market price. This biorefinery case study is a partial analysis, specifically adapted to Belgian conditions. Therefore, the specific impact on regional production and changing world prices has not been included.

The second challenge is the high salt content of the waste water, which can be a hurdle for the commercial implementation of this process. In the current model we assume a tax for water disposal. However, in reality it will be difficult to obtain legal approval for this process in Belgium. Therefore an additional water treatment technology should be added to further iterations. This could increase the recycling ratio of the water and enable the recycling of salt. An appropriate technology for this application could be a membrane distillation (Eykens et al., 2016). The use of this technology for desalination is currently developed at a pilot scale and is therefore an interesting innovative technology to include in further models (Ruiz-Aguirre, Alarcón-Padilla, & Zaragoza, 2014).

The third challenge is the land occupation of the entire process. Belgium is a country with a high population density, which could render a large production scale unfeasible. According to a report of ILVO, the flower region in Belgium consists of 13.24 hectares of free greenhouses (Verhoeve, Kerselaers, & Baeyens, 2015). As greenhouses have been used for microalgae cultivation in PBRs before, this could give an indication of the feasible production scale. In our model, a cultivation area of 13.24 corresponds to a total plant area of 20 hectares, which was the total plant area for the alternative scenario. The production scales as assumed in this study could therefore be a realistic case for Belgium. In our model, we assume a centralized production plant. However, in reality the cultivation plants can also be shattered with a centralized downstream processing plant. In this case, additional logistic costs should be added to the model.

The two algae species used in this TEA have a relatively low biomass productivity. As only a small amount of microalgae is currently used, the ideal microalgae for a biorefinery may yet be discovered. The selection of an appropriate microalgae species for a certain application can be facilitated by screening tools (Picardo et al., 2012).

This TEA assesses the technological and economic feasibility of algal-based biorefineries. However, for the biobased economy, environmental aspects are also crucial. An example of an environmental impact which needs to be taken into account is the land use. Another environmental impact, which is important in the current model, is the freshwater consumption. Excessive water use may lead to water scarcity, which will also influence the water purchase costs. Process water or ground water can be a cheaper water source. However, in this case additional water treatment will be required to obtain the required water quality for food applications. These linkages between environmental impacts and economic costs are an interesting field of research, but can only be identified in a fully-fledged assessment which integrates technological, economic and environmental aspects.

6. Conclusion

This chapter has analyzed the technological and economic potential of four different algal-based biorefinery scenarios, based on two different microalgae species. Based on the results, we can conclude that algal-based biorefineries can be economically viable. However, large differences between the technological and economic parameters have been observed. The inclusion of the IPC® membrane increases the economic viability of the production process, although other process parameters are more critical to the overall techno-economic viability. The use of PBRs is currently too expensive to be implemented on a commercial scale for the cultivation of *Dunaliella salina*. However, for the cultivation of *Haematococcus pluvialis*, PBRs can be used for an economically viable production process. Further process optimization can increase the techno-economic viability of these technologies. The carotenoid content and price are identified as the critical parameters for the open pond cultivation. This implies that an accurate estimate of the carotenoid accumulation is required to narrow down the error range of the analysis. Moreover, price volatilization of carotenoid prices can have a large impact on the profitability of the project. For the PBR cultivation, the scale assumption for the PBR investment is crucial. A more specific price estimate on large scale for the PBR costs is therefore required in future TEA iterations. These further iterations should also integrate an environmental assessment. Such an integrated environmental and techno-economic assessment will be able to identify the critical parameters which can both increase the economic profitability and lower the environmental impact and can therefore decrease the time-to-market for algal-based biorefineries.

Chapter 4.

Environmental Techno-Economic Assessment[3]

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[3] *Parts of this section have been published:*
Thomassen, G., Van Dael, M., Van Passel, S. (2018) The potential of microalgae-biorefineries in Belgium and India: an environmental techno-economic assessment. Bioresource Technology 267, 271-280.

In this chapter, the TEA methodology will be extended with an environmental assessment, based on the LCA methodology. The methodology, as illustrated in Figure 13, is applied to multiple microalgal-based biorefinery scenarios in both Belgium and India.

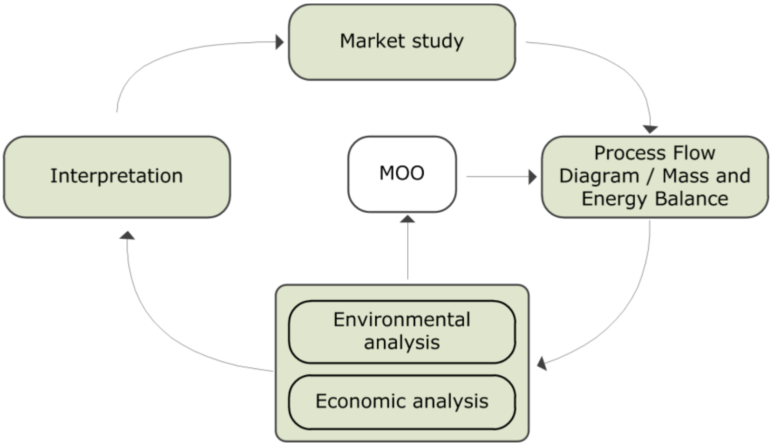

Figure 13. The ETEA methodology

Abstract

This study performs an ETEA for multiple microalgae biorefinery scenarios at different locations, those being Belgium and India. The ETEA methodology, which integrates aspects of the TEA and LCA methodologies and provides a clear framework for an integrated assessment model, has been proposed and discussed. The scenario in India has a higher profitability with a NPV of €40 million over a period of 10 years, while the environmental impact in Belgium is lower. The inclusion of a medium recycling step provides the best scenario from both perspectives. The crucial parameters for feasibility are the β-carotene price and content, the upstream environmental impact of electricity and the maximum biomass concentration during cultivation. The identification of these parameters by the ETEA guides future technology developments and shortens the time-to-market for microalgal-based biorefineries.

1. Introduction

A new and innovative technology in the biobased economy can only thrive if it can positively answer the following three questions: 1) Is it technologically feasible: are all production steps between the source and the end product workable?; 2) Is it economically profitable: can the new technology be produced at a lower cost than its market value?; 3) Is it environmentally sustainable: does the new technology have an acceptable environmental impact?

Biorefineries, where multiple products are valorized out of a biomass feedstock, are an example of such a new and innovative technology. An overview of available biomass residue and wastes for biorefineries in Belgium and India was provided by Cardoen, Joshi, Diels, Sarma, and Pant (2015a). However, the use of biomass residues for industrial production can be undesirable if it leads to a decrease in soil fertility due to carbon and nutrient depletion (Cardoen, Joshi, Diels, Sarma, & Pant, 2015b). A potential feedstock for a biobased refinery that does not impact soil fertility, are microalgae. These small photosynthetic organisms can have a high productivity and can grow on degraded lands (R. E. Lee, 2008). These characteristics give them an advantage over other biomass sources. Most of the research in the last decades on microalgae has focused on energy applications. However, the cultivation of microalgae is still too costly to introduce microalgae biofuels to the market and no consensus exists over their potential environmental impact (Quinn & Davis, 2015). Microalgae have another advantage: they are capable of accumulating large amounts of valuable products. The production of high-value products from microalgae is economically viable: multiple companies cultivate microalgae for antioxidants or food supplements (Spolaore et al., 2006). The coproduction of these high-value products in a biorefinery could lead to larger revenues and a lower environmental impact (Chew et al., 2017).

The feasibility of a microalgae production plant is also location-dependent (R. E. Davis et al., 2014). Currently, most microalgae production plants are situated in countries with warm climates, such as Australia, China or southern locations in the USA (Maeda, Yoshino, Matsunaga, Matsumoto, & Tanaka, 2018). The high temperature and solar irradiation creates optimal growth conditions. Locations with more moderate climates, such as Germany, Belgium or Norway, have invested in microalgae production plants as well (Steinrücken et al., 2018). To cope with the less optimal growth conditions, other technologies, such as photobioreactors (PBR), are more frequently used in these settings (Schreiber et al., 2017). Besides the influence on the technological design and process, the choice of the location has an impact on the economic and environmental potential of the microalgae biorefinery. For example, the local price of utilities and wages, and the composition of the local electricity mix, can alter the feasibility of the project.

Based on a review of the existing economic and environmental assessments of microalgal-based biorefineries, four methodological recommendations were formulated to decrease the wide variety in results (G. Thomassen, Van Dael, Lemmens, & Van Passel, 2017). The ETEA methodology, as developed in this study, builds on this literature as it incorporates these four recommendations by 1) providing a sound framework; 2) streamlining the methodology according to the appropriate TRL; 3) clearly stating methodological assumptions and providing alternative results for the different assumptions; 4) integrating the process design into the methodology.

The newly developed ETEA methodology will be applied to a microalgae biorefinery which valorizes both an antioxidant, β-carotene, and a fertilizer. The biorefinery is based on the microalgae, *Dunaliella salina*, which is already cultivated on a commercial scale. The existing production process is modelled with fertilizer as an additional product based on two locations, Belgium and India. India has a commercial microalgae cultivation plant, where *Haematococcus pluvialis*, *Chlorella vulgaris* and *Spirulina* sp. are produced in open ponds. Moreover, multiple papers, such as Sudhakar, Premalatha, and Rajesh (2012), have confirmed India as an excellent location for microalgae cultivation. Belgium has ongoing research on microalgae, focusing mostly on PBR and medium recycling technologies (Taelman, De Meester, Roef, Michiels, & Dewulf, 2013). We will compare among each location three different scenarios, ranging from a low technology scenario using open ponds, an intermediate scenario with open ponds and medium recycling to a high technology scenario using PBRs. The ETEA assesses if the scenarios can positively answer the three above-stated questions and identifies the main influencing parameters.

The objectives of this chapter are therefore twofold. The first objective is the development, application and discussion of the ETEA methodology. The second objective is the integrated technological, economic and environmental assessment of different microalgal-based biorefinery concepts in different locations.

2. Materials and methods

2.1. Methodology

The potential of microalgae biorefineries is assessed using the ETEA methodology, which integrates aspects of LCA and TEA (ISO 14040; Van Dael, Kuppens, et al., 2014). By integrating all three dimensions in one methodology, instead of combining separate models, direct linkages, synergies and trade-offs between the dimensions are identified. The term “environmental techno-economic assessment” was selected to highlight the extension of the TEA with an environmental assessment in one integrated model, in contrast to the combination in an environmental and techno-economic assessment. Efforts have been made to combine or integrate these dimensions into one study, for example by Quinn and Davis (2015), and good examples of integrated LCA and TEA studies of biorefineries are available, for example by Gnansounou, Vaskan, and Pachón (2015). However, a clear methodology definition of a fully-integrated assessment, based on best practices, is still lacking.

The TEA methodology was defined by Kuppens (2012) as *“The evaluation of the technic performance or potential and the economic feasibility of a new technology that aims to improve the social or environmental impact of a technology currently in practice, and which helps the decision makers in directing research and development or investments.”* The development of new technologies is a stage-gate process, where after each gate a go/no go decision has to be made (Cooper, 1990). The TEA assists in this decision by providing information on the feasibility of the process and the underlying parameters that have the largest influence (Van Dael et al., 2013). The TEA model is an integrated model, with direct linkages between the economic and technological parts. The dynamic character of TEA, where a change in one parameter directly effects all output indicators, is key in identifying the most influencing parameters for a feasible technology. The TEA usually assesses the entire project. This project does not have to include all upstream lifecycle stages of a specific product. Instead, a selection of production processes is defined as the main system boundary and assessed. The scale and time period is defined and a power relation is often assumed to define the costs for the appropriate scale. As the TEA starts with the calculation of the mass and energy balance, this is an intermediate result. The sensitivity analysis provides insights in which process parameters are crucial for an economically viable process (Van Dael, Kuppens, et al., 2014). The TEA model is made in Excel, but inputs from specific process design software, such as Aspen or ChemCad are possible. However, as discussed by Kuppens et al. (2015), the TEA methodology is still missing an environmental sustainability check. The ETEA methodology, as proposed in this study, provides an answer to this issue.

The LCA methodology is a widely used method to analyze the environmental burden of products (Guinée et al., 2002). It is defined by the ISO 14044 norm as a "*compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.*" The aim of an LCA is to assess the impacts of a product over their entire lifecycle. The functional unit is based on the function of the end product. The process is assumed to be linear and is independent of the time period of the production process. The mass and energy balance are used as an input to the process to construct the life cycle inventory (Guinée et al., 2002). Emissions to the environment are included if they are part of the defined system boundaries. The assessment is often executed in specific LCA software, such as SimaPro or Gabi. The contribution of the different life cycle stages and inputs and outputs to the process can be assessed. However, a sensitivity analysis of the underlying process parameters is usually not performed as these parameters are not included in the main model. Although the main target of LCA studies is the assessment of existing products, the LCA methodology can also be used as a stage-gate process for new technologies where the level of detail will advance in each stage (Villares, Işıldar, van der Giesen, & Guinée, 2017). Different streamlining methods, such as proxy data, can be used to cope with the limited data availability in each stage (Graedel, 1998). The ETEA methodology uses LCA to calculate the up or downstream environmental impact of each input and output to the technological process. This way, the environmental impact is treated in a similar way as the price of a specific input or output. Accordingly, the environmental assessment can be integrated in the same manner as the economic assessment into a joint, integrated model.

Based on the above, the ETEA methodology is defined as follows: "*The integrated evaluation of the technological performance, economic feasibility and potential environmental impact of a (new) technology and the identification of the most important underlying parameters that aims to help the decision makers in directing research and development or investments*."

The evaluation of a new technology generates the need for a framework concerning the different levels of technological maturity. Accordingly, the stage-gate approach, which has also been used by the TEA and LCA methodologies, is adopted. The different gates of technology development are defined by TRL levels (Mankins, 2009). Each TRL level corresponds to a certain level of data availability and accuracy of the provided information. The chosen TRL level of the ETEA is the minimum of the following two conditions: 1) the maturity of the technology; 2) the required accuracy of the results. In this study the ETEA will be performed at TRL level five, which corresponds to the demonstration stage of the technology, which is the lowest TRL level of the technologies in all different scenarios.

The ETEA includes all life cycle steps influenced by the technology or product. This can be done in a direct way, by specifically including the up and downstream steps in the process design, or in an indirect way, if the up or downstream costs and impacts are already represented, for example in the price. In this study the production process, starting from microalgae cultivation until the purification of the end product, is included in a direct way. The upstream costs and impacts are included indirectly in the price and impact of the process inputs. The downstream costs and impacts of all waste sources are included indirectly by the addition of costs and impacts for the waste treatment. The downstream costs and impacts of the end products are not included as they are assumed to be the same as the reference product.

The ETEA will be performed according to the following five steps, which are executed alongside the different TRL levels and lifecycle stages (Figure 7).

Step 1. Market study: Besides the market study from the TEA methodology, this step includes the definition of the goal and scope of the assessment originating from the LCA methodology framework. The main goal of the ETEA is to identify the crucial parameters that have the highest influence on the technological, economic and environmental feasibility of microalgal-based biorefineries. Therefore, a full range of environmental indicators will be required. The scope of the assessment is further elaborated in the description of the case study.

Step 2. Process Flow Diagram and Mass and Energy balance: This step is the same as in the original TEA framework and forms the basis of both the economic and environmental analysis.

Step 3. The economic analysis: This step is also the same as in the original TEA framework. Data on market prices was updated to 2016 prices by means of the CEPCI index. A regression function, mostly based on a power relation, was constructed to estimate the equipment cost on the appropriate scale (Kuppens et al., 2015). Location factors, were retrieved from the Richardson's International Construction Factors Location Cost Manual, updated to 2016 values and used to adapt the equipment costs to the different process plant locations (Towler & Sinnott, 2013).

Step 4. The environmental analysis: The environmental impact of the different scenarios are quantified using the seventeen midpoint indicators of the ReCiPe 2016 method: Global warming potential (GWP), Ozone depletion potential (ODP), Ionizing radiation potential (IRP), Particulate matter formation potential (PMFP), Photochemical oxidant formation potential for ecosystems (EOFP), Photochemical oxidant formation potential for humans (HOFP), Terrestrial acidification potential (TAP), Freshwater eutrophication potential (FEP), Human toxicity potential cancer (HTPc), Human toxicity potential non-cancer (HTPnc), Terrestrial ecotoxicity potential (TETP), Freshwater ecotoxicity potential (FETP), Marine ecotoxicity potential (METP), Agricultural land occupation potential (LOP), Water consumption potential (WCP), Surplus ore potential (SOP) and Fossil fuel potential (FFP) (Huijbregts et al., 2016). In our study the environmental impact is calculated relative to the fossil-based reference products: fertilizer and synthetic β-carotene. To calculate which environmental indicators are the most relevant for the scenarios, the contribution of each midpoint indicator to the endpoint indicators of the ReCiPe methodology is calculated. There are three endpoint indicators: Human health (HH), Ecosystem quality (EQ) and Resource scarcity (RS) (Huijbregts et al., 2016). To ensure the integrated character of the methodology, the characterization factors, calculated with SimaPro using the ecoinvent database, are directly linked to the mass and energy balance, in the same way as for the economic analysis. Infrastructure is taken into account using the six-tenth rule, with the use of the same power exponents as for the economic analysis (Caduff, Huijbregts, Koehler, Althaus, & Hellweg, 2014). To differentiate between the two locations, it was assumed that all direct inputs to the process were produced in the specific location, unless the market for the product was global. For most inputs, differentiating on a country-level was not feasible due to data limitation. In these cases, a global characterization factor for India and a European characterization factor for Belgium were used. This assumption was also used for the fossil-based β-carotene production scenario. As the ETEA forms one integrated methodology, the environmental impact is assessed on the same scale as the technological process design and the economic viability. The functional unit equals therefore the entire project.

Step 5. The interpretation step: In this step, the underlying parameters for the economic and environmental indicators are identified. This step includes first a contribution analysis, which assesses which production process has the highest contribution to the output indicators. The second part includes a sensitivity analysis, similar as in the TEA methodology. Hence, all parameters in the model are varied according to a triangular distribution (-10%; +10%) for 10,000 iterations. The impact of a more realistic distribution for the crucial parameters is further assessed using a what-if analysis or an uncertainty analysis. Based on the results, recommendations can be made for the next iteration.

The integrated ETEA approach harmonizes the differences in approach between the LCA and TEA methods as summarized in Table 10. The LCA model is integrated in the TEA model by an additional step, where the environmental impacts are calculated. The characterization factors are based on inputs from LCA software, but the main model remains in Excel. This enables direct linkages between the different steps, which is not possible if the main model is constructed in different software as done in a combined LCA and TEA approach. In an integrated approach, a change in an input parameter in one dimension is directly translated in the output indicators of all three dimensions. This allows for a full sensitivity analysis for both the economic and environmental impacts over all underlying process parameters. The TEA is extended to include emissions, with no direct related costs. One integrated model, instead of two combined models enables a faster and cheaper assessment as the technological module is shared.

The ETEA methodology, as developed in this study, is not restricted to the assessment of microalgae biorefineries, but can be applied to broader applications. Applications at other TRL levels are feasible as well. For this case study, the ETEA was performed at TRL level five. At a lower TRL level, less data will be available which results in a more rough assessment. For example, the environmental assessment can be a screening ETEA with a hotspot analysis where more qualitative data are used. At a higher TRL level, the process design is assessed in more detail, and other analyses, such as a full uncertainty analysis, where the triangular distribution is replaced by a more realistic distribution, can be added. An example of this uncertainty analysis can be found in the computational framework of Gerber, Tester, Beal, Huntley, and Sills (2016), which integrated process design, LCA, TEA and uncertainty analysis, and whom applied this framework to two pathways of microalgae biofuel production.

Table 10. Differences between a combined LCA and TEA and an ETEA

	(Combined) LCA	(Combined) TEA	ETEA (integrated)
Functional unit	Product	Project	Project
Lifecycle	Entire lifecycle	Process	Entire lifecycle
Economies of scale	Linear	Power relation	Power relation
Time	Independent	Period defined	Period defined
TRL level	Late	Early	All levels
Mass and energy balance	Input to the model	Intermediate result	Intermediate result
Sensitivity analysis	Optional	Required	Required
Emissions	Included	Not included	Included
Software main model	LCA software	Excel	Excel
Process parameters in the sensitivity analysis	Inputs and outputs	Underlying parameters	Underlying parameters

The ETEA extends the original TEA methodology with an environmental sustainability analysis. However, the social dimension of sustainability has not been incorporated yet. This would be a valuable addition to obtain a full techno-sustainability analysis (Rafiaani et al., 2018).

The proposed ETEA methodology results in multiple economic and environmental indicators. The decision maker can use these results to perform a multi-criteria analysis which results in one final value for each scenario. A multi-criteria method based on a sustainability analysis of biorefineries was proposed by Gnansounou, Alves, Pachón, and Vaskan (2017). Another approach to deal with the multiple output indicators would be the extension of the ETEA model with a multi-objective optimization, including both economic and environmental objectives. This way, the optimal microalgae biorefinery process design can be defined from different perspectives.

2.2. Case study

Three different microalgal-based biorefinery designs have been assessed, both in Belgium and in India. The market share of natural β-carotene is 30% of the global β-carotene market with approximately 10 different suppliers (Enzing, Ploeg, Barbosa, & Sijtsma, 2014; Research and Markets, 2017). The hypothetical production plant was assumed to have a similar scale to an average supplier, corresponding to 3% of the global β-carotene market. Accordingly, all scenarios produce 11 tons of β-carotene and 128 tons of fertilizer per year over a project lifetime of 10 years. This is also the functional unit for all scenarios.

The first scenario is based on the basic scenario from Chapter 3. Therefore, the assumptions which remain the same are not discussed in detail. Similar as in the basic scenario, *Dunaliella salina* is cultivated in open ponds. This cultivation consists of two stages: one stage for optimal biomass production and one nutrient-limiting stage for optimal β-carotene production. The growth of the microalgae was modeled using a logistic growth curve (Jesus & Filho, 2010). The parameters used in this study were based on multiple pilot scale outdoor cultivation studies of *Dunaliella salina* (M. García-González et al., 2003; Prieto et al., 2011; Tafreshi & Shariati, 2006; Z. Wu et al., 2017). A correction factor for the local temperature and solar irradiation was taken into account (Slegers, Lösing, Wijffels, van Straten, & van Boxtel, 2013). An overview of the main growth parameters for all scenarios is provided in Table 11.

Table 11. Main growth parameters

	Unit	1 Be	2 Be	3 Be	1 In	2 In	3 In
K	$g \cdot l^{-1}$	0.5	0.5	2	0.5	0.5	2
N_0	$g \cdot l^{-1}$	0.06	0.06	0.23	0.06	0.06	0.23
$r_{stage\ 1}$	day^{-1}	0.12	0.12	0.35	0.25	0.25	0.35
$r_{stage\ 2}$	day^{-1}	0.08	0.08	0.23	0.17	0.17	0.23
$t_{stage\ 1}$	days	23	23	9	12	12	9
$t_{stage\ 1}$	days	6	6	5	6	6	5

K: maximum biomass concentration; r: maximum specific growth rate; N_0 : initial biomass concentration; t:cultivation time.

In the Belgian scenario, freshwater was used and the wastewater was sent to a wastewater treatment plant. The Indian scenario assumed the use of seawater and the disposal of the wastewater into the sea. The amount of evaporated and precipitated water was calculated using the local evaporation and precipitation rate. In each scenario, the same amount of nutrients per mass of microalgae was provided. No heating was provided in the open pond scenario as the heat would dissipate almost immediately. The microalgae were harvested by means of a centrifuge, washed to decrease the salt content and dried using a spray dryer. Subsequently, the β-carotene was extracted using hexane as a solvent. After separation by means of a membrane filtration, the solid fraction went to an evaporation step to retrieve the hexane as a solvent. To estimate the fugitive emissions and the energy requirement of general process steps such as filtration and distillation, the framework of Piccinno, Hischier, Seeger, and Som (2016) was used. The solid residue was sold as a fertilizer. The liquid fraction went to a vacuum distillation step to purify the β-carotene fraction and enable hexane recycling. The purified β-carotene was sold as a food supplement.

The second scenario assessed the effect of a medium recycling step after each cultivation stage. The medium consists mainly of water and salt. For this preharvesting step, the Integrated Permeate Channel (IPC®) membrane was included in the production process (De Baerdemaeker et al., 2013). According to previous papers, this recycling step has an important impact on the economic feasibility (Monte et al., 2018; G. Thomassen, Egiguren Vila, Van Dael, Lemmens, & Van Passel, 2016). The remainder of the production process is similar to the first scenario.

The microalgae were cultivated in a tubular PBR in the third scenario. In the Belgian scenario, the water was heated to 20°C, with a 5% daily heat loss. The growth parameters were based on studies of (Mercedes García-González et al., 2005) and Prieto et al. (2011). The other steps in the process remained the same as for the second scenario.

The price of the equipment and the utilities for all production steps were based on peer-reviewed literature data and price quotes from commercial suppliers. The indirect costs for all equipment was added in accordance to the estimates of Peters et al. (2003). The purity of β-carotene in the end product is 80%. A price range of €215-2712 per kg was found for β-carotene of varying purities (Brennan & Owende, 2010; Guedes et al., 2011; Hejazi & Wijffels, 2004; Pharmacompass; Richmond, 2004). For this study, a β-carotene price of €1000 per kg was selected. The price of fertilizer was set at €390 per ton, based on personnel communication with a supplier.

All environmental impact parameters were retrieved from the ecoinvent database (Wernet et al., 2016). The reference process for β-carotene was modeled mainly based on patent data and publications. Other inputs and outputs for the different steps of the reference process, such as energy consumption and waste emissions, were estimated using the general assumptions of Hischier, Hellweg, Capello, and Primas (2004). These assumptions are also used in the ecoinvent database and in the study of van Kalkeren, Blom, Rutjes, and Huijbregts (2013). The reference process for fertilizer is taken from the ecoinvent database. The environmental impact of a pump was used as a proxy for the environmental impact of similar equipment such as mixers, blowers and compressors. In a similar way, the environmental impact of a spray dryer was used as a proxy for the evaporator and distillation equipment.

Although this study includes two locations, the assessment of multiple locations is feasible as well. The two locations were chosen to maximize the difference in parameters, while still allowing for accurate and available data. The optimization of the location and the technologies, included in the biorefinery, would be an interesting path for further research.

The scenarios are further referred to as 1 Be, 2 Be and 3 Be for the Belgian scenarios and 1 In, 2 In and 3 In for the Indian scenarios.

3. Results and discussion

3.1. Process flow diagram and mass and energy balance

The summary of the mass and energy balance is illustrated in Table 12. The water and salt requirement decreased when the medium was recycled. The microalgae reached a higher concentration in the PBR, which further decreased the water and salt requirement. However, in the second Indian scenario, the water consumption increased compared to the first scenario. This is explained by the large influence of evaporation. As the water and salt was recycled, the salinity increased due to evaporation. Freshwater was required to maintain a viable salinity for the microalgae. Salt was only required at the beginning of the project. The PBR in the third scenario did not lose water through evaporation, therefore, freshwater only needed to be added in the washing step. The salt consumption was higher to obtain the optimal salinity in the cultivation stages. Microalgae grew slower in Belgium than in India. Therefore, a larger production plant was required in the three Belgian scenarios. The electricity consumption was much higher in the third scenarios as the PBR required a large amount of energy to pump the microalgae through the tubes (Jorquera et al., 2010).

The land occupation in Belgium was 50 hectares for open ponds and 9 hectares for PBR. According to a report of ILVO, a total of 13.24 hectares of unoccupied greenhouses can be found in the flower region in Belgium (Verhoeve, Kerselaers, & Baeyens, 2015). This could be a potential location for the microalgae cultivation and indicates the feasible scale. The current microalgae cultivation plant of Parry Nutraceuticals in India spans 53 hectares. As the population density is comparable in Belgium and India, the 50 hectares of open pond cultivation are assumed to be a feasible production scale as well.

Table 12. Summary of the mass and energy balance over the total lifetime

Parameter	Unit	1 Be	2 Be	3 Be	1 In	2 In	3 In
Input							
Salt	tons	530,277	26,040	20,846	235,780	1,890	16,108
Fresh water	m³	3,996,913	552,079	509,823	366,199	4,427,101	366,199
Nutrients	tons	5,173	5,173	5,173	5,173	5,173	5,173
CO_2	tons	6,699	6,699	4,268	6,696	6,696	4,268
Hexane	tons	94	94	94	96	96	94
Inoculum	tons	2	2	0.6	0.9	0.9	0.6
Electricity	MWh	34,968	31,615	355,526	32,313	29,196	358,653
Heat	MWh	0	0	6,683	0	0	0
Land	ha	50	50	9	23	23	9
Output							
Fertilizer	tons	1,285	1,285	1,285	1,285	1,285	1,285
β-carotene	tons	113	113	113	113	113	113
Wastewater	m³	4,243,969	566,214	521,303	4,008,218	539,198	521,303
Emissions	tons	5,563	5,563	2,865	5,561	5,561	2,865

3.2. Economic Results

The results of the economic analysis are provided in Table 13. The only economic viable scenario in Belgium was the second scenario with open ponds and medium recycling. In India, all scenarios were economically viable under the assumptions made. The yearly revenues were higher than the yearly operational costs in all scenarios. The investment costs were higher for the third scenario than for the second scenario for both locations. Including the medium recycling technology lowered the operational costs. This reduction compensated for the higher investment costs. Overall, the second scenario in India with open pond cultivation and medium recycling was the preferred scenario from an economic point of view.

A study by Ben-Amotz (2008) calculated the annual production costs of the existing NBT *Dunaliella* plant for a scale of 70 tons dry biomass per year. Their results indicated an equipment cost of €63 per kg dry biomass and an operational cost €12 per kg dry biomass operational cost. These estimates are higher than the €51 and €11 per kg biomass for the second Indian scenario as found in the current study. However, the scale in the current study was twice as large which induces economies of scale to lower the price. A TEA of another algae production process focusing on carotenoids was performed by Panis and Carreon (2016). In their study, astaxanthin was produced out of a *Haematococcus pluvialis* feedstock cultivated in a hybrid cultivation process of PBR and open ponds. Their study included two locations being Amsterdam in the Netherlands and Livadeia in Greece. They found that the production of microalgal-based astaxanthin is currently not economically feasible in both locations if the carotenoid is used for feed purposes instead of food supplements. The production costs in Amsterdam were higher compared to the production costs in Greece as less astaxanthin was produced per hectare. More freshwater, which was the most important mass inflow, was required in Greece compared to the Netherlands. These results are similar to the results of the current study. However, as *Haematococcus pluvialis* is a freshwater alga, no salt was required in the study of Panis and Carreon (2016) and seawater could not be used. The study of Ben-Amotz (2008) calculated the costs for an alternative bio-fuel algal plant as well, which were approximately 50 times lower. Therefore, the results of the current study will not be compared with the results of algal-fuel studies.

Table 13. Economic results over the total lifetime

Parameter	Unit	1 Be	2 Be	3 Be	1 In	2 In	3 In
NPV	10^6 €	-7	25	-29	33	40	2
Investment costs	10^6 €	17	18	47	7	8	31
Operational costs	10^6 €·yr^{-1}	10	5	10	3	2	6
Revenues	10^6 €·yr^{-1}	11	11	11	11	11	11

3.3. Environmental results

The results of the environmental analysis for the seventeen midpoint categories are provided in Table 14. The environmental impacts that are lower than the reference scenario are bold. The second Belgian scenario had a lower environmental impact compared to the reference scenario on all impact categories except for IRP. This was caused by the high contribution of nuclear energy in the Belgian electricity mix. The second Indian scenario had a positive relative environmental impact on all impact categories except for PMFP and WCP. This is explained by the relatively high contribution of fossil fuels in the Indian electricity mix and the high evaporation rate. The third Indian scenario scored the worst on nine of the seventeen environmental impact categories. The only impact categories for which this scenario had a lower impact than the reference scenario are ODP, SOP and WCP.

There are three feasible scenarios that have a positive NPV and a lower environmental impact compared to the reference scenario on three of the four selected environmental impact indicators, under the assumptions made. The second Belgian scenario is the only scenario that has a positive relative environmental impact on the four impact categories, but has the lowest positive NPV. The first and second Indian scenarios have a relatively high NPV but a worse environmental impact compared to the second Belgian scenario. As the first Indian scenario scores worse on all categories compared to the second Indian scenario, this is not the preferred scenario. The second scenario is in both locations identified as the best scenario, where the Belgian scenario is the most environmental-friendly and the Indian scenario is the most profitable scenario under the assumptions made.

The scenarios with a positive environmental impact compared to the reference scenario do not have a positive absolute environmental impact. Even if the CO_2 used would be originated from flue gas or the atmosphere, there would be between eight and one hundred four times more CO_2-equivalent emissions emitted than captured.

Table 14. Absolute environmental impact results over total lifetime

Parameter[a]	Unit	1 Be	2 Be	3 Be	1 In	2 In	3 In	Ref Be	Ref In
GWP	10^7 kg CO_2-eq	**14**	**4**	**12**	**13**	**8**	53	26	26
ODP	10^2 kg CFC_{11}-eq	**2**	**1**	**2**	**2**	**1**	**3**	7	7
IRP	10^6 kBq Co-60-eq	57	18	135	19	**2**	14	9	6
HOFP	10^4 kg NOx-eq	**38**	**8**	**20**	**33**	**19**	138	43	44
PMFP	10^4 kg PM2.5-eq	**22**	**5**	**10**	56	44	428	31	35
EOFP	10^4 kg NOx-eq	**39**	**9**	**21**	**34**	**20**	140	45	46
TAP	10^5 kg SO_2-eq	**6**	**2**	**3**	**7**	**4**	31	23	24
FEP	10^4 kg P-eq	9	**2**	**3**	8	**4**	32	6	6
TETP	10^4 kg 1,4-DCB-eq	35	**8**	**11**	19	**7**	14	11	11
FETP	10^6 kg 1,4-DCB-eq	12	**2**	4	7	**3**	12	4	4
METP	10^6 kg 1,4-DCB-eq	17	**3**	6	10	**4**	16	5	5
HTPc	10^6 kg 1,4-DCB-eq	11	**2**	**4**	7	**3**	18	6	6
HTPnc	10^9 kg 1,4-DCB-eq	14	**3**	**4**	8	**3**	11	4	4
LOP	10^6 m² yr	12	**3**	14	6	**2**	10	3	3
SOP	10^4 kg Cu-eq	178	**36**	77	88	**26**	**39**	67	66
FFP	10^6 kg oil-eq	**37**	**10**	**36**	**28**	**16**	110	63	59
WCP	10^5 m³ water-eq	**33**	**7**	**15**	101	57	**34**	39	38

[a] GWP = Global warming potential; ODP = Ozone depletion potential; IRP = Ionizing radiation potential; PMFP = Particulate matter formation potential; EOFP = Photochemical oxidant formation potential for ecosystems; HOFP = Photochemical oxidant formation potential for humans; TAP = Terrestrial acidification potential; FEP = Freshwater eutrophication potential; HTPC = Human toxicity potential cancer; HTPnc = Human toxicity potential non-cancer; TETP = Terrestrial ecotoxicity potential; FETP = Freshwater ecotoxicity potential; METP = Marine ecotoxicity potential; LOP = Agricultural land occupation potential; WCP = Water consumption potential ; SOP = Surplus ore potential; FFP = Fossil fuel potential.

A study by Kyriakopoulou, Papadaki, and Krokida (2015) performed an LCA for β-carotene extraction techniques comparing algal-based β-carotene with carrot-based β-carotene. They concluded that the production and harvesting of algal-based β-carotene had a higher environmental impact than the carrot-based production. However, the environmental impact for the extraction process was larger for the carrot-based β-carotene. Therefore, microalgae are considered a better raw material for the recovery of β-carotene then carrots. In general, the environmental impacts as found in the current study are higher than the results from Kyriakopoulou et al. (2015). This can be explained by the lack of a stress stage during cultivation. The study of Kyriakopoulou et al. (2015) used the CML2 baseline 2000 method. Therefore, an exact comparison with the results of the current study, where the ReCiPe 2016 method is used, is not feasible.

The endpoint analysis in Figure 14 illustrates which midpoint impact categories have the highest contribution to the endpoint categories. The unit for Human health is the disability-adjusted life years (DALY). The midpoint impact category PMFP has the highest impact on human health. The important midpoint categories for ecosystem quality are GWP and TAP. FFP is the most important impact category for resource availability. Therefore, the rest of the analysis will focus on the following four midpoint categories: PMFP, GWP, TAP and FFP. The results of the other midpoint categories are provided in Appendix 2.

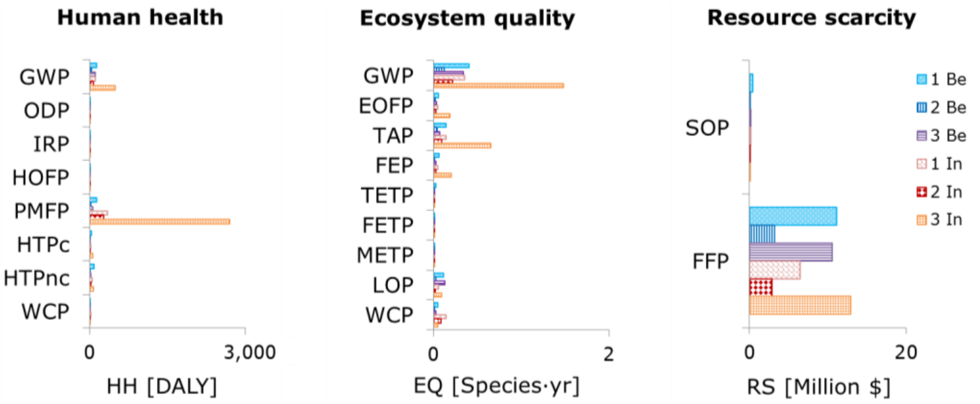

Figure 14. Endpoint analysis

3.4. Interpretation: Contribution analysis

The contribution of the different production stages to the investment and operational costs is illustrated in Figure 15. The contribution to the investment costs was similar for both locations in the three scenarios. In the first scenario the liner, the spray dryer and the centrifuge had the highest investment costs. In the second scenario, the centrifuge costs were drastically reduced. This was compensated by the costs of the IPC® membrane in the preharvesting stage. In the third scenario, the investment cost of the PBR during cultivation had the highest contribution. The highest contribution to the operational costs was provided by the cultivation stage and the indirect costs. In the cultivation stage, the salt and water consumption led to a high contribution in the first scenario. In the second scenario, the indirect costs, which were the personnel, insurance and repair costs, are more important than the cultivation costs in Belgium. This was caused by the medium recycling, which reduced the salt and water requirement. The second scenario in India had much lower indirect costs due to lower wages. The main operational costs were the nutrient costs. Although seawater was used, freshwater was required to compensate for the evaporated water. In the third scenario, the electricity cost for the mixing in the PBR had a high contribution. As the investment costs were much higher, the repair and insurance were higher as well, leading to higher indirect costs.

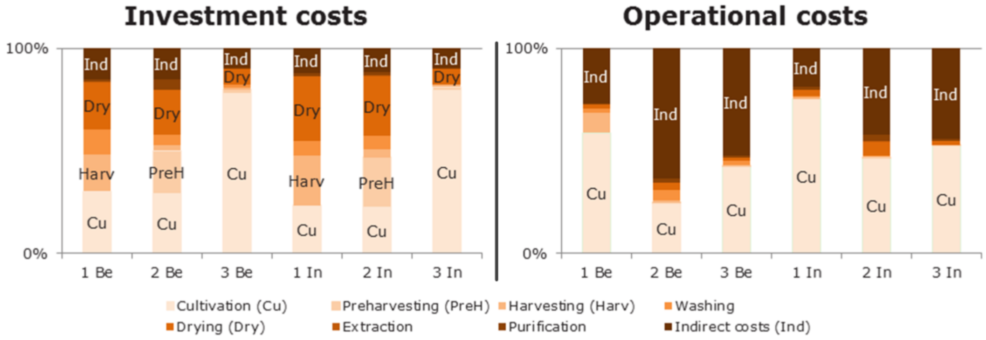

Figure 15. Contribution analysis economic results

The contribution of the different production stages to the environmental impact categories GWP, PMFP, TAP and FFP is provided in Figure 16. The cultivation stage had the highest contribution to the four environmental impact categories for the three Belgian scenarios and the first and third Indian scenario. In the second Indian scenario, the impact of the electricity used in the drying stage had a high impact as well. The impact in the cultivation stage in the first scenario was mainly caused by the impact of salt, nutrients and direct CO_2 emission. In the second scenario, the salt consumption was much lower. The electricity use during cultivation in the first two Indian scenarios had a big impact as well. Due to the difference in electricity mix, this impact was lower for the Belgian scenarios. In the third scenarios, the environmental impact in the cultivation stage was almost entirely caused by the upstream impact of the electricity.

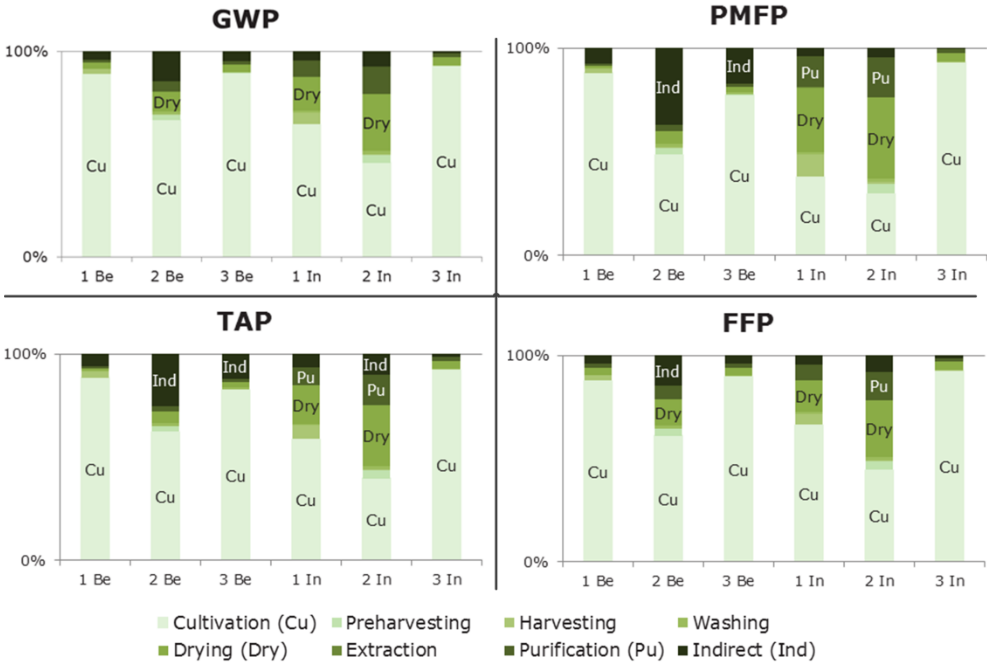

Figure 16. Contribution analysis environmental results

3.5. Interpretation: Sensitivity analysis

Although the climate in India was much better for microalgae production compared to the Belgian climate, the environmental impact in India was higher. This was mainly caused by the difference in electricity mix. The Belgian electricity mix had a relatively high nuclear energy contribution. This was translated into a worse environmental impact in the IRP category. However, this category did not have a high contribution to the endpoint indicators. The Indian electricity mix had a higher contribution of fossil fuels which led to more air pollution. This was translated into a high environmental impact in the PMFP category. As the third scenario had the highest energy consumption, this was the worst scenario in almost all categories. If the assumption was made that renewable energy was used with no related environmental impact, the second and third scenarios would have a lower environmental impact than the reference scenario for all impact categories, except for WCP in the second Indian scenario. The third scenario would even score better than the second scenario in Belgium and become the preferred scenario from an environmental point of view. The second scenario would score better in India than in Belgium on most categories due to the lower salt and water requirements.

The relative influence of the crucial parameters to the output indicators is provided in Table 15. A positive influence signifies that an increase in this parameter will lead to an increase in the corresponding output indicator. Only the parameters that contribute more than 10% to the variation of the output indicators are provided in the table. The most influential parameters for the NPV were the β-carotene content and the β-carotene price per kg. The maximum biomass concentration in the cultivation, one of the underlying growth parameters, was identified as crucial for both the economic and the environmental indicators. In the first Belgian scenario, the salt impact and consumption were important for the environmental indicators. In the second Belgian scenario, the growth parameters played a more important role. The impact of the electricity was important for all Indian scenarios. This was also a crucial parameter in the third scenario for both locations, alongside the energy consumption during the mixing in the PBR.

An important parameter which was identified in the sensitivity analysis was the energy consumption of the spray dryer. The energy consumption was assumed to originate from electricity. However, if this energy was gas-based, the operational costs would decrease with one to three percent points. The environmental impacts would decrease as well. The second Indian scenario would have the lowest environmental impact on ODP and HTPnc. The largest decrease was identified for the second Indian scenario for the PMFP indicator, which decreased with 39 percent points. Although the differences between the Indian and Belgium scenario were smaller, the Belgium second scenario remained the optimal scenario for the environmental indicators which were identified as the most important.

Table 15. Results sensitivity analysis [%]

	1 Be NPV	GWP	PMFP	TAP	FFP	1 In NPV	GWP	PMFP	TAP	FFP
β-c. content^a [%]	+26					+40				
β-c. price^a [€·kg^{-1}]	+26					+39				
Max. conc.^{b} [g·l^{-1}]	+10	-18	-17	-16	-19		-16		-16	-19
r^c [day^{-1}]		-10	-10		-11					
Sal. stress^d [M]		+23	+24	+22	+21					
Salt [imp.·kg^{-1}]^e		+21	+22	+23	+21		+13		+11	+14
El.^{g} [imp.·kWh^{-1}]^e							+11	+40	+14	
Sal. water^d [g·l^{-1}]							-15		-14	-17

	2 Be NPV	GWP	PMFP	TAP	FFP	2 In NPV	GWP	PMFP	TAP	FFP
β-c. content^a [%]	+35					+40				
β-c. price^a [€·kg^{-1}]	+30					+39				
Max. conc.^{b} [g·l^{-1}]		-19	-20	-26	-21					
r^c [day^{-1}]		-11	-11	-15	-13					
Solar irr.^{f} [%]		-11	-11	-14	-13					
CO_2 upt.^{i} [%]		-11								
Salt [imp.·kg^{-1}]^e			+13							
El.^{g} [imp.·kWh^{-1}]^e							+39	+46	+42	+36
W. conc.^{h} [g·l^{-1}]							-11	-14	-13	-10
Op. rate^j [%]					-11					
Drying E.^{k} [GJ·t^{-1}]								+11	+10	

	3 Be NPV	GWP	PMFP	TAP	FFP	3 In NPV	GWP	PMFP	TAP	FFP
β-c. content^a [%]	+21					+24				
β-c. price^a [€·kg^{-1}]	+20					+23				
Max. conc.^{b} [g·l^{-1}]	+16	-21	-21	-21	-21	+12	-21	-21	-21	-22
El.^{g} [imp.·kWh^{-1}]^e		+23	+23	+22	+22		+23	+23	+22	+23
Mix. cul.^{l} [W·m^{-3}]		+17	+18	+18	+18		+19	+18	+19	+18
Mix. cul.^{l} [h]		+19	+18	+18	+19		+19	+20	+20	+20

[a] β-c. = β-carotene; [b] Max. conc. = Maximum microalgae concentration during cultivation; [c] r = maximum specific growth rate; [d] Sal. = Salinity; [e] imp. = environmental impact; [f] Solar irr. = Solar irradiation correction factor; [g] El. = Electricity; [h] W. conc. = biomass concentration after washing step; [i] CO_2 upt. = CO_2 uptake rate; ; [j] Op. rate = Operational rate; [k] E. = Energy; [l] Mix. cul.= Mixing during cultivation.

The price of β-carotene has a wide range, but is identified as a crucial parameter. It can also have a different value depending on the location. Therefore, a what-if analysis is performed to assess the impact of this price on the NPV (Figure 17). The minimum price to obtain a positive NPV varies between €258 per kg for the second Indian scenario to €1,342 per kg for the third Belgian scenario. This is still in the price range of €1 to €2,712 per kg. Although the third Belgian scenario has a negative NPV for the β-carotene price assumed in this study, it can still be an economically viable scenario. The price curves of different scenarios at the same locations run in parallel until taxes have to be paid in one of the scenarios. The price curves return to a parallel path when taxes are paid in all scenarios. The curves of the same scenario at different locations do not run parallel due to differences in tax, inflation and interest rates. If the β-carotene price reaches € 2,878 kg^{-1}, the NPV of the second scenario becomes the highest NPV.

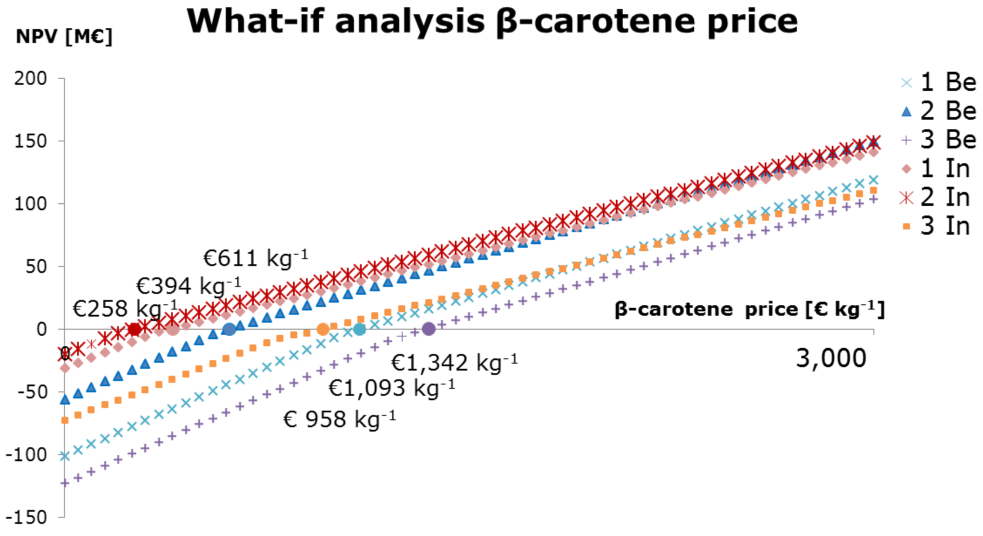

Figure 17. What-if analysis β-carotene price

Although in the past a large amount of the microalgae research focused on biofuels, this study does not look at energy applications of microalgae. A biorefinery producing both biofuels and antioxidants seems to be a difficult concept due to the disparate market size. Moreover, the microalgae species that can accumulate high-valuable products, are not necessarily the microalgae species that are most suited for biofuel production. Therefore, microalgal-research is increasingly refocusing to higher value applications. Fertilizer was chosen as an intermediate product in our proposed biorefinery. However, the revenues of the fertilizer production are only 0.4% of the revenues from β-carotene. The environmental impact of the reference fertilizer is less than 3% of the reference β-carotene. If the biorefinery would only produce fertilizer, it would not be feasible from both an economic and environmental perspective. The set-up of different viable biorefineries, such as the ones proposed in this study, may reduce the costs and the uncertainty related to the start-up of new biorefineries and increase research funding opportunities. Although the next biorefinery would still be focused on at least medium value products, energy applications may become feasible on a longer term.

4. Conclusions

The ETEA methodology enables the direct comparison of technological, economic and environmental criteria for a feasible microalgae biorefinery. Different synergies and trade-offs are identified which provide essential information for the further improvement of the process. As multiple scenarios were technologically feasible, economically profitable and environmentally sustainable, a viable microalgae-biorefinery seems to be a possible route for the future.

Chapter 5.

Multi-Objective Optimization

In this chapter, the ETEA methodology is extended with a MOO. The extended methodology, as illustrated in Figure 18, is then applied to a superstructure of potential algal-based biorefinery designs in order to identify the optimal scenarios.

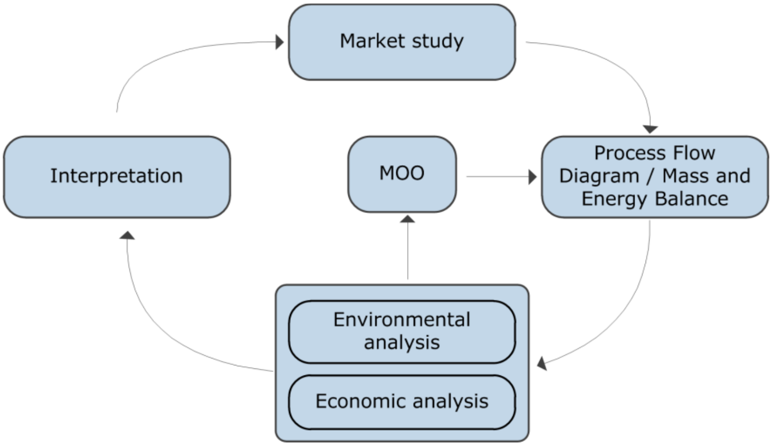

Figure 18. The MOO-extended ETEA methodology

Abstract

The use of fossil-based products has induced a large burden on the environment. Biobased products can lighten this burden if they have a lower environmental impact and are economically viable. Microalgae biorefineries produce multiple biobased products, using a microalgae feedstock. Due to the large variety in potential microalgae species, conversion processes, and end products, numerous microalgae biorefinery scenarios can be formulated. This chapter will use the ETEA methodology to assess these scenarios. As the individual assessment of all scenarios is not practical, a superstructure, containing a large range of potential microalgae biorefinery scenarios, is formulated. This superstructure is optimized to select the optimal microalgae biorefinery scenario from both an environmental and economic perspective. To perform this multi-objective optimization (MOO), the ETEA methodology is extended towards a MOO-extended ETEA. According to the results of this assessment, the optimal scenario includes cultivation in open ponds, the

inclusion of a membrane for medium recycling and spray drying. The optimal economic scenario uses *Nannochloropsis* sp. in a one-stage cultivation to produce animal feed, while the optimal environmental design uses *Dunaliella salina* or *Haematococcus pluvialis* to produce β-carotene or astaxanthin and fertilizer or energy products, by means of gasification or anaerobic digestion. Intermediate optimal scenarios cultivate both *Dunaliella salina* and *Haematococcus pluvialis* and vary the process for energy production to torrefaction or pyrolysis. The crucial parameters for both environmental and economic feasibility are the biomass content, price and reference impact of the main end product, the growth parameters and the recovery efficiency of the biomass and carotenoids alongside the different process steps of the value chain. By identifying these crucial parameters, the MOO-extended ETEA guides the technology development of microalgal-based biorefineries and shortens the time-to-market.

1. Introduction

Technological research is often directed by an economic motivation. When improving the performance of an existing technology or introducing a new technology to the market, the main objective is in general to obtain maximal profits. However, this focus on economic optimization has led to technologies and processes which have a large impact on the environment. The consequences of climate change and other environmental problems have urged researchers to include a new objective during technology development. Besides maximizing profits, minimalizing the environmental impact needs to be a main objective as well. As technology development has become a process with multiple objectives, a multiple criteria decision method is required.

A large variety in potential algae species exists, each with their own characteristics and end products (Guiry, 2012). These end products can vary from high-value products, such as food supplements, and pharmaceuticals to low-value products, such as energy (Chew et al., 2017). The process value chain of an algae biorefinery contains multiple different process steps, starting from cultivation towards purification of the end products. For each step, different options exist. Due to this variety in species, end products and process steps, multiple algae biorefinery scenarios can be formulated.

The aim of this chapter is to identify the optimal algal-based biorefinery scenarios according to economic and environmental objectives. In the previous chapters, multiple algal-based biorefinery scenarios have been assessed on their technological, economic and/or environmental impact. For these individual assessments, the ETEA methodology which integrates process design, TEA and LCA, was developed (G. Thomassen et al., 2017). However, the ETEA methodology assesses different scenarios one by one. As this approach is not practical for a large amount of potential scenarios, the ETEA methodology needs to be extended with an optimization step. In this chapter, the assessment of these few selected scenarios will be extended towards an optimization of a large range of possible scenarios. As this optimization follows both economic and environmental objectives, a multi-objective optimization (MOO) method is used. The ETEA methodology will therefore be adapted towards a MOO-extended ETEA methodology.

The optimization model used in this chapter builds further on previous papers. Gong and You (2014b) optimized a range of algae-biorefinery scenarios, producing energy products out of a *Chlorella vulgaris* feedstock, with the objective to minimize unit carbon sequestration and utilization cost. The same authors also optimized towards multiple objectives, those being unit cost and unit global warming potential (Gong & You, 2014a). A third paper optimized towards total annual costs and global warming potential and included routes for medium-value byproducts, such as poly-3-hydroxybutyrate as well. This paper was further extended to include uncertainty considerations (Gong & You, 2017). Garcia and You (2015) assessed a broad range of bioconversion technologies and optimized towards profits and global warming potential. The current study extends these papers in four different ways. First, a full set of environmental indicators, using the ReCiPe endpoint indicators, is included. Second, a methodological framework for the integrated use of ETEA and MOO is provided. Third, a large range of algae biorefinery scenarios containing different sorts of microalgae species and products, ranging from high value antioxidants to low-value energy applications, is assessed. Finally, a cradle-to-grave LCA perspective is used by including the conventional reference processes for all end products.

The application of the MOO-extended ETEA to a large range of biorefinery scenarios enables the identification of the optimal process routes and can guide further technology development on algal-based biorefineries. By optimizing both economic and environmental objectives the time-to-market for sustainable microalgal-based biorefineries can be shortened.

2. Data and methodology

2.1. Superstructure

The potential microalgae biorefinery scenarios are grouped in a superstructure, containing the different options for each process step of the value chain. The included options were selected based on their TRL level. Technologies which are already technologically mature can be modelled with a higher accuracy than technologies on a low TRL level. Multiple technologies for bioenergy production were included as well. Although the application for algal-based bioenergy is not yet commercially available, the technologies required for this production are on a high TRL level. The model did not include a constraint for multiple products, as this would exclude optimal scenarios. Therefore, not all optimal scenarios have to be biorefineries. The superstructure is illustrated in Figure 19. The hypothetical microalgae biorefinery is situated in Belgium and a total project lifetime of ten years is considered. The production scale is limited to 3% of the global market of the end product.

The superstructure includes three potential microalgae species: *Dunaliella salina*, *Haematococcus pluvialis* and *Nannochloropsis* sp. The first two species are currently used for antioxidant production on a commercial scale (Trivedi, Aila, Bangwal, Kaul, & Garg, 2015). This commercial process can be extended to produce multiple products in a biorefinery concept. *Nannochloropsis* sp. is included as it has been proposed as a potential species for a microalgae biorefinery by multiple studies (Ferreira et al., 2013; Nobre et al., 2013).

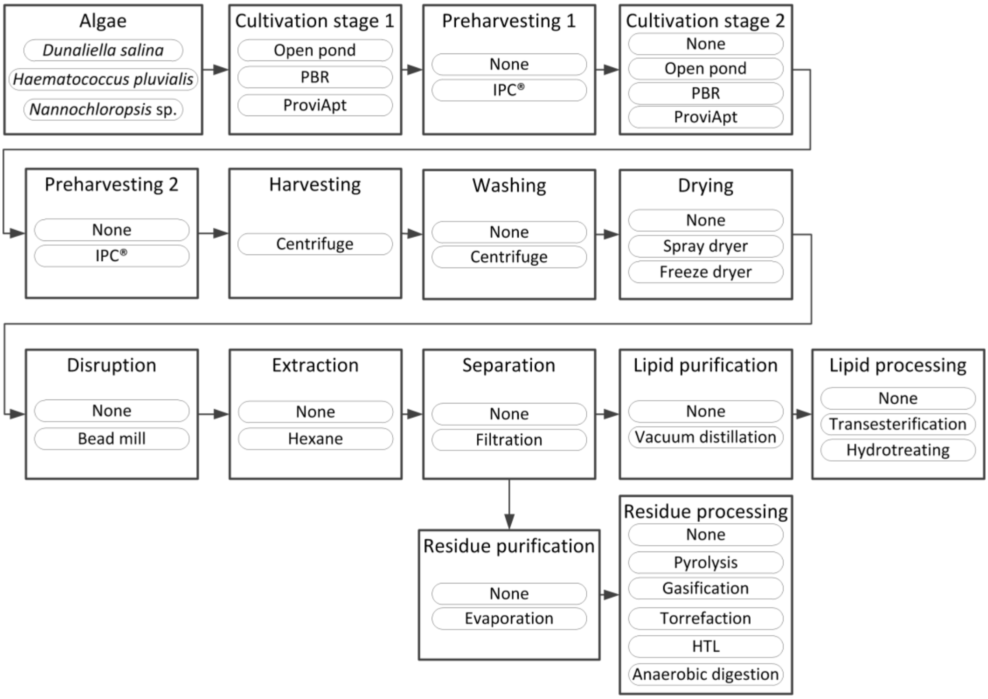

Figure 19. Superstructure

In the first cultivation stage the biomass is accumulated in optimal growth conditions. The three process options for this cultivation stage are an open pond, a photobioreactor (PBR) and the Proviron Advanced Photobioreactor Technology (ProviApt), as was used in the study of Taelman et al. (2013). The ProviApt reactor consists of multiple reactor chambers, contained by a plastic bag (Mark Michiels, 2009). The water in the plastic bag acts as a buffer against outside contamination and temperature variations (M. Michiels, 2013).

The algae could be cultivated in one stage or in two stages. If a two-stage cultivation was selected, the second stage was a stress stage. In this stress stage the nutrients were limited and the salinity was increased. Under these conditions the algae accumulate specific components such as β-carotene, astaxanthin and triacylglycerols (TAG) (Markou & Nerantzis, 2013; Pal, Khozin-Goldberg, Cohen, & Boussiba, 2011). For *Dunaliella salina*, a maximum β-carotene content after stress stage of 8.8% was included (M. García-González et al., 2003; Prieto et al., 2011; Z. Wu et al., 2017). The astaxanthin content of *Haematococcus pluvialis* reached 3% after stress stage (Olaizola, 2000). The growth parameters of the different cultivation options for the different algae species are summarized in Table 16. To model the cultivation stage, a logistic growth curve was used. The maximum specific growth rate *r* was corrected for a lower irradiation rate under Belgian conditions for open pond cultivation. The algae were transported to the stress stage as the concentration c_1 reached 67% of their maximum concentration. The algae were harvested from the stress stage when the concentration c_2 reached 77% of their maximum concentration.

Table 16. Summary of the main growth parameters

Species	*Dunaliella s.*			*Haematococcus p.*			*Nannochloropsis s.*		
Cult. option	Op	PBR	PrApt	Op	PBR	PrApt	Op	PBR	PrApt
C_0 [g·l^{-1}]	0.06	0.23	0.23	0.06	0.50	0.50	0.2	0.25	0.25
C_1 [g·l^{-1}]	0.35	1.41	1.41	0.35	2.90	2.90	0.73	1.75	1.75
C_2 [g·l^{-1}]	0.40	1.59	1.59	0.40	3.27	3.27	0.82	1.98	1.98
Time$_1$ [days]	23	8	3	23	11	4	29	7	3
Time$_2$ [days]	6	2	1	6	3	1	9	2	1
r_1 [day^{-1}]	0.12	0.35	0.90	0.12	0.25	0.64	0.08	0.41	1.05
r_2 [day^{-1}]	0.08	0.23	0.60	0.08	0.17	0.43	0.06	0.27	0.70

Abbreviations: Cult=Cultivation; PrApt = ProviApt

The same amount of nutrients was provided in each cultivation option. These nutrients included KNO_3, KH_2PO_4, $NaHCO_3$, MgSO4 and $FeCl_3.6H_2O$. The CO_2 consumption was calculated based on the carbon composition of the microalgae, taking into account an uptake efficiency of 59% for open ponds and 71% for the PBR and the ProviApt (Acién et al., 2012; Jiří Doucha, Straka, & Lívanský, 2005; Mazzuca Sobczuk, García Camacho, Camacho Rubio, Acién Fernández, & E., 2000; Pires, Alvim-Ferraz, Martins, & Simões, 2012; Ramanan, Kannan, Deshkar, Yadav, & Chakrabarti, 2010). Besides CO_2, also N_2O, NH_3 and O_2

emissions were included. The bioreactors were both heated to obtain the optimal cultivation temperature. The electricity consumption for cultivation was caused by mixing and the CO_2, water, salt and nutrient supply.

After the cultivation step, the medium, containing water and salt, can be recycled using a membrane. The Integrated Permeate Channel (IPC®) membrane, as discussed by De Baerdemaeker et al. (2013), is used for this step. This preharvesting step can be repeated if a two-stage cultivation process is used.

After cultivation and preharvesting, the biomass is harvested in a centrifuge until a biomass concentration of 12% is reached (Molina Grima, Belarbi, Acién Fernández, Robles Medina, & Chisti, 2003). The electricity consumption for this centrifuge equaled 1.40 $kWh \cdot m^{-3}$ (Milledge & Heaven, 2011). In case of a marine algae species, a washing step was included to reduce the salt content under 4 $g \cdot l^{-1}$. The washing step included a mixer and a centrifuge.

In the next step, two process options are included for the drying step: a spray dryer and a freeze dryer. The atomization energy for the spray dryer came from electricity. In the spray dryer the biomass was dried until an end solid concentration of 5% (Leach et al., 1998). For the freeze dryer, the end solid concentration was 6% (Y. Liu, Zhao, & Feng, 2008). An energy consumption of 1445 $kWh \cdot ton^{-1}$ was calculated for the spray dryer. For the freeze dryer, an energy consumption of 2000 $kWh \cdot ton^{-1}$ was used, based on the technical properties of a commercial freeze dryer.

If the microalgae have a thick cell wall, a disruption step needs to be included after the drying step. Bead milling is included as the process option as it is one of the technologies generally preferred by the industry (Günerken et al., 2015). For the beadmilling, an energy consumption of 2.82 $kWh \cdot kg$ dry $weight^{-1}$ was modelled (J. Doucha & Lívanský, 2008).

After cell disruption, the desired fractions can be extracted. The different desired products, being carotenoids and TAGs, reside in the lipid fraction of the algae biomass. This lipid fraction is extracted using hexane as a solvent (Mubarak, Shaija, & Suchithra, 2015). A recovery rate of 95% was assumed. Six extraction steps were included, requiring each time 1 liter hexane per liter biomass fraction (Cerón et al., 2008). The hexane emissions are 5.20 g·kg hexane^{-1} (Lardon, Hélias, Sialve, Steyer, & Bernard, 2009; Stephenson et al., 2010). The electricity consumption of this extraction step was 1.70 kWh·kg lipid fraction^{-1} (Lardon et al., 2009; Lundquist, Woertz, Quinn, & Benemann, 2010; Stephenson et al., 2010).

After the extraction step, the two fractions are separated using a filtration step. The hexane in the lipid fraction is recycled in a vacuum distillation step, while the hexane in the residue is recycled in an evaporator.

The lipid fraction can be sold as such or can be further processed into fuel and energy, using a transesterification or a hydrotreating step. In the transesterification step, the triglycerides react with an alcohol to form esters and glycerol in the presence of an acid or base catalyst. The main end product resulting from this process is biodiesel (Amin, 2009). To model this process, the data parameters from the GREET soybean oil transesterification process were used (Omni Tech International, 2010). GREET is a software tool that calculates the emissions resulting from multiple fuel and vehicle life cycles. It contains data on multiple conversion processes and feedstocks (Argonne National Laboratory, 2014). Although the process for soybean oil is not identical to the microalgae oil process, this process has been used before as a good proxy for this process (Batan, Quinn, Willson, & Bradley, 2010). For the modelling of the equipment, the process design of Pokoo-Aikins, Nadim, El-Halwagi, and Mahalec (2009) was used. Hydrotreating consists of multiple processes where hydrogen reacts with the lipid fraction to produce renewable diesel and naphtha. For this process, the data from Davis, Kinchin, Markham, Tan, and Laurens (2014) was used. Before the hydrotreating itself, a three-step purification process consisting of degumming, demetallization and bleaching was included to remove gums, metals and other impurities which could cause problems for the subsequent catalytic upgrading step (Davis et al., 2014). For the equipment modelling, the process design of Wu and Liu (2016) was used.

The residue can be sold as fertilizer or can be further processed into energy products. If the carotenoids have not been extracted, the biomass can be sold as animal feed. The included process options for the processing of the residue into energy are pyrolysis, gasification, torrefaction, hydrothermal liquefaction (HTL), and anaerobic digestion. Pyrolysis, gasification, torrefaction and HTL are thermochemical processes which produce a mixture of biochar, syngas and bio-oil. However, the composition differs over these different processes. In the pyrolysis process, the carbon fraction of the algae biomass is decomposed at high heating rates in the absence of oxygen. The main end product of pyrolysis is bio-oil. In gasification, mainly syngas is produced by reacting the biomass fraction under high temperatures with a controlled amount of oxygen and/or steam. Biochar is the main end product in the torrefaction process. This process occurs at relatively lower temperatures, (<300°C). The biomass is partly decomposed and can be further pelletised to achieve high densification (Khoo et al., 2013). The HTL process produces an aqueous phase which can be recycled for the nutrients. The HTL process is related to pyrolysis, however, the biomass does not need to be dry (Biller & Ross, 2011). The drying costs can therefore be reduced when the HTL process is selected. The bio-oil resulting from the four thermochemical conversion processes is upgraded and refined into gasoline and diesel before it can be sold. In the anaerobic digestion process, biogas is produced. The digestate, containing nutrients is recycled to the cultivation stage (Collet et al., 2011).

All technological, economic and environmental input data for the different processes can be found in Appendix 3.

2.2. Methodology

2.2.1. Environmental Techno-Economic Assessment

The MOO extension will optimize the ETEA results for all process designs, and is therefore an extension of the second, third and fourth step of the ETEA.

The ETEA model is built in Excel. The upstream environmental impact factors of the material and utilities used in the process are extracted from SimaPro and added in a separate sheet in the Excel-model. This way, the entire model remains in Excel and dynamic linkages between the different parts exist. This dynamic linkage means that a change in one input parameter is automatically translated into all the different output parameters.

2.2.2. MOO-extended ETEA

The result of the optimization algorithm is the Pareto frontier, which consists of all Pareto-optimal scenarios. A Pareto-optimal scenario is a scenario which cannot be improved in one objective, without deteriorating another objective (Deb, 2001).

The MOO–extended ETEA has four objectives, including one economic and three environmental objectives. The environmental objectives are calculated as environmental savings compared to a reference scenario using the substitution method. In the reference scenario the same products are produced, based on a conventional feedstock, such as a fossil feedstock, instead of a microalgae feedstock. If the environmental impact of the microalgal-based product is lower than the environmental impact of the reference product, the environmental savings, indicated by Δ, are positive. The four objectives of the MOO problem are: 1) Maximization of the NPV; 2) Maximization of the Human health environmental savings (ΔHH); 3) Maximization of the Ecosystem quality environmental saving (ΔEQ); 4) Maximization of the Resource scarcity environmental saving (ΔRS).

The decision variables which are optimized are: 1) the binary variables $b_{g,h}$ which select which process option h is included in step g; and 2) a continuous variable a for the production scale. Based on these decision variables, the four objectives can be calculated for each possible scenario. The MOO problem can therefore be formulated as follows:

$$Max\ NPV(b_{g,h}, a) \qquad \forall\ g \in G, h \in H \qquad (1)$$

$$Max\ \Delta HH(b_{g,h}, a) \qquad \forall\ g \in G, h \in H \qquad (2)$$

$$Max\ \Delta ED(b_{g,h}, a) \qquad \forall\ g \in G, h \in H \qquad (3)$$

$$Max\ \Delta RA(b_{g,h}, a) \qquad \forall\ g \in G, h \in H \qquad (4)$$

$$s.t. \sum_{h \in H} b_{g,h} = 1, \qquad \forall\ g \in G \qquad (5)$$

$$s.t. 0 \leq a\ \leq Maximum\ scale \qquad (6)$$

$$s.t. b\ \in \{0,1\} \qquad (7)$$

An overview of all notations used in the MOO problem is provided in Table 17.

In the MOO problem, equations (1-4) are the objectives, equation (5) ensures that for each process step exactly one option is chosen and equation (6) and (7) determine the bounds on the variables. To calculate the objective functions based on these decision variables, non-linear functions are required for two reasons. First, the mass and energy balance contains non-linear equation. For example, the total electricity consumption is calculated as follows: $Total\ electricity = \sum_{g \in G} \sum_{h \in H} Electricity\ requirement_{g,h} * scale(a)_{g,h} * b_{g,h}$ (8). The second non-linearity is situated in the cost and environmental impact calculation of the equipment. For example the cost of equipment unit *k* in process option *h* of process step *g* is calculated following the six-tenth rule: $Cost\ equipment\ unit_{g,h,k} = Cost\ reference\ capacity\ \alpha_{g,h,k} * \left(\frac{capacity(a_{g,h,j})}{reference\ capacity\ \alpha_{g,h,k}}\right)^{\beta_{g,h,k}}$ (9). The optimization problem can therefore be classified as a Multi-Objective Mixed Integer Non-Linear Problem (MOMINLP). However, no solvers exist which can solve this sort of problem to a global maximum in a reasonable amount of time. Therefore, we will relax this problem using three strategies in the same model.

The first strategy is to remove the non-linearity in the mass and energy balance. In the second strategy, the non-linearity in the cost and environmental impact calculation of the equipment is removed. Following the third strategy, the multi-objective problem is transformed into multiple single objective problems.

In the first strategy, new continuous decision variables are introduced for each process option of each process step, following the big-M method (Griva, Nash, & Sofer, 2009). New constraints are added to set the variable at zero, if the corresponding process option has not been selected: $0 \leq a_{g,h} \leq M * b_{g,h}$ (10). If the binary variable is one, the M indicates the upper bound of the variable. This way, the binary variables are removed from the mass and energy balance equations and added in these additional constraints. The variables a are also divided in input and output variables for each process option. New variables a are created for each component j of the mass throughput as well. The meaning of the different continuous decision variables $a_{g,h,j}$ is illustrated in Figure 20.

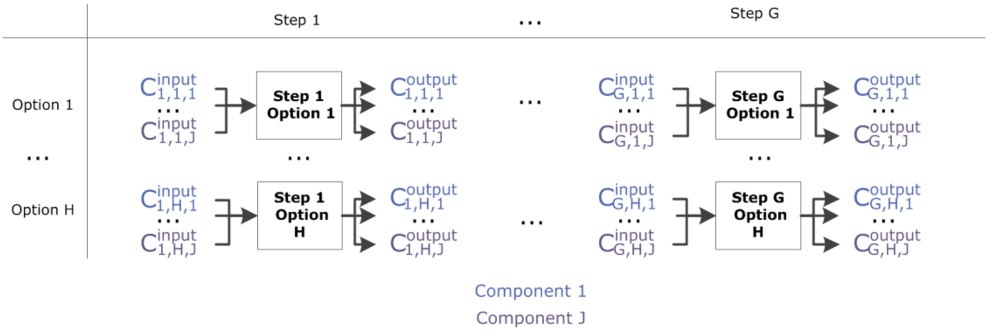

Figure 20. Continuous decision variables

The following equations will ensure that the value of the a variables is transferred and modified throughout the selected value chain: $\sum_{h \in H} a^{input}_{g,h,j} = \sum_{h \in H} a^{output}_{g-1,h,j}, \forall\, g \in G, j \in J$ (11); $a^{output}_{g,h,j} = a^{input}_{g,h,j} * \gamma_{g,h,j}, \forall\, g \in G, h \in H, j \in J$ (12).

In the second strategy, a piecewise linear approximation is added, which estimates the linear function which results in the same cost for the corresponding scale (You et al., 2011). Figure 21 illustrates the concept, by dividing the cost curve into two partition parts, using two partition points (PP). As the scale is situated in the second part of the curve, *Cost*($c_{g,h}$) will be approximated by *Cost*($c_{g,h,p=2}$). The cost will therefore always be underestimated (Gong & You, 2014b).

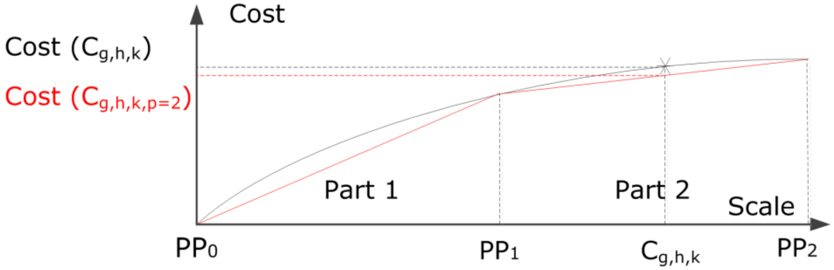

Figure 21. Piecewise linear approximation

If the non-linear cost function is written as $Cost = \delta_{g,h,k} * {c_{g,h,k}}^{\beta_{g,h,k}}$, (13), with $\delta_{g,h,k}$ being a constant, dependent on the cost of the reference capacity, and $\beta_{g,h,k}$ being the power exponent referring to the economics of scale for the equipment *k* of option *h* of step *g*, then the corresponding linear approximated function will be: $Cost = \sum_{p\in P} e_{g,h,k,p}c_{g,h,k,p} + f_{g,h,k,p}d_{g,h,k,p}$ (14). The binary variable $d_{g,h,k,p}$ will ensure that only one part of the curve is selected. The continuous variable $c_{g,h,k,p}$ equals the appropriate capacity and ensures that the part of the curve is selected which contains this capacity: $\sum_{p\in P} d_{g,h,k,p} = 1, \ \forall\, g \in G, h \in H, k \in K$; $d_{g,h,k,p} \in \{0,1\}, \forall\, g \in G, h \in H, k \in K, p \in P\ (15)$; $\sum_{p\in P} c_{g,h,k,p} = c_{g,h,k}, \forall\, g \in G, h \in H, k \in K\ (16)$; $PP_{g,h,k,p-1}d_{g,h,k,p} \leq c_{g,h,k,p} \leq PP_{g,h,k,p}d_{g,h,k,p}, g \in G, h \in H, k \in K, p \in P\ (17)$.

The continuous variables $e_{g,h,k,p}$ and $f_{g,h,k,p}$ calculate the cost for the selected partition point $PP_{g,h,k,p}$: $e_{g,h,k,p} = \frac{\delta_{g,h,k}(PP_{g,h,k,p})^{\beta_{g,h,k}} - \delta_{g,h,k}(PP_{g,h,k,p-1})^{\beta_{g,h,k}}}{PP_{g,h,k,p} - PP_{g,h,k,p-1}}, \ \forall\, g \in G, h \in H, k \in K, p \in P\ (18)$; $f_{g,h,k,p} = \delta_{g,h,k}\left(PP_{g,h,k,p}\right)^{\beta_{g,h,k}} - e_{g,h,k,p}PP_{g,h,k,p}, \forall\, g \in G, h \in H, k \in K, p \in P\ (19)$.

In the third strategy, the ε-constraint method, as introduced by Haimes, Lasdon, and Wismer (1971), is used to transform the multi-objective problem into four single-objective problems. In each single-objective problem, one objective is kept as the main objective and the other objectives are added as an additional constraint. In this additional constraint the transformed objective needs to be larger than the ε-value for that objective. By varying the ε–value between the nadir and utopian value of that objective, a discontinuous Pareto frontier is obtained. This concept is illustrated in Figure 22 for five ε-value iterations and two objectives.

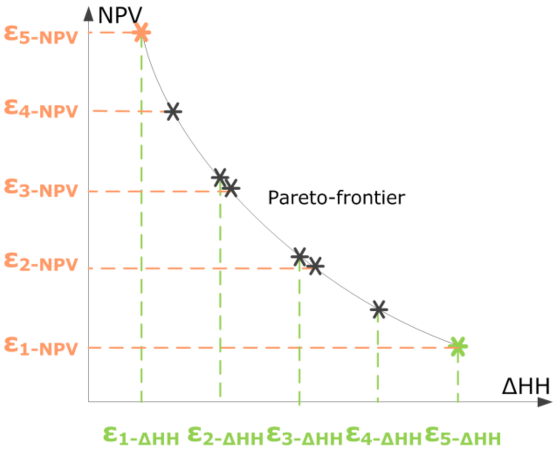

Figure 22. ε-constraint method

The resulting single optimization problem has been transformed into a Mixed-Integer Linear Problem (MILP). As the model is linear, the objectives can be calculated with vectors *npv*, *hh*, *eq* and *rs*. The problem is formulated as follows:

$$Max\ NPV(x_{g,h,j,k,p}) = npv_{g,h,j,k,p} * x_{g,h,j,k,p} \qquad \forall\ g \in G, h \in H, j \in J, k \in k, p \in P \qquad (20)$$

$$s.t. \sum_{h \in H} a_{g,h}^{input} = \sum_{h \in H} a_{g-1,h}^{output} \qquad \forall\ g \in G \qquad (21)$$

$$s.t.\ a_{g,h}^{ouput} = a_{g,h}^{input} * \gamma_{g,h} \qquad \forall\ g \in G, h \in H \qquad (22)$$

$$s.t. 0\ \leq\ a_{g,h,j} \leq\ M_{g,h,j} * b_{g,h} \qquad \forall\ g \in G, h \in H, j \in J \qquad (23)$$

$$s.t. \sum_{h \in H} b_{g,h} = 1 \qquad \forall\ g \in G \qquad (24)$$

$$s.t. \sum_{p \in P} d_{g,h,k,p} = 1 \qquad \forall\, g \in G, h \in H, k \in k \tag{25}$$

$$s.t. \sum_{p \in P} c_{g,h,k,p} = Scale_{g,h,k}\left(x_{g,h,j}\right) \qquad \forall\, g \in G, h \in H, j \in J, k \in k \tag{26}$$

$$s.t. PP_{g,h,k,p-1} d_{g,h,k,p} \leq c_{g,h,k,p} \leq PP_{g,h,k,p} d_{g,h,k,p} \qquad \forall\, g \in G, h \in H, k \in k, p \in P \tag{27}$$

$$s.t. hh_{g,h,j,k,p} * x_{g,h,j,k,p} \geq \varepsilon_{it-\Delta HH,g,h,j,k,p} \qquad \forall\, g \in G, h \in H, j \in J, k \in k, p \in P \tag{28}$$

$$s.t. ed_{g,h,j,k,p} * x_{g,h,j,k,p} \geq \varepsilon_{it-\Delta EQ,g,h,j,k,p} \qquad \forall\, g \in G, h \in H, j \in J, k \in k, p \in P \tag{29}$$

$$s.t. ra_{g,h,j,k,p} * x_{g,h,j,k,p} \geq \varepsilon_{it-\Delta RS,g,h,j,k,p} \qquad \forall\, g \in G, h \in H, j \in J, k \in k, p \in P \tag{30}$$

$$s.t. b_{g,h}, d_{g,h,k,p} \in \{0,1\} \qquad \forall\, g \in G, h \in H, k \in k, p \in P \tag{31}$$

$$s.t. b_{g,h}, a_{g,h,j}, c_{g,h,k,p}, d_{g,h,k,p} \subset x_{g,h,j,k,p} \qquad \forall\, g \in G, h \in H, j \in J, k \in k, p \in P \tag{32}$$

Multiple iterations of this MILP were run, each varying the objective function and the different values of the ε-constraint.

The MOO step is directly linked to the other steps of the ETEA. During the previous steps, technological, economic and environmental data for each process option of each process step was stored in the Excel model. This data is then transferred into two matrices (*Aq* and *Aeq*) and seven vectors (*Bq*, *Beq*, x_0, *npv*, *hh*, *eq*, *rs*) in order to solve the problem:

$$Max\ npv * x_{g,h,j,k,p} \qquad \forall\, g \in G, h \in H, j \in J, k \in K, p \in P \tag{33}$$

$$Aeq * x_{g,h,j,k,p} = Beq \qquad \forall\, g \in G, h \in H, j \in J, k \in K, p \in P \tag{34}$$

$$Aq * x_{g,h,j,k,p} \leq Bq \qquad \forall\, g \in G, h \in H, j \in J, k \in K, p \in P \tag{35}$$

$$s.t. b_{g,h}, d_{g,h,k,p} \in \{0,1\}, \qquad \forall\, g \in G, h \in H, j \in J, k \in K, p \in P \tag{36}$$

$$s.t. b_{g,h}, a_{g,h,j}, c_{g,h,k,p}, d_{g,h,k,p} \subset x \qquad \forall\, g \in G, h \in H, j \in J, k \in K, p \in P \tag{37}$$

The matrix *Aeq* contains the equality constraints, where each column stands for one decision variable. Here, all correlations between the different variables of *x* are stated, in correspondence with equations (21), (22) and (26). The potential combinations of process options and parts of the cost curve are also specified in this matrix, following equations (24) and (25). The matrix *Aq* contains the inequality constraints of equations (23) and (27) and has the same columns as

Aeq. The last lines of matrix *Aq* contain the vectors *npv*, *hh*, *eq* and *rs*. The corresponding parameters of vector *Bq* contain the ε-value for the corresponding iteration. The values of x_0 equal the decision variables of the selected ETEA scenario. This way, the matrices can be checked in the ETEA model in Excel. The optimization problem was solved using the global SCIP solver in Matlab, by use of the OPTI-tool which provides an interface for a broad range of solvers in Matlab (Achterberg, 2009; Currie & Wilson, 2012).

Table 17. Overview of the notations used in the MOO problem

Set of indices

G = set of process steps, indexed by g
H = set of process options of step g, indexed by h
J = set of mass components of option h of step g, indexed by j
K = set of equipment units of option h of step g, indexed by k
P = set of partition parts, indexed by p
IT_{npv} = set of iterations for the ε-constraint of the NPV, indexed by it-npv
IT_{hh} = set of iterations for the ε-constraint of the HH, indexed by it-hh
IT_{eq} = set of iterations for the ε-constraint of the ED, indexed by it-eq
IT_{rs} = set of iterations for the ε-constraint of the RA, indexed by it-rs

Variables

$a_{g,h,j}$ = continuous decision variable of component j of option h of step g
$b_{g,h}$ = binary decision variable of step g, option h
$c_{g,h,k,p}$ = continuous variable indicating the capacity at part p of the equipment k of option h of step g
$d_{g,h,k,p}$ = binary variable selecting part p of the cost curve of equipment k of option h of step g
$x_{g,h,j,k,p}$ = decision variable, consisting of $a_{g,h,j}$, $b_{g,h}$, $c_{g,h,k,p}$, $d_{g,h,k,p}$
$e_{g,h,k,p}$ = continuous variable to calculate the cost at part p of equipment k of option h of step g
$f_{g,h,k,p}$ = continuous variable to calculate the cost at part p of equipment k of option h of step g
$PP_{g,h,k,p}$ = Partition point of part p of equipment k of option h of step g

Parameters

$\alpha_{g,h,k}$ = reference capacity of equipment k of option h of step g

$\beta_{g,h,k}$ = power exponent of equipment k of option h of step g

$M_{g,h,j}$ = upper bound of continuous decision variable $a_{g,h,j}$

$\gamma_{g,h,j}$ = parameter assigning the amount of component j that goes from the input to the output of option h of step g

$\delta_{g,h,k}$ = constant variable related to the reference price of equipment k of option h of step g

$\varepsilon_{it\text{-}npv}$ = epsilon-constraint for NPV indexed by amount of iterations

$\varepsilon_{it\text{-}hh}$ = epsilon-constraint for HH indexed by amount of iterations

$\varepsilon_{it\text{-}eq}$ = epsilon-constraint for EQ indexed by amount of iterations

$\varepsilon_{it\text{-}rs}$ = epsilon-constraint for RS indexed by amount of iterations

$npv_{g,h,j,k,p}$ = parameter to multiply with $x_{g,h,j,k,p}$ to calculate the NPV savings

$hh_{g,h,j,k,p}$ = parameter to multiply with $x_{g,h,j,k,p}$ to calculate the HH savings

$eq_{g,h,j,k,p}$ = parameter to multiply with $x_{g,h,j,k,p}$ to calculate the EQ savings

$rs_{g,h,j,k,p}$ = parameter to multiply with $x_{g,h,j,k,p}$ to calculate the RS savings

3. Results

3.1. Optimization: Pareto frontier

The Pareto frontier consists of the four scenarios which are optimal in each dimension and of seven intermediate scenarios which cannot be improved in one dimension without deteriorating in another dimension. A summary of the results of the eleven Pareto-optimal scenarios which constitute the Pareto-frontier is provided in Table 18.

In all eleven optimal scenarios, the algae are cultivated in an open pond and the medium, containing water and salt, is recycled. The algae are harvested in a centrifuge, dried using a spray dryer and no lipid processing step is included. In the scenario with the highest NPV, scenario Ns AF, *Nannochloropsis* sp. is cultivated in one stage and animal feed is sold. No disruption, extraction, separation, residue processing, residue purification or lipid purification step was included in this scenario. The animal feed is used for larvae in aquaculture. The optimal scenario for human health savings is scenario Ds AD. In this scenario, *Dunaliella salina* is cultivated in two stages. The biomass residue goes through an anaerobic digestion step. The lipid fraction is purified but not further processed. β-carotene is sold as an end product. In the optimal scenario for ecosystem quality saving, scenario Ds F, *Dunaliella salina* is cultivated as well. The only difference with scenario Ds AD is that the residual biomass is not further processed but sold as fertilizer. The optimal scenario for resource scarcity savings is scenario Hp G. In this scenario *Haematococcus pluvialis* is cultivated. No washing step is required, but a bead mill is included for cell disruption. The lipid fraction is purified and sold for the astaxanthin. The residual biomass is processed in a gasification step. The intermediate scenario are scenarios Hp F, Hp AD, Ds G, Hp T, Ds T, Hp P and Ds P. Scenarios Hp F and Hp AD are similar to scenario Ds F and Ds AD however, *Haematococcus pluvialis* is cultivated instead of *Dunaliella salina*, no washing step is required, a bead mill is included and astaxanthin is sold. Scenarios Ds G, Ds T and Ds P are similar to scenario Ds AD. The only difference is that the processing of the residual biomass is a gasification, a torrefaction or a pyrolysis step instead of anaerobic digestion. In the same way scenarios Hp T and Hp P resemble scenario Hp AD.

Table 18. Scenarios of the Pareto frontier

Scenario	NPV [10^6 €]	ΔHH [DALY]	ΔEQ [species·yr]	ΔRS [10^6 $]	Scale [ton bm·yr^{-1}]
Ns AF	33,415	-2,885	-11,22	-172	22,359
Hp F	165	355	0.81	23.9	331
Ds F	21.9	416	1.22	18.7	149
Hp AD	164	356	0.81	23.9	331
Ds AD	21.5	416	1.21	18.7	149
Hp G	160	351	0.79	24.2	331
Ds G	19.4	415	1.21	18.8	149
Hp T	160	351	0.79	24.2	331
Ds T	19.3	415	1.21	18.8	149
Hp P	160	354	0.80	24.2	331
Ds P	19.3	416	1.21	18.8	149

3.2. Process flow diagram and mass and energy balance

The PFDs of the optimal scenarios are provided in Appendix 3. The summary of the mass and energy balances of the optimal scenarios is provided in Table 19 and Table 20.

Table 19. Summary of the mass and energy balance. Part 1

Parameter	Ns AF	Hp F	Ds F	Hp AD	Ds AD
Water [hm³]	37.5	0.43	0.55	0.45	0.56
Salt [kton]	578	0	26.1	0	26.1
CO_2 [kton]	992	14.7	6.6	14.7	6.6
Nutrients [kton]	565	11.8	5.34	11.8	5.34
Hexane [ton]	0	96.4	43.6	96.4	43.6
Electricity [TWh]	2.87	0.08	0.03	0.08	0.03
Heat [GWh]	0	0	0	1.96	0.60
Fertilizer [kton]	0	2.89	0.88	0	0
Animal feed [kton]	204	0	0	0	0
Carotenoids [ton]	0	84.00	111.4	84.00	111.4
Biogas [GWh]	0	0	0	7.94	2.42
Fertilizer [ton]	0	0	0	218.8	66.7
CO_2 [dam³]	0	0	0	325	99
Wastewater [dam³]	38,053	439.5	564	459	571
Emissions [kton]	825	12.3	5.56	12.34	5.56
Land [ha]	4,133	114	52	114	52

The animal feed scenario has a larger scale than the scenarios producing antioxidants. Therefore, they will also have a larger consumption of all inputs. *Haematococcus pluvialis* is a freshwater alga and does not require salt addition or a washing step, which reduces the water consumption for this species compared to the other species. The dry weight biomass content of carotenoids is lower for *Haematococcus pluvialis* than for *Dunaliella salina*, which leads to a larger production scale for *Haematococcus pluvialis*. This is only partially compensated by the lower market volume for astaxanthin compared to the market volume of β-carotene. In the anaerobic digestion scenarios, fertilizer and CO_2 are generated in an aqueous phase, which is assumed to be recycled to the cultivation stage. The syngas production in the gasification scenarios is larger than in the other scenarios. In the pyrolysis scenarios, the most diesel and gasoline is produced.

Table 20. Summary of the mass and energy balance. Part 2

Parameter	Hp G	Ds G	Hp T	Ds T	Hp P	Ds P
Water [hm³]	0.43	0.55	0.43	0.55	0.43	0.55
Salt [kton]	0	26.1	0	26.1	0	26.1
CO_2 [kton]	14.7	6.62	14.7	6.62	14.7	6.62
Nutirents [kton]	11.8	5.34	11.8	5.34	11.8	5.34
Hexane [ton]	96.4	43.6	96.4	43.6	96.4	43.6
Hydrogen [kton]	41.1	12.7	55.1	17.1	71.7	22.2
Electricity [TWh]	0.08	0.03	0.08	0.03	0.08	0.03
Heat [GWh]	0.04	0.01	0.05	0.02	0.07	0.02
Carotenoids [ton]	84.0	111.4	84.0	111.4	84.0	111.4
Syngas [GWh]	16.5	5.10	10.9	3.39	8.52	2.64
Diesel [m³]	143.9	44.55	193.2	59.79	251.4	77.82
Gasoline [m³]	133.2	41.24	178.8	55.35	232.7	72.03
Wastewater [dam³]	439.5	564.3	439.5	564.3	439.5	564.3
Emissions [kton]	12.34	5.56	12.34	5.56	12.34	5.56
Land [ha]	114	52	114	52	114	52

The animal feed scenario has a larger scale than the scenarios producing antioxidants. Therefore, they will also have a larger consumption of all inputs. *Haematococcus pluvialis* is a freshwater alga and does not require salt addition or a washing step, which reduces the water consumption for this species compared to the other species. The dry weight biomass content of carotenoids is lower for *Haematococcus pluvialis* than for *Dunaliella salina*, which leads to a larger production scale for *Haematococcus pluvialis*. This is only partially compensated by the lower market volume for astaxanthin compared to the market volume of β-carotene. In the anaerobic digestion scenarios, fertilizer and

CO_2 are generated in an aqueous phase, which is assumed to be recycled to the cultivation stage. The syngas production in the gasification scenarios is larger than in the other scenarios. In the pyrolysis scenarios, the most diesel and gasoline is produced.

3.3. Economic results

The economic results for the optimal scenarios are provided in Table 21. The NPV for the animal feed scenario is higher due to the larger production scale and the high price of animal feed. In the ten scenarios which produce carotenoids, the *Haematococcus pluvialis* scenarios have a higher NPV than the *Dunaliella salina* scenarios. Although the larger scale corresponds to higher investment and operational costs, astaxanthin has a higher price. The higher revenues more than compensate for the higher costs. The anaerobic digestion scenarios have a higher NPV than the gasification, torrefaction and pyrolysis scenarios, which is mainly explained by the higher investment costs and the hydrogen cost for the biocrude refining.

Table 21. Economic results for Pareto-optimal scenarios

Scenario	NPV [10^6 €]	Investment costs [10^6 €]	Operational costs [10^6 €·yr^{-1}]	Revenues [10^6 €·yr^{-1}]
Ns AF	33,415	1,303	299	6,487
Hp F	165.1	34.80	7.64	42.11
Ds F	21.94	19.08	5.05	11.17
Hp AD	164.2	35.37	7.76	42.06
Ds AD	21.52	19.36	5.10	11.16
Hp G	160.0	38.98	8.02	42.06
Ds G	19.42	21.23	5.24	11.16
Hp T	159.8	39.03	8.03	42.06
Ds T	19.34	21.26	5.24	11.16
Hp P	159.6	39.09	8.06	42.06
Ds P	19.27	21.28	5.25	11.16

3.4. Environmental results

The environmental results for the optimal scenarios are provided in Table 22, including both the endpoint and the underlying midpoint environmental impact categories. The animal feed scenario only has negative environmental impacts, except for the ΔTETP, ΔHTPc and ΔSOP impact category. The ΔIRP category is negative for all scenarios due to the upstream impact of electricity. The fossil-based reference scenario for astaxanthin has a higher environmental impact than the β-carotene reference scenario. However, due to the larger production scale, the *Haematococcus pluvialis* scenarios have lower environmental savings on most environmental impact categories.

In Figure 23, the contribution of the midpoint indicators to the endpoint indicators is analyzed to identify the most relevant midpoint indicators. As the environmental impacts for ΔHH and ΔEQ of the animal feed scenario go of the chart, their value has been added. In the endpoint impact category ΔHH, ΔGWP, ΔPMFP and ΔHTPnc have the highest contribution. In the endpoint impact category ΔEQ, ΔGWP, ΔTAP and ΔLOP have the highest contribution. However, ΔHTPnc and ΔLOP only have a high contribution for the animal feed scenario. Therefore, they will not be further assessed. The last endpoint impact category, ΔRS, is mainly determined by ΔFFP. Therefore, the main midpoint categories which will be further assessed are ΔGWP, ΔPMFP, ΔTAP and ΔFFP.

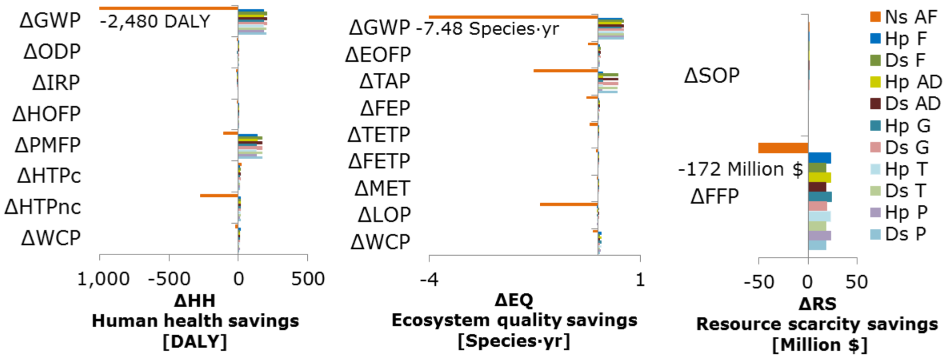

Figure 23. Contribution of the midpoint indicators to the endpoint indicators

Table 22. Environmental savings results optimal scenarios

Parameter[a]	Ns AF	Hp F	Ds F	Hp AD	Ds AD	Hp G	Ds G	Hp T	Ds T	Hp P	Ds P
ΔHH	-2.89	0.36	0.42	0.36	0.42	0.35	0.41	0.35	0.41	0.35	0.42
ΔEQ	-11	0.81	1.22	0.81	1.21	0.79	1.21	0.79	1.22	0.80	1.21
ΔRS	-172	23.9	18.7	23.9	18.7	24.2	18.8	24.2	18.8	24.2	18.8
ΔGWP	-2.67	0.20	0.22	0.20	0.22	0.20	0.22	0.20	0.22	0.20	0.22
ΔODP	-18.9	0.02	0.58	0.01	0.57	-0.01	0.57	-0.01	0.57	-0.01	0.57
ΔIRP	-1.42	-0.03	-0.01	-0.03	-0.01	-0.03	-0.01	-0.03	-0.01	-0.03	-0.01
ΔHOFP	-1.73	0.30	0.36	0.30	0.36	0.30	0.36	0.30	0.36	0.30	0.36
ΔPMFP	-174	214	275	215	275	211	274	211	274	213	275
ΔEOFP	-1.79	0.31	0.37	0.31	0.37	0.31	0.37	0.31	0.37	0.32	0.37
ΔTAP	-7.17	0.52	2.19	0.52	2.19	0.51	2.19	0.51	2.19	0.51	2.19
ΔFEP	-436	46.4	53.4	48.6	54.0	46.5	53.4	46.6	53.4	46.6	53.4
ΔTETP	12.8	0.02	0.06	0.02	0.06	-0.74	-0.17	-0.90	-0.22	-0.61	-0.13
ΔFETP	-63.7	1.50	2.41	1.70	2.47	1.49	2.41	1.49	2.41	1.51	2.41
ΔMETP	-88	2.16	3.44	2.44	3.52	2.18	3.44	2.19	3.44	2.20	3.44
ΔHTPc	6.55	3.22	4.25	3.35	4.29	3.26	4.27	3.28	4.27	3.31	4.28
ΔHTPnc	-41.7	1.90	2.66	2.04	2.70	1.95	2.68	1.98	2.69	2.01	2.70
ΔLOP	-154	-0.93	0.68	-1.00	0.65	-1.04	0.64	-1.01	0.65	-0.99	0.66
ΔSOP	0.30	2.61	0.48	2.61	0.48	2.61	0.48	2.61	0.48	2.62	0.48
ΔFFP	-517	64.1	52.9	64.1	52.9	65.0	53.1	64.9	53.1	64.9	53.1
ΔWCP	-8.92	5.54	3.18	5.53	3.17	5.39	3.13	5.36	3.12	5.40	3.13

[a] ΔHH = Human health savings [10^3 DALY]; ΔEQ = Ecosystem quality savings [species*yr]; ΔRS = Resource scarcity savings [10^6 $]; ΔGWP = Global warming potential [10^9 kg CO$_2$-eq]; ΔODP = Ozone depletion potential [10^3 kg CFC$_{11}$-eq]; ΔIRP = Ionizing radiation potential [10^9 kBq Co-60-eq]; ΔPMFP = Particulate matter formation potential [10^3 kg PM2.5-eq]; ΔEOFP = Photochemical oxidant formation potential for ecosystems [10^6 kg NOx-eq]; ΔHOFP = Photochemical oxidant formation potential for humans [10^6 kg NOx-eq]; ΔTAP = Terrestrial acidification potential [10^6 kg SO$_2$-eq]; ΔFEP = Freshwater eutrophication potential [10^3 kg P-eq]; ΔHTPC = Human toxicity potential cancer [10^6 kg 1,4-DCB-eq]; ΔHTPnc = Human toxicity potential non-cancer [10^9 kg 1,4-DCB-eq]; ΔTETP = Terrestrial ecotoxicity potential [10^6 kg 1,4-DCB-eq]; ΔFETP = Freshwater ecotoxicity potential [10^6 kg 1,4-DCB-eq]; ΔMETP = Marine ecotoxicity potential [10^6 kg 1,4-DCB-eq]; ΔLOP = Agricultural land occupation potential [10^6 m² yr]; ΔWCP = Water consumption potential [10^6 m³ water-eq] ; ΔSOP = Surplus ore potential [10^6 kg Cu-eq]; ΔFFP = Fossil fuel potential [10^6 kg oil-eq].

3.5. Interpretation

The contribution of the different process steps to the economic investment and operational costs for the Pareto-optimal scenarios is illustrated in Figure 24. The highest investment costs are caused by the spray dryer, pond liner, land costs and the preharvesting membrane. The main operational costs are the indirect costs, which include the personnel costs and insurance and repair costs of the equipment. The investment costs in the Ns AF scenario are much lower due to the larger productivity of *Nannochloropsis* sp. This leads as well to a smaller contribution of the indirect costs to the operational costs.

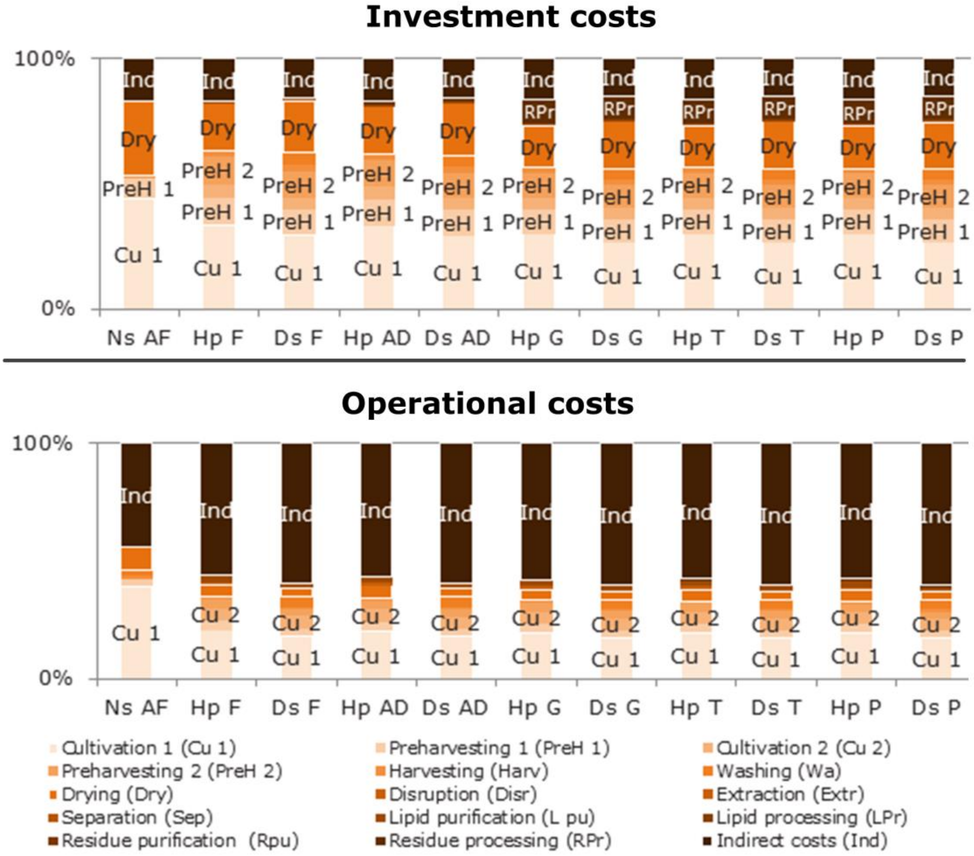

Figure 24. Contribution analysis investment and operational costs

Figure 25 provides the contribution analysis for the main midpoint indicators. The main contributor to all environmental impacts is the upstream impact of the nutrients and CO_2 in the cultivation stage. The electricity consumption during the drying stage has a significant contribution to all environmental impact categories as well. In the sensitivity analysis the most crucial parameters for each objective in each scenario are identified. A first iteration of the sensitivity analysis indicated that the carotenoid content, carotenoid price, animal feed price, carotenoid reference impact, animal feed reference impact and weighted average cost of capital shared approximately ninety percent of all variation for all impact categories and all scenarios. As the cost and impact of the algal-based production scenarios is compensated by the price and reference impact of the carotenoids and animal feed, it is logic that these parameters are important.

However, this first iteration only provides limited insights in the importance of underlying process parameters which differentiate the scenarios. Therefore, the sensitivity analysis has been iterated for a second time without these crucial parameters to identify other important parameters as well. The results of the second iteration of the sensitivity analysis are provided in Table 23. As the scenarios including gasification, torrefaction or pyrolysis resulted in similar results for each algae, they have been grouped in scenarios Ds E and Hp E. A positive value means that an increase in this parameter will ensure an increase in the corresponding indicator. The value indicates the percentage of change in the indicator explained by this parameter. In the second iteration, the most important parameters for most impact categories are either the process parameters which induce a loss of biomass or carotenoids in the process, during drying, extraction or harvesting; and/or the growth-related parameters, such as the correction factor for the lower solar irradiation in Belgium. For the GWP and PMFP indicators, the CO_2 requirement and fixation efficiency of the algae in open pond cultivation are crucial as well. The KNO_3 requirement and NH_3 emissions are important for the TAP impact category for the *Haematococcus pluvialis* scenarios. The material requirement for the liner of the open ponds is also important for the FFP in the Ns AF scenario.

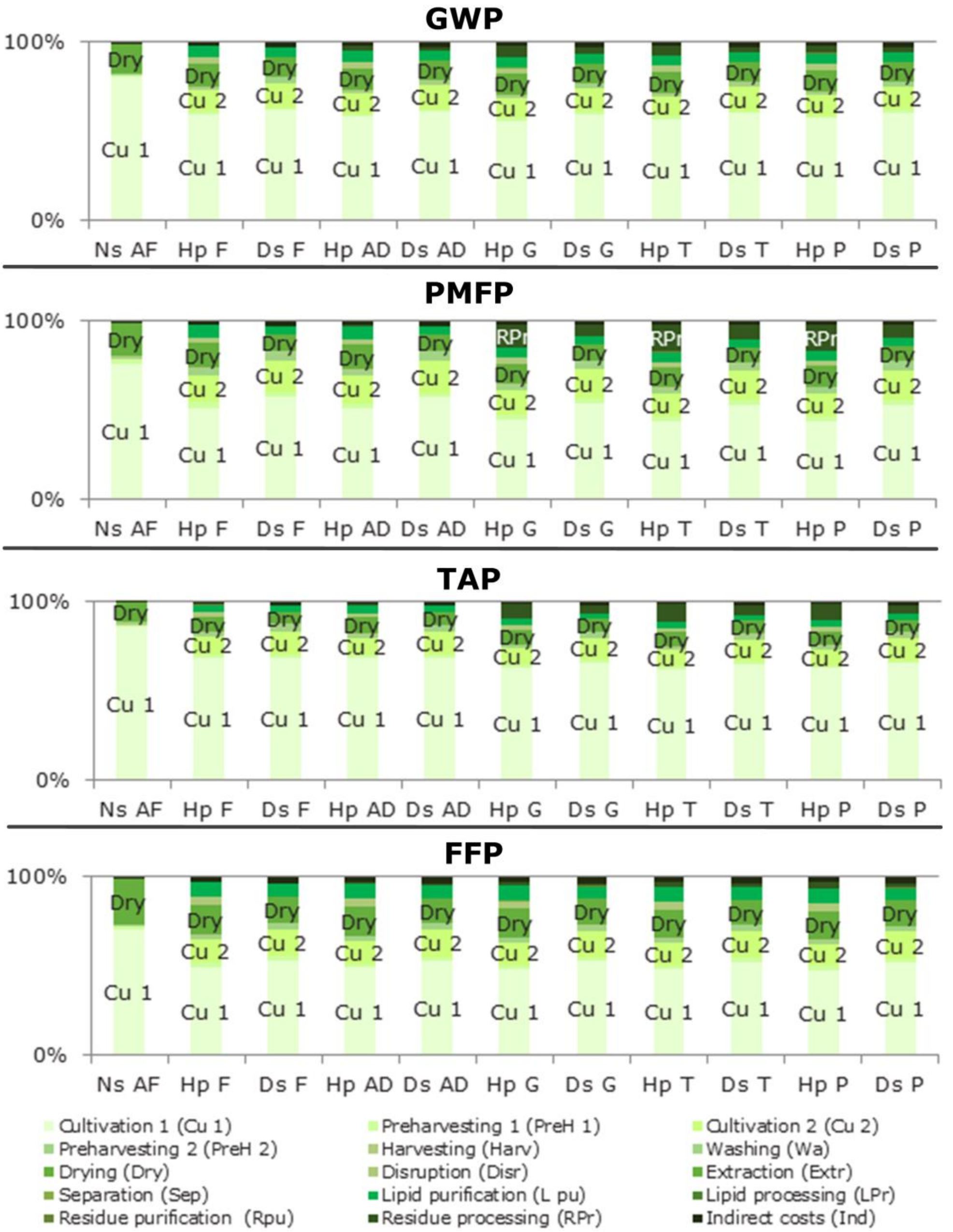

Figure 25. Contribution analysis environmental output indicator

Table 23. Sensitivity analysis second iteration [%]

	Scenario	Ns AF	Hp F	Ds F	Hp AD	Ds AD	Hp E	Ds E
NPV	Drying bm loss	-34						
	Centrifuge bm loss	-11						
	Sol. irr. corr.		-14	-17	-14	-16	-14	-17
	Max. conc. growth		+16	+19		+19	+16	+19
	Max. spec. growth		+15	+15	+13	+15	+13	+17
	Cult. time 1st stage				+10		+11	
ΔGWP	CO_2 fixation eff.	+33		+10	+16	+10	+18	+11
	CO_2 req.	-18	-19		-10			
	Car. loss extr.			-15		-17		-14
	Drying bm loss			-15		-16		-15
ΔTAP	Car. loss extr.			-32		-32		-33
	Drying bm loss			-30		-33		-31
	Centrifuge bm loss			-12		-11		-11
	KNO_3 req.	-43	-29		-30		-29	
	NH_3 em.	-15	-13		-11		-12	
	NH_3 em. impact	-15	-11		-11		-11	
ΔPMFP	CO_2 fix. eff.	+10						
	CO_2 req.	-10						
	Drying bm loss		-12	-22	-12	-24	-13	-23
	Car. loss extr.		-13	-22	-14	-24	-13	-22
ΔFFP	Max. conc. growth	+20	+13	+13	+12	+12	+13	+12
	Sol. irr. corr.	-17	-11	-10	-11	-10	-11	-12
	Max. spec. growth	+18	+10			+11	+10	+10
	Drying bm loss			-12		-13		-12
	Car. loss extr.			-13		-14		-11
	Liner pond impact	-12						

Abbreviations: Drying bm loss [%] = loss of biomass in drying; Centrifuge bm loss [%] = loss of biomass in centrifugation; Sol. irr. corr. [%] = Solar irradiation correction factor; Max. conc. growth [g l^{-1}] = Maximum biomass concentration in growth stage; Max. spec. growth [day^{-1}] = Maximum specific growth rate; Cult. time 1st stage = Cultivation time 1st stage [days]; CO_2 fixation eff. = CO_2 fixation efficiency [%]; CO_2 req. = CO_2 requirement [g CO_2 g $biomass^{-1}$]; Car. loss extr. = Carotenoid loss in extraction [%];KNO_3 req. = KNO_3 requirement 1st growth stage [g l^{-1}]; NH_3 em.= NH_3 emission [g NH_3 g KNO_3^{-1}]; NH_3 em. impact = NH_3 emission impact [impact kg^{-1}]; Liner pond impact =upstream impact of pond liner [Impact kg^{-1}].

4. Discussion

The animal feed which is produced in the optimal economic scenario is used for the early life stages of fish larvae. As a specialty feed, the price for this product is high compared to other feed. The algae which are currently sold for this purpose have been grown in the ProviApt reactor and have been freeze dried instead of spray dried. This scenario is also economically profitable, although less profitable than the optimal animal feed scenario as identified in this chapter. Quality considerations can have additional influences and affect the final price of the product. However, as no reliable estimate for this relation was available, it was not included in the model.

The animal feed scenario has a higher environmental impact than the reference scenario. The reference scenario was based on conventional fishmeal (Pelletier, 2006). However, there is no environmental impact category included in the ReCiPe 2016 indicator set which includes the environmental impact of overfishing or biotic resource use in general. The additions of a biotic resource indicator, as discussed by Crenna, Sozzo, and Sala (2018), can overcome this gap.

The land used in the animal feed scenario is 4,133 hectares. Although algae can grow on degraded land and the cultivation can be done on different locations, finding this large land area in a small and densely populated country such as Belgium will be difficult. However, even if the size of the animal feed scenario would be restricted to the size of the other optimal scenarios, being 52 hectares, this scenario would still be the optimal scenario from an economic perspective.

The use of equipment is often neglected in LCA studies. However, the upstream impact of the liner was identified as an important parameter for the FFP of the animal feed scenario. Neglecting the upstream impact of the pond manufacture would have had a significant impact on the outcome result. Therefore, as was discussed by Frischknecht et al. (2007), the environmental impact of equipment cannot be excluded per se.

The superstructure contains a wide range of different microalgae biorefinery scenarios. However, the aim is not to capture all potential scenarios. The preference was given to processes with a higher TRL level to minimize the uncertainty. New processes and improved data can be added to extend and update the superstructure.

The environmental indicators were optimized relative to a reference scenario, using the conventional production processes, as environmental savings. This means that a scenario that has a lower environmental impact than the reference scenario will be optimal if it produces at the maximal scale. By selecting the environmental savings as an objective, all objectives will be maximized in the optimization problem. If one of the objectives would be minimized instead, the production scale would function as a trade-off, and a continuous Pareto frontier would be assumed. However, this also means that the optimal value for this objective would be zero and no biomass would be produced. Although all these processes still have an absolute environmental impact on the environment and a negative absolute environmental impact should remain the end goal, an environmental saving compared to the reference scenario can already be considered an improvement and was therefore selected as the objective in the optimization problem.

The sensitivity analysis assumed a triangular distribution on all parameters to identify the most sensitive parameters. To obtain an uncertainty range on the output indicators, a more accurate distribution needs to be added to all parameters. However, a large amount of parameters in different dimensions was included and some parameters, such as the productivity of the algae, were highly uncertain. More specific uncertainty distributions on all parameters would lead to a large range on the output indicators which would not provide any useful information. Therefore, the main result of this MOO-extended ETEA is not the value of the output indicators, but the identification of the optimal value chains and the most sensitive parameters, underlying the output indicators.

In this chapter, the MOO analysis was performed using the ε-constraint method to transform the problem with four objectives into multiple iterations of a single-objective problem. Another possibility to deal with the multiple objectives would be the use of evolutionary algorithms, such as the NSGA III algorithm (Deb & Jain, 2016). The advantage of these algorithms is that they can better handle non-linear problems and can include more objectives. However, they are not able to confirm a solution as the global optimal. As the differences between the different process options in a process step which does not have a large contribution can be very small, evolutionary algorithms may have a hard time to identify the global optimal value chain. The ε-constraint method, as implemented in this chapter, is the generic version. An augmented version was developed by Mavrotas (2009) in order to accelerate the process. The implementation of this augmented version could be an interesting addition to the MOO-extended ETEA model.

The indicators used for the optimization are the three endpoint indicators of the ReCiPe2016 method. Optimizing the seventeen midpoint indicators instead would provide more information. However, using the ε-constraint method, this would lead to a large amount of iterations and the optimization problem would become complex. The use of evolutionary algorithms can better handle multiple objectives. The NSGA III algorithm was developed to handle a large amount of objectives. However, this algorithm has also not been tested for more than 15 objectives (Deb & Jain, 2016). Another solution would be the development of a specific indicator set which selects the most important environmental indicators for the corresponding case study (Van Schoubroeck, Van Dael, Van Passel, & Malina, 2018).

The results of the MOO-extended ETEA include the Pareto frontier with all Pareto-optimal scenarios. No weights or subjective preferences have been included to choose between the different scenarios. If one optimal scenario needs to be selected, the decision maker himself should decide on the weighting method after the Pareto-frontier has been calculated. This weighting method can for example use goal programming, or be based on a multiple-criteria decision analysis.

All microalgae biorefinery scenarios are situated at the same location in Belgium. As the solar irradiation was an important parameter in the model, an interesting extension of this model would be to optimize this location, first in Belgium and later in other countries. This can have an impact on the cultivation characteristics, resource availability, prices, financial parameters and the upstream environmental impact factors. However, the current MOO method might need improvement, for example by using the augmented ε-constraint method to keep the computational efficiency at a satisfactory level.

The current multi-objective optimization takes economic and environmental objectives into account. However, to perform a full techno-sustainability analysis, social objectives need to be included as well (Rafiaani et al., 2018). The integration of such a social analysis into the MOO-extended ETEA framework would be an interesting path for further research.

The microalgae biorefinery scenarios, which were assessed in the previous chapters, were identified as optimal by the MOO-extended ETEA model. However, other scenarios which were not previously assessed, were optimal as well. Therefore, the MOO-extended ETEA model can assist in selecting the scenarios which will be assessed in more detail.

The methodological framework of ETEA-MOO is used in this chapter for a microalgae-biorefinery case study, but can be used in other applications as well. The structure of the matrices used in the optimization problem is constructed in such a way that it can be generally applied for MOO problems including a superstructure with different process options and steps.

5. Conclusion

The optimal value chain for a microalgal-based biorefinery consists of an open pond cultivation, a medium recycling step and a spray dryer. In the optimal economic scenario, *Nannochloropsis* sp. is cultivated in a one-stage cultivation process and the biomass is sold as animal feed for early life cycle stage phases of aquaculture. In the optimal environmental scenarios, *Dunaliella salina* and *Haematococcus pluvialis* are cultivated in a two-stage process and β-carotene or astaxanthin and fertilizer or energy, are produced using gasification or anaerobic digestion. Intermediate scenarios include the two-stage cultivation of *Haematococcus pluvialis* and *Dunaliella salina* for astaxanthin and β-carotene production. The residual biomass is sold as fertilizer or further processed into energy products using anaerobic digestion, gasification, pyrolysis or torrefaction. The crucial parameters for economic and environmentally feasible scenarios are the content, price and reference impact of the main end product, growth parameters and the loss of biomass and carotenoids alongside the value chain. The MOO-extended ETEA as developed in this chapter provides useful insights into the broad range of potential microalgae biorefinery designs. The identification of the most promising scenarios from different perspectives and the identification of the most sensitive parameters can guide and accelerate the further technology development of this concept.

Chapter 6.

Conclusions

1. General conclusions

The main research question of this dissertation is "How can the technological, environmental and economic potential of new technologies be assessed?". This question can be answered by means of the different subquestions.

Subquestion 1, "Can an existing methodology be used to assess the technological, environmental and economic potential of microalgal-based biorefineries?", can be answered by means of the results of Chapter 2. According to these results, the required methodology needs to fulfill four requirements. First, the methodology needs to contain a generic integrated framework with clear steps. Second, the TRL of the technology needs to be taken into account by adapting the methodology to the appropriate TRL. The generic framework should therefore cover all TRL levels, guiding the technology from the first idea to market introduction. The third requirement is a clear statement of the methodological choices and assumptions. Results for alternative methodological choices should be provided when feasible. This facilitates the harmonization of different assessments and enables comparison of the results. The fourth requirement is the integration of the technological process in the economic and environmental assessment. Direct linkages should be provided to enable a dynamic assessment where the alteration in an input parameter directly results in a change of the output indicators in all dimensions. A clear example of such a dynamic link is provided by the optimization studies, which simultaneously optimize economic and environmental objectives. No current methodology is available that fulfills all four requirements, which answers this first Subquestion. Therefore, the ETEA methodology was proposed, which integrates the current TEA and LCA methodologies.

The TEA methodology was applied to a case study of microalgal-biorefineries in Chapter 3 to answer Subquestion 2 "What is the techno-economic potential of an algal-based biorefinery concept?". The case study included four different scenarios, ranging from a basic scenario, where conventional technologies are used, to an advanced scenario, including more state-of-the art technologies. An intermediate scenario and an alternative scenario, where a different algal-based biorefinery concept was assessed, were included as well. All scenarios produce carotenoids, being β-carotene or astaxanthin and fertilizer. A positive economic NPV was found for three of the four scenarios. The inclusion of a membrane for medium recycling is important for a feasible process. The crucial parameters which influence the techno-economic potential of algal-based refineries are the carotenoid content and price. The scale assumption of a PBR has an important impact on the economic viability of PBR cultivation. Subquestion 2 can now be answered as follows: The concept of algal-based biorefineries has a significant techno-economic potential as multiple techno-economically feasible scenarios can be designed.

In the fourth chapter, the environmental assessment was added to the TEA methodology to answer Subquestion 3: "How can the environmental assessment be integrated in the techno-economic assessment methodology?". In this chapter, the ETEA methodology is constructed and applied to a case study of microalgal-based biorefineries. The ETEA methodology consists of five steps: 1) market study; 2) PFD and mass and energy balance; 3) economic analysis; 4) environmental analysis; 5) interpretation. The case study included three scenarios, based on the basic, intermediate and advanced scenario of the third chapter. These three scenarios were assessed on two locations, being Belgium and India. This comparison enabled the integration of geographical aspects in the ETEA methodology. The results of the case study indicated that the algal-based biorefinery concept was in general more economically feasible in India, but more environmentally-friendly in Belgium under the assumptions made. The optimal scenario in both dimensions included an open pond cultivation with medium recycling. The most relevant environmental impact categories were GWP, PMFP and FFP. The crucial parameters with the largest influence on the economic and environmental indicators were the β-carotene price and content, the growth parameters and the requirement and upstream environmental impact of salt and electricity. Subquestion 3 can now be answered as follows: The environmental assessment and the techno-economic assessment methodology can be integrated using the ETEA methodology.

Subquestion 4: ”How can the technological, economic and environmental potential of algal-based biorefineries be optimized?” can be answered with the methodology described in Chapter 5. In this chapter the ETEA methodology was extended with a multi-objective optimization to define the optimal microalgal-biorefinery design. In the previous chapters, scenarios have been identified before the assessment. In this chapter a wide range of potential scenarios is included. The MOO-extended ETEA identifies the optimal scenarios both from an environmental and economic perspective. An optimal scenario is defined as a scenario which cannot be improved in one dimension without deteriorating in another dimension. This MOO-extension facilitates the assessment of the technological, economic and environmental potential of a broad concept such as microalgal-based biorefineries, as it decreases the subjectivity in the scenario definition. Furthermore, a new technology can be included, which can then be compared to other scenarios including conventional technologies. The optimal value chain, as identified in Chapter 5 consists of an open pond cultivation, a medium recycling step and a spray dryer. The optimal economic scenario produces animal feed, while the optimal environmental scenarios produce carotenoids and fertilizer or energy products, by means of a two-stage cultivation, hexane extraction and a gasification or anaerobic digestion process. The intermediate scenarios produce carotenoids and fertilizer or energy products and include a two-stage cultivation, hexane extraction, gasification, torrefaction, pyrolysis or anaerobic digestion process. The crucial parameters underlying the optimal scenarios are the price, content and reference environmental impact of the main end product, the growth parameters and the loss of biomass and carotenoids alongside the production process. Subquestion 4 can now be answered as follows: The technological, economic and environmental potential of algal-based biorefineries can be optimized using the MOO-extended ETEA methodology.

The main research question, "How can the technological, environmental and economic potential of new technologies be assessed?", can be answered as follows: The technological, environmental and economic potential of new technologies can be assessed using the MOO-extended ETEA methodology, as illustrated in Figure 26. This methodology was constructed using algal-based biorefineries as an example, but other applications are possible as well. The ETEA methodology assesses new technologies by calculating their economic and environmental feasibility and identifying the crucial parameters which have the highest impact on this feasibility. In the multi-objection optimization extension, the potential of the new technology is compared to other technologies in a range of alternative product value chains. This way, the MOO-extended ETEA methodology can be used to guide new technologies during their development by identifying crucial parameters and shortening the time-to-market.

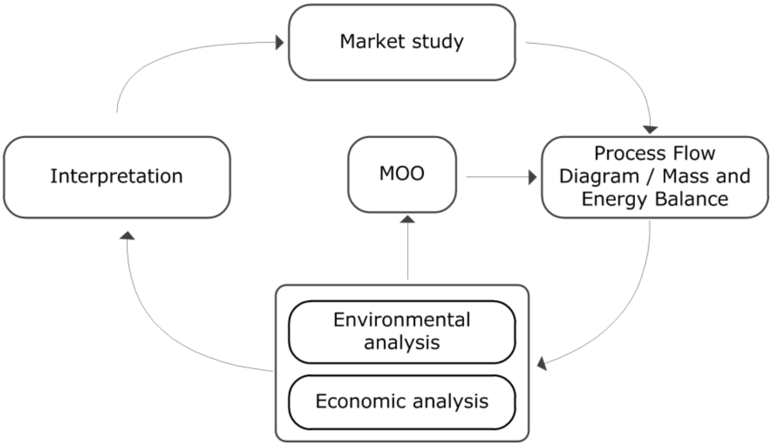

Figure 26. The MOO-extended ETEA methodology

2. Methodological discussion

The ETEA methodology follows the four recommendations as formulated in Chapter 2. The first and fourth recommendation posed that a framework was required which needs to contain the integrated assessments. The steps of this integrated framework are illustrated in Figure 26. The second and third recommendation asked for clear methodological choices and the incorporation of the TRL levels. These two recommendations will be further discussed in the next section.

2.1. Methodological assumptions

The main methodological assumptions which differed over the different studies which were reviewed in Chapter 2 were: the approach of the LCA, the selection of the functional unit, the allocation method, the system boundaries, the impact indicators, the temporal and spatial scale, the depreciation period and the discount rate.

In general, the environmental impact assessment in the ETEA methodology follows an attributional approach. However, the inclusion of the reference processes of the end products is also related to the consequential approach, as the new technologies are assumed to replace these reference processes.

The functional unit equals the project. This means that the environmental impact is not defined relative to a specific amount or function of a specific end product. Instead, the environmental impact of the total hypothetical production process is quantified. This way, the same functional unit is selected for both the economic and environmental analysis of the ETEA and the end products do not need to be classified as the main end product and the additional end products. No allocation of the environmental impact to the different end products is required. As the amount and price of the end products is provided, comparisons with other studies can be made as well.

The system boundaries of the ETEA follow the lifecycle perspective. The detailed modelling of the entire lifecycle requires a lot of time and data. Therefore, a difference is made between foreground data and background data. Foreground data is directly related to the process of interest and will be modeled in detail. Background data is related to the other parts of the lifecycle, which are not of main interest. Excluding the background data would mean the environmental impact of the process of interest cannot be put into perspective by being compared to the whole lifecycle. Including the background data in the same way as the foreground data would require a large amount of data and time. Therefore, the background data is included in a more rough way, by using secondary data or proxy data. The difference in approach towards background data and foreground data is illustrated in Figure 27.

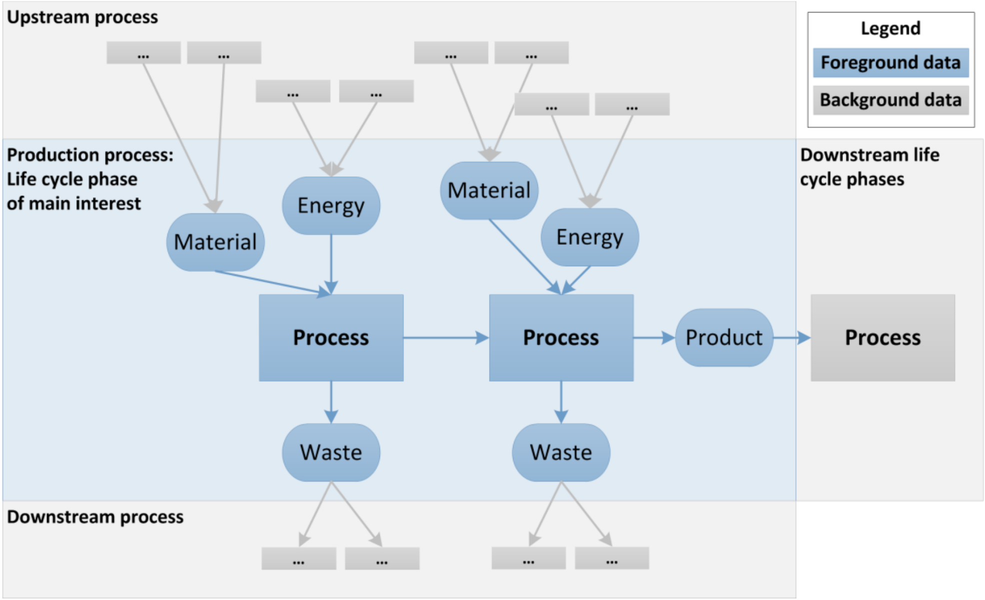

Figure 27. Background and foreground data

An important part of the background data is the data corresponding to the downstream life cycle phases, which requires information about the end use of the product. For a lot of products and processes, multiple end uses can be defined. In order to include the end stage in the ETEA methodology, a relative approach was followed. In this relative approach, the environmental impact of the reference product was modelled as well. The assumption was made that these similar products would have the same end use. By comparing the biobased product to the reference product, the relative environmental impact compared to a reference scenario was calculated instead of the absolute environmental impact. The calculation of this reference product adds complexity to the model as the corresponding production scenario needs to be modeled. In this dissertation the production process of the reference product was modeled using general assumptions as stated by Hischier et al. (2004) and used as well by van Kalkeren et al. (2013). The environmental impact of the reference product is therefore a rough estimate. However, we do prefer to include a rough estimate instead of excluding parts of the lifecycle of the product, which automatically leads to an underestimation of the total environmental impact. The ETEA methodology does not automatically have to follow a relative approach. If data on the downstream life cycle stages is available, the absolute environmental impact can be estimated as well. This can provide additional information on which parts of the lifecycle contributes the most to the environmental impact. However, it is difficult to interpret an absolute environmental impact if no benchmark is available.

According to Chapter 2 multiple impact indicators were used. The goal of the environmental part of an ETEA is to provide insights on the environmental impact of a new technology and how this can be minimized. Therefore, a full range of environmental impacts is required. In this dissertation, the ReCiPe 2016 indicator set was used for this purpose.

The ETEA methodology assumes an evaluation period for the project. In this period, some reinvestments can occur if the economic lifetime of the equipment ends within this evaluation period. In general, a lifetime between ten to fifteen years is selected (Van Dael, Kuppens, et al., 2014). In the scenarios in this dissertation a lifetime of ten years was selected to remain conservative. For the TEA case study, an extension of the lifetime from ten to twenty years would lead to an increase between 71 and 111% for the three positive scenarios. The NPV of the advanced scenario would decrease with 50%. In the ETEA case study, this extension would lead to an increase of the NPV with 59% to 94% for the first and second scenario at both locations. In the third scenario, the NPV decreases with 63% and 33%.

In each of the scenarios a location was defined. This location influences the growth and technological parameters, the costs and the upstream environmental impacts. In Chapter 4 the impact of a varying location on a similar algal-based biorefinery scenario was assessed. Therefore, the location is an important assumption that needs to be specified.

A linear depreciation was used for the calculation of the taxes which needed to be paid in each scenario. At the end of the lifetime, no additional revenues or costs were related to the equipment.

A nominal discount rate of 12% was used for the TEA case study. This was increased to 15% for the ETEA and MOO case study to better incorporate the risk relating to new technology. Based on this nominal discount rate, the weighted average cost of capital was defined for each scenario, based on the tax rate, inflation rate, equity ratio and interest ratio.

2.2. Technology Readiness Level (TRL)

The case studies of the ETEA methodology, as developed in this dissertation, focused on TRL stages halfway technology development. However, the main aim of the ETEA is to guide technology alongside all TRL stages. The ETEA as presented in this dissertation is therefore part of an overarching framework, which specifies streamlining and assessment methods which can be used alongside the different TRL stages. To discuss the overarching framework, we have divided the TRL levels in five stages: concept stage (TRL 1-2), proof-of-concept stage (TRL 3-4), demo stage (TRL 5-6), pilot stage (TRL 7-8) and commercial stage (TRL 9). The ETEA methodology follows a gate-stage approach as illustrated in Figure 28. After each stage, the ETEA methodology provides information for a go-no go decisions. In case of a ‘go’ the technology can pass the gate to the next stage, while in case of a ‘no go’ decision, the technology needs to be adapted or abandoned.

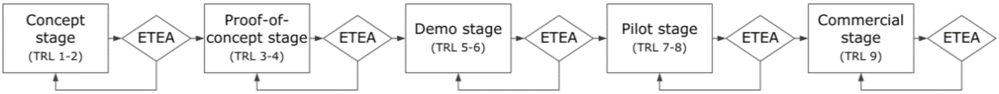

Figure 28. Stage-gate approach

The different gates differ in terms of data availability, uncertainty of the results, flexibility and costs of technological changes. The ETEA methodology is therefore not a fixed methodology but will differ in each stage, ranging from a screening ETEA at the early stages, to a streamlined ETEA at the middle stages towards a full ETEA at the commercial stage.

2.2.1. TRL 1-2: concept stage

In the first stage of technology development, the goal of the ETEA is a first check of the potential of the concept. It will be a fast assessment and the results will be rough and relatively inaccurate. The process flow diagram will consist of a blackbox process, where only the main inputs and outputs are defined. In the economic analysis, a short comparison of the quantities and prices of the outputs and the inputs is performed. The environmental analysis in this stage is based on a hotspot analysis. In this analysis, the environmental hotspots during the entire lifecycle are defined. As not enough quantitative information is available to calculate a meaningful environmental impact, the environmental analysis in this stage will be limited to a qualitative analysis.

2.2.2. TRL 3-4: proof-of-concept stage

In the proof-of-concept stage, a first streamlined ETEA is performed. A streamlined ETEA has the same methodological characteristics as a full ETEA, but uses different proxy values and generic estimates to cope with the low data availability at this stage. A streamlined ETEA is therefore a simplified version of a full ETEA. In reality, most ETEAs will be streamlined, as a full ETEA with primary reliable data on all parameters is not feasible due to time and money constraints (Graedel, 1998). To streamline the ETEA model, an evaluation grid can be used, such as proposed by Arena, Azzone, and Conte (2013) for a streamlined LCA of vehicle development. In the process design, the process will be modelled at an industrial scale. To scale up from the laboratory environment, different streamlining techniques, such as provided in the framework of Piccinno et al. (2016), can be used. In the economic analysis, the NPV will be calculated based on the preliminary process design. The preliminary process design is also the basis of the environmental analysis, in which a quantitative environmental impact analysis will be performed including a full range of environmental indicators. The precise amount of the NPV and environmental impact is too uncertain to provide fixed conclusions. The main results at this level are therefore which parameters are the most influential and which parameters determine which scenario will be optimal. As the technology is not mature when performing the ETEA, a lot of assumptions are required. A full transparency on these assumptions is advocated by providing all input information. This way, the models can be rebuilt by others and the assumptions can be improved by other researchers if required.

2.2.3. TRL 5-6: demo stage

In the demo stage, the streamlined model of the previous stage will be further refined. In this stage, the difference between the background and foreground data, as illustrated in Figure 27 becomes important. This is also the first stage where a MOO study becomes feasible. A data quality analysis, for example by means of a Pedigree matrix, can be used to assess the reliability of the parameters (Guinée et al., 2002). The ETEA models as provided in this dissertation are all performed at this stage.

2.2.4. TRL 7-8 pilot stage

In the pilot stage, the ETEA model is further refined as more data becomes available. At this stage, it becomes harder to change the parameters and the process is relatively fixed.

2.2.5. TRL 9: commercial stage

In the commercial stage, the ETEA will include a detailed assessment of the existing process design, an ex-post analysis, instead of a modeled design. Adaptations in the main process parameters will cost more compared to early development phases. However, performing an ETEA at the commercial stage of a technology is still valuable as it identifies possible improvements due to for example scale economics or learning-effects (Erickson, Magee, Roussel, & Saad, 1990).

3. Other methodologies

The goal of this dissertation was to develop an integrated technological, economic and environmental assessment framework. By including a social assessment, an integrated techno-sustainability assessment could be achieved. However, there exist multiple other methods for sustainability assessment. A review by Ness, Urbel-Piirsalu, Anderberg, and Olsson (2007) categorized these methods into indicators, product-assessments and integrated assessments. These categories are interrelated as assessment methodologies require an indicator and vice versa. An overview of different indicators used for assessing sustainability is provided by R. K. Singh, Murty, Gupta, and Dikshit (2009). LCA is the most established product assessment methodology (Ness et al., 2007). Another group of methods are the eco-design methods. Eco-design methods are broader and provide guidelines in how to design sustainable products. The product-assessment, where often LCA is used, is a part of this concept (Navajas, Uriarte, & Gandia, 2017). These methods can be valuable assets to the ETEA framework in the first stage of technology development. The objective of all these sustainability assessment methods is very broad ranging from assessing consumer behavior to project approval processes.

The project ‘SAMT’ aimed to review and make recommendations about the most potential methods for evaluating sustainability in process industries (Saurat, Ritthoff, & Smith, 2015). According to a study involving different companies, the most commonly applied methods are LCA, carbon footprint and water footprint. However, a full LCA is only seldom applied as it is too cost and time consuming (Saurat, Ritthoff, Pihkola, & Alonso, 2015). One of the recommended methods from the SAMT project was the SEEBALANCE method. This method integrates economic, environmental and social indicators into one sustainability indicator. Without the social indicator, this method is known as the eco-efficiency method (López, Mabe, Sanchez, Tapia, & Alonso, 2015). The main focus of the SEEBALANCE and eco-efficiency method is obtaining one integrated indicator (Saling et al., 2004). The underlying assessment methodology to obtain the indicators is based on Life Cycle Analysis, Environmental Life Cycle Costing and Social Life Cycle Analysis (Kolsch, Saling, Kicherer, Sommer, & Schmidt, 2008).

Environmental Life Cycle Costing is defined as: *"Environmental Life Cycle Costing summarizes all costs associated with the life cycle of a product that are directly covered by 1 or more of the actors in that life cycle; these costs must relate to real money flows."*(Ciroth et al., 2008). It follows a lifecycle approach and can therefore relatively easy be integrated with the LCA method. However, according to the interview of SAMT with BASF, the SEEBALANCE method is mainly used for large investment decisions and not for R&D. In the R&D phase, streamlined LCAs are used.

The main novelty of the ETEA methodology compared to all these methods is the integration with process design. The environmental assessment in an ETEA is a streamlined version of the LCA and is therefore more appropriate in the R&D phase of a new technology. Where Life Cycle Costing extends the economic analysis to a full LCA approach, the ETEA streamlines the environmental analysis to a TEA approach. In a TEA the focus is on the specific new technology, where the LCA focusses on the entire lifecycle of the end product of this new technology. Another difference of the ETEA approach with the LCC approach is the inclusion of a specific scale and time frame. The hypothetical production plant based on the new technology is assessed over its economic lifetime. The ETEA results in multiple indicators. The methods from the eco-efficiency tool can be used to aggregate these indicators into one indicator. However, as weighting includes subjective choices, this should be done by the final decision-maker and not by the practitioner of the assessment. This way, the ETEA model itself remains objective.

4. Microalgal-based biorefineries

Different microalgal-based biorefinery scenarios have been assessed throughout this dissertation. Microalgal-based biorefineries were selected as a case study because they have a large potential and although a lot of research has focused on this concept, no broad market introduction of these technologies has occurred yet. By selecting this concept as a case study, we aimed to investigate the reasons why this market introduction has not occurred yet and how the research can be facilitated. Based on the case studies performed in this dissertation, these questions can now be answered.

Microalgae applications are not a new concept. Antioxidants such as β-carotene and astaxanthin have been commercialized for decades (Spolaore et al., 2006). However, most algal-based research did not focus on these high-value applications (G. Thomassen et al., 2017). The main interest of algae has been their energy applications, as a third-generation of biofuels. However, the price for these applications is much lower compared to antioxidants or food supplements. The costs of the production process needs to be lowered to enable market commercialization of energy products as well (Chisti, 2013). Reducing the dewatering costs with medium recycling technologies or processes which can use wet biomass such as HTL, can decrease the production costs, but currently not to an extent that energy applications are economically viable.

The concept of biorefineries, where multiple products are produced, does not decrease the production costs, but increases the revenue stream (Laurens et al., 2017). However, according to the results of chapter 5, the production of energy products is only economically feasible when combined with the production of high-value products such as antioxidants. The main parameters influencing the techno-economic feasibility of this process are the accumulation of carotenoids, their price, the growth parameters and the loss of biomass and carotenoids throughout the production process. Improving these parameters, when feasible, can have a large impact on the economic viability of the process. A disadvantage of such a biorefinery is that the scale of energy products that can be produced is limited, due to market saturation of the high-value products.

The environmental impact of microalgal-based biorefineries is not per se lower than its reference products. In the biorefineries which were identified as optimal in chapter 5, the positive environmental impact savings were caused by the production of the carotenoids. The reference products for these carotenoids are synthetic versions which are produced using a large amount of organic chemical processes with a relatively large environmental impact. The reference impact of the energy products alone would not have compensated for the environmental impact of the algae production process for most indicators.

5. Limitations

The models which were assessed in the different case studies are simulations of hypothetical production plants and are not exact representations of future algal-based biorefineries. The aim of these simulations is to provide insights into the drivers and barriers of algal-based biorefineries and not to obtain an exact value for the profits or environmental impacts. Therefore, the results should be interpreted with consideration of the limitations of the study. The different scenarios in the case studies are always simplifications as a full-scale simulation including all details is time-consuming and not possible for technologies under development. The simulations were based on data from different dimensions, being technological, economic and environmental data. The quality of this data influences the uncertainty of the overall conclusions. To safeguard the quality of the data, a hierarchy in data sources was followed. This hierarchy consists of five different groups of data: primary data, secondary data, average data, calculations and assumptions.

Primary data, which was directly generated by the researcher, was preferred. This data group contains parts of the technological data for the IPC® membrane. For the economic data, this data group included most of the equipment through price quotes. Also input and utility prices, based on current market prices, are included in this category. If primary data was not available, we looked for secondary data which was based on experimental studies on an appropriate scale. The technological cultivation data was, for example, based on multiple outdoor pilot studies, running for multiple months. If no specific price quote was obtained, secondary data was also used for equipment prices. For the environmental data, ecoinvent was considered as secondary data. In conclusion, most data on environmental characterization factors relating to inputs and outputs to the system was categorized in this group. If no secondary data was available, we looked at average data where multiple studies were taken into account. If previous data groups were not available, calculations were used. For example, the betas were calculated based on regression functions. However, the equipment costs underlying these regression functions were mostly primary data originating from price quotes. Other calculated data was the energy consumption of downstream processes such as filtration and spray drying. For the environmental data, not all inputs, such as $NaHCO_3$, were available in ecoinvent. The environmental impact was estimated using the stoichiometric ratios and calculation procedure as identified by Hischier, Hellweg, Capello, and Primas (2004) and applied by previous studies such as van Kalkeren, Blom, Rutjes, and Huijbregts (2013). If no calculation method was available, assumptions were used and discussed with experts. However, the amount of assumptions used was minimized. Although laboratory data could be considered primary data, they do not represent the considered scale of the hypothetical production plant. Sometimes lower quality data from a higher TRL is more reliable than high quality data from a low TRL.

The data related to the crucial parameters, as identified by the sensitivity analysis was refined in later iterations. For example, in the first case study, the PBR scaling factor was a crucial parameter. In the second case study, price quotes were added to fine-tune the estimation of the PBR scaling factor.

6. Applications

The ETEA methodology has been applied in this dissertation to a case study of microalgal-based biorefineries to identify the technological, economic and environmental potential. However, other applications of this methodology are feasible as well.

The ETEA methodology can be used by technology developers to safeguard the optimal economic and environmental impact during technology development. By linking the ETEA methodology to a general stage-gate approach, it can be used during all stages of development for a large range of new technologies. By the early stage identification of the potential of a new technology, pitfalls can be identified before large expenditures have been made. Alterations to a technology at an early TRL stage are much easier and cheaper compared to a late TRL stage. The integration of technological, economic and environmental assessment in one model enables a faster assessment. The additional time for performing an environmental analysis in an ETEA model is much lower than the time required for an independent environmental analysis. This is explained by the large overlap between the assessments in these different dimensions. As the same process is analyzed, the process flow diagram and mass and energy balances, underlying both assessments are equal and only need to be constructed once. As this is often the most time-consuming part of both the economic and environmental assessment, the ETEA methodology can be done faster than a combined economic and environmental assessment using two separate models. The ETEA methodology uses a basic Excel model, which does not require specific advanced software knowledge. This improves the general applicability of the methodology and ensures that the different dimensions of a technology are no longer assessed by different people based on different assumptions.

A second application of the ETEA methodology is the use by policy makers. By means of the ETEA methodology, the environmental impact of new technologies can be easier determined together with their economic viability. New environmental-friendly technologies, which are not economically viable yet due to their small scale application, might receive subsidies until economies of scale render them profitable. Regulations can provide limitations based on allowable environmental impact to encourage the development of sustainable state-of-the art technologies.

A third application of the ETEA methodology is directed towards the users of the technologies. If the environmental and economic trade-offs can be identified, the technology users can make more sustainable choices based on their available budget.

7. Suggestions for further research

7.1. Social sustainability

The sustainability concept consists of three pillars: environment, economy and society. The social impact of a new technology is not considered in the ETEA methodology as developed in this dissertation. Although methodologies such as social LCA exist, social aspects are rarely considered in technology assessments. This can be explained by the differences in approach for example in the selection of the functional unit, the system boundaries, the selection and analysis of social indicators, the aggregation of the inventory into impact categories and the uncertainties associated with social technology assessment. If these challenges can be overcome, an inclusion of the social dimensions in ETEA would allow for a fully-integrated Techno-Sustainability Analysis (TSA) (Rafiaani et al., 2018). This would be an interesting path for further research.

7.2. Indicators

The environmental assessment of the ETEA methodology uses the ReCiPe indicators. For a new technology, it is important to get a grasp on the broad environmental impact by including a wide range of environmental indicators. However, different technologies might have different priorities and not all environmental impacts are yet considered by an appropriate indicator. For example, the effects of overfishing are not yet included in any indicator of the ReCiPe indicator set. Another example is the circularity of a process, for which currently no reliable indicator exists. Instead of a standardized indicator set, such as the ReCiPe set, a specific set of indicators can be selected. However, a large amount of indicators exists covering all sorts of environmental problems. A specific framework to facilitate indicator selection is therefore required. Such a framework was proposed by Van Schoubroeck et al. (2018), for the development of a specific set of indicators for biobased processes. The addition of this framework to the ETEA methodology would be a useful asset to the ETEA methodology.

7.3. Uncertainty

The local sensitivity analysis, included in the interpretation phase does not incorporate the uncertainty of the parameters. Therefore, the interpretation phase could be extended with a global sensitivity analysis and an uncertainty analysis. However, the range on the output indicators would be very large, due to the large amount of data and the large uncertainty range in early TRL stages. Moreover, the aim of the ETEA methodology is not to provide an exact estimate on the output indicators but to provide strategies on how the process can be improved. As the technology matures, more accurate estimates will automatically follow, as more accurate data will be available. This concept is explained by the estimating accuracy trumpet, as illustrated in Figure 29. The specification of the error range for both environmental and economic impacts alongside the TRL levels would be a valuable addition. A data quality analysis could then include a maximum error rate at each TRL in the stage-gate approach

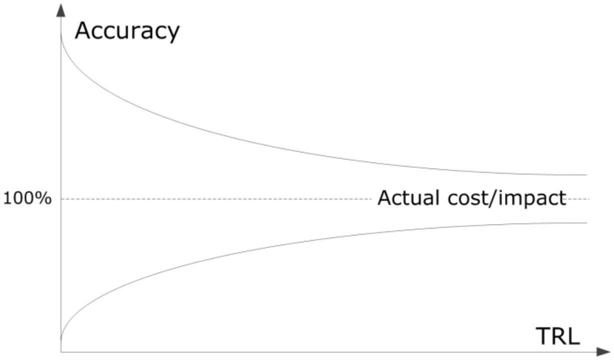

Figure 29. Estimating accuracy trumpet (based on Van Dael, Kuppens, et al. (2014))

7.4. Spatially-explicit ETEA

The ETEA methodology explicitly states the geographical location of the process. This spatial specification influences the ETEA in multiple ways. The technological analysis is influenced by location-specific growth models, due to differing irradiation and temperature. The economic analysis is influenced by country-specific costs such as labor costs or equipment costs. Also resource scarcity can increase the prices. The environmental analysis is influenced by location-specific upstream environmental impacts, such as the upstream environmental impact of the electricity mix (Ciroth, Hagelüken, Sonnemann, Castells, & Fleischer, 2002; B. Weidema, 2003). The environmental impacts themselves can have a local or a worldwide impact. However, each production process is linked to a large amount of background processes around the world. As a consequence, it is not always useful or practical to assign the environmental impact to a specific location (Heijungs, 2012).

By adding these geographical aspects to the optimization model, the optimal location can also be defined (Roostaei & Zhang, 2017). Another opportunity for a spatially-explicit model is the optimization of logistic aspects (Slegers, Leduc, Wijffels, van Straten, & van Boxtel, 2015). At a biorefinery, the biomass feedstock can be produced at different locations. The transport of the biomass to the conversion facility has multiple economic and environmental implications, which can be optimized as well (De Meyer et al., 2014). The further development of this spatial linkage in a spatially-explicit MOO-extended ETEA would be an interesting topic for further research.

7.5. Streamlined process design

The modelling of the process design in early TRL stages requires streamlining methods. An interesting addition to the process design would be a heat integration analysis, in which the potential for combining process parts to reduce resource consumption or emissions is explored (Klemeš & Kravanja, 2013).

7.6. Microalgal-based biorefineries

There are multiple strategies to improve the technological, economic and environmental potential of microalgal-based biorefineries. One of these strategies is the addition of waste CO_2 from industrial processes instead of commercial CO_2. Another strategy could use wastewater in the cultivation stage. However, care should be taken that the quality of the end products is still sufficient, that enough waste CO_2 is available and that there are no legal problems. Other microalgae components can also be extracted and used for multiple applications, such as the use of proteins for cosmetics. The microalgal growth is not optimal in outdoor cultivation in the Belgium climate conditions. Therefore, a lot of microalgae cultivation research in Belgium focusses on PBRs. This cultivation method is more expensive, but allows for a better control of growth conditions. Distinct conditions could be created for the accumulation of specific microalgae components, which would not naturally accumulate in open ponds. A biorefinery could extract multiple components and increase the economic viability of microalgal-based biorefineries in Belgium. However, such a concept has not been developed yet.

7.7. I=PAT

The I=PAT equation, where the environmental impact is a function of the total population, the affluence of the population and the impact of the technologies used by that population, has been used in this dissertation to illustrate the link between technology and environmental impact. However, it also illustrates the importance of affluence. If our consumption pattern prefers technologies with a high environmental impact, the development of sustainable technologies might be in vain. Even if consumers might prefer sustainable products, they require the knowledge in which products are sustainable to make a sustainable choice. A large responsibility lies here with the policy makers. If they can provide incentives for a system of objective information on the sustainability of products, the consumers could valorize their sustainable preferences. Such a system of objective sustainable information would be valuable as well for companies who want to demonstrate the sustainability of their products. Greenwashing could be identified and proper sustainability strategies could be rewarded. Moreover, objective information can also enable imposing limits for the industry on the environmental impacts of products. A push and pull strategy can be implemented, all starting from an objective source of sustainable information. The ETEA methodology provides a way to measure the environmental impact. The translation of ETEA results into clear labels or other measures of information is therefore also an interesting path for further research. This way a linkage between sustainable production and sustainable consumption can be made.

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APPENDICES

Appendix 1. Supplementary information chapter 3

Technological data TEA case study

Table A1.1 gives an overview of all technological input data with their corresponding references which have been used in the TEA model. The data is grouped according to the different production process steps.

Table A1.1 Technological input data

Parameter	Unit	Value	Reference
General			
Solar irradiation Belgium	kWh·m^{-2}	1040.00	(a)
Solar irradiation Iran	kWh·m^{-2}	2100.00	(a)
Solar irradiation Cadiz	kWh·m^{-2}	1900.00	(a)
Solar irradiation Hawaii	kWh·m^{-2}·day^{-1}	5.12	(b)
Ambient temperature Belgium	°C	13.60	(c)
Biological			
Carbohydrate content	% DW	30.23	(d)
Lipid content	% DW	21.73	(d)
Protein content	% DW	37.76	(d)
Molecular weight	pg·cell^{-1}	153.00	(e)
Cultivation 1st stage			

Temperature culture *Dunaliella salina*	ºC	25.00	(f)
Temperature culture *Haematococcus pluvialis*	ºC	27.00	(g)
Time open pond	days	16.00	(h)
Time PBR	days	5.00	(e)
NaCl concentration *Dunaliella salina*	M	2.00	(f,h)
NaCl concentration *Haematococcus pluvialis*	M	0.00	(i)
CO_2 flow rate	$l\cdot(\text{min.per } 20\ m^2)^{-1}$	0.40	(j)
KNO_3 concentration open pond	mM	5.00	(h)
KNO_3 concentration	$g\cdot g\ \text{biomass}^{-1}$	1.69	(k)
$NaHCO_3$ concentration open pond	mM	2.00	(j)
$NaHCO_3$ concentration	$g\cdot g\ \text{biomass}^{-1}$	0.35	(k)
$MgSO_4$ concentration open pond	mM	2.00	(h)
$MgSO_4$ concentration	$g\cdot g\ \text{biomass}^{-1}$	0.80	(k)
KH_2PO_4 concentration open pond	mM	0.10	(h)
KH_2PO_4 concentration	$g\cdot g\ \text{biomass}^{-1}$	0.05	(k)
$FeCl_3.6H_2O$ concentration open pond	mM	0.01	(h)
$FeCl_3.6H_2O$ concentration	$g\cdot g\ \text{biomass}^{-1}$	0.01	(k)
CO_2 injection energy	$kWh\cdot t\ CO_2^{-1}$	22.20	(l)
Hours of mixing	$h\cdot day^{-1}$	10.00	(m)
Mixing energy open pond	$W\cdot m^{-3}$	3.72	(m)
Mixing energy PBR	$W\cdot m^{-3}$	2500.00	(m)
Heat loss open pond	$\%\cdot day^{-1}$	30.00	(i)
Heat loss PBR	$\%\cdot day^{-1}$	5.00	(i)
Initial concentration open pond	$10^6\ cell\cdot ml^{-1}$	0.40	(e)
Initial concentration PBR *Dunaliella salina*	$10^6\ cell\cdot ml^{-1}$	1.50	(e)
End concentration 1st stage PBR *Haematococcus pl.*	$g\cdot l^{-1}$	0.81	(n)
Maximum specific growth rate open pond	day^{-1}	0.25	(h)
Productivity PBR *Dunaliella salina*	$g\cdot m^{-3}\cdot day^{-1}$	80.00	(f)

Maximum specific growth rate PBR *Haematococcus pl.*	day^{-1}	0.25	(o)
Maximum concentration open pond	$g\ DW \cdot l^{-1}$	0.50	(e)
Maximum concentration PBR *Dunaliella salina*	$g\ DW \cdot l^{-1}$	2.00	(e)
Maximum concentration PBR *Haematococcus pluvialis*	$g\ DW \cdot l^{-1}$	4.10	(n)
Volume/surface ratio open pond	$m^3 \cdot m^{-2}$	0.15	(h)
Volume/surface ratio PBR	$m^3 \cdot m^{-2}$	0.07	(p)
Energy consumption medium preparation	$MJ \cdot m^{-3}$	0.99	(p)
Cultivation 2nd stage			
Time open pond	days	16.00	(h)
Time PBR	days	5.00	(e)
Salinity *Dunaliella salina*	M NaCl	2.50	(h)
Salinity *Haematococcus pluvialis*	M NaCl	0.00	(i)
KNO_3 concentration open pond	mM	0.10	(h)
KNO_3 concentration	$g \cdot g\ biomass^{-1}$	0.03	(k)
$NaHCO_3$ concentration open pond	mM	2.00	(j)
$NaHCO_3$ concentration	$g \cdot g\ biomass^{-1}$	0.26	(k)
$MgSO_4$ concentration open pond	mM	2.00	(h)
$MgSO_4$ concentration	$g \cdot g\ biomass^{-1}$	0.61	(k)
KH_2PO_4 concentration open pond	mM	0.10	(h)
KH_2PO_4 concentration	$g \cdot g\ biomass^{-1}$	0.03	(k)
$FeCl_3.6H_2O$ concentration open pond	mM	0.01	(h)
$FeCl_3.6H_2O$ concentration	$g\ g\ biomass^{-1}$	0.01	(k)
CO_2 flow rate	$l \cdot (min\ per\ 20\ m^2)^{-1}$	0.40	(j)
Maximum concentration open pond	$g \cdot l^{-1}$	0.50	(e)
Maximum concentration PBR *Dunaliella salina*	$g \cdot l^{-1}$	2.00	(e)
Maximum concentration PBR *Haematococcus pluvialis*	$g \cdot l^{-1}$	4.10	(n)

Ratio maximum growth rate 2nd stage/1st stage	%	66.67	(i)
β-carotene content	% DW	9.78	(e)
Astaxanthin content	% DW	2.90	(o)
Volume/surface ratio open pond	$m^3 \cdot m^{-2}$	0.12	(h)
Volume/surface ratio PBR	$m^3 \cdot m^{-2}$	0.07	(p)
Heat loss	$\% \cdot day^{-1}$	30.00	(i)
Heat loss	$\% \cdot day^{-1}$	5.00	(i)
CO_2 injection energy	$Wh \cdot kg\ CO_2^{-1}$	22.20	(l)
Mixing energy open pond	$W \cdot m^{-3}$	3.72	(m)
Mixing energy PBR	$W \cdot m^{-3}$	2500	(m)
Hours of mixing	$h \cdot day^{-1}$	10.00	(m)
Energy consumption medium preparation	$MJ \cdot m^3$	0.99	(p)
Membrane filtration			
End concentration	$g\ DW \cdot l^{-1}$	10.00	(q)
Energy consumption	$GJ \cdot t\ DW^{-1}$	0.78	(q)
Maximum recycling ratio	%	97.00	(q)
Recovery biomass	%	100.00	(q)
Centrifuge			
Energy consumption	$kWh \cdot m^{-3}$	1.40	(r)
Maximum concentration	%	12.00	(s)
Recovery	%	97.00	(i)
Washing			
Water consumption	$l \cdot l^{-1}$	30.00	(i)
Mixing time	h	1.00	(i)
Energy consumption mixing	$W \cdot m^{-3}$	3.72	(i)
Energy consumtion centrifuge	$kWh \cdot m^{-3}$	1.40	(r)
Maximum concentration	%	12.00	(s)

Recovery	%	97.00	(i)
Bead mill			
Energy consumption	kWh·kg DW^{-1}	2.82	(t)
Disruption time	h	7.00	(u)
Drying			
T_{inlet} air	ºC	200.00	(v)
T_{outlet} air	ºC	110.00	(v)
T_{outlet} biomass	°C	72.00	(w)
Solid $content_{outlet}$	%	94.72	(v)
Biomass recovery	%	95.00	(i)
Correction factor for energy consumption		2.90	(w)
Total energy consumption	GJ·t(water removed)$^{-1}$	5.07	(w)
Extraction			
Extraction time	min·step^{-1}	60.00	(i)
Carotenoid recovery	%	95.00	(i)
Hexane concentration	l·l^{-1}	1.00	(x)
Extraction steps		6.00	(x)
Energy consumption	W·m^{-3}	3.72	(i)
Other components extracted	%	1.50	(i)
Filtration			
Energy consumption	J·m^{-3}	0.00	(i)
Solvent in residu	%	10.00	(i)
Evaporation			
Water evaporation	%	10.00	(i)
Solvent evaporation	%	100.00	(i)
Other components evaporation	%	5.00	(i)

Evaporation time	min	60.00	(i)
Evaporation temperature	K	341.60	(k)
Energy heating water	kJ·l^{-1}	229.93	(k)
Energy heating hexane	kJ·l^{-1}	81.85	(k)
Energy heating biomass	kJ·kg^{-1}	74.05	(k)
Energy evaporation hexane	kJ·l^{-1}	241.01	(k)
Energy evaporation water	kJ·l^{-1}	2257.00	(k)
Energy cooling water	kJ·l^{-1}	229.93	(k)
Energy cooling hexane	kJ·l^{-1}	81.85	(k)
Correction factor for energy consumption		2.90	(i)
Vacuum distillation			
Distillation carotenoids	%	5.00	(i)
Distillation other components	%	1.00	(i)
Distillation hexane	%	100.00	(i)
Temperature	°C	30.00	(y)
Steps		3.00	(i)
Time	min·step^{-1}	60.00	(i)
Pressure	kPa	24.91	(k)
Energy heating water	kJ·l^{-1}	68.75	(k)
Energy heating hexane	kJ·l^{-1}	24.47	(k)
Energy heating biomass	kJ·kg^{-1}	22.14	(k)
Energy compression water	kJ·l^{-1}	197.63	(k)
Energy compression hexane	kJ·l^{-1}	91.92	(k)
Energy compression biomass	kJ·l^{-1}	16.20	(z)
Energy evaporation hexane	kJ·l^{-1}	241.01	(k)
Energy evaporation water	kJ·l^{-1}	2257.00	(k)
Energy cooling hexane	kJ·l^{-1}	24.47	(k)
Energy evaporation water	kJ·l^{-1}	68.75	(k)

Correction factor for energy consumption		2.90	(i)
Other			
On site pumping energy	$Wh \cdot l^{-1}$	0.098	(aa)

(a) (SolarGIS); (b) (Giambelluca et al., 2014); (c) (Koninklijk Meteorologisch Instituut van België); (d) (Tibbetts, Milley, & Lall, 2014); (e) (Prieto et al., 2011); (f) (Mercedes García-González et al., 2005); (g) (Evens et al., 2007); (h) (Tafreshi & Shariati, 2006); (i) Assumption; (j) (M. García-González et al., 2003); (k) Calculation; (l) (M. García-González et al., 2003); (m) (Jorquera et al., 2010); (n) (J. Wang et al., 2013); (o) (Olaizola, 2000) (p) (Acién et al., 2012); (q) VITO estimate; (r) (Milledge & Heaven, 2011); (s) (Molina Grima et al., 2003); (t) (J. Doucha & Lívanský, 2008); (u) (Vaňková, Onderková, Antošová, & Polakovič, 2008); (v) (Leach et al., 1998); (w) Course “Sproeidrogen”, Technotrans BV(2001); (x) (Cerón et al., 2008); (y) (C.-C. Hu, J.-T. Lin, F.-J. Lu, F.-P. Chou, & D.-J. Yang, 2008); (z) (Beal, Hebner, Webber, Ruoff, & Seibert, 2011); (aa) (J. N. Rogers et al., 2014).

Economic data TEA case study

Table A1.2 gives an overview of all economic input data with their corresponding references which have been used in the TEA model. The data is grouped for in general, investment, operational and revenue data.

Table A1.2 Economic input data

Parameter	Unit	Value	Reference
General			
Evaluation period	Years	10.00	(a)
Site preparation	$\%I_0$	10.00	(b)
Algae farm occupation factor	%	150.00	(c)
Nominal discount rate	%	12.00	(a)
Equity	%	50.00	(a)
Interest loan	%	1.67	(d)
Inflation rate	%	2.00	(a)
Tax rate	%	33.99	(e)
VAT	%	21.00	(e)
Investment costs			
Cultivation			
Cost liners	EUR	97,422 Area $[ha]^{0.8}$	(f)
Lifetime liners	year	20.00	(h)
Cost landscaping	$EUR \cdot ha^{-1}$	10,222	(i)
Cost paddlewheels	$EUR \cdot ha^{-1}$	22,153 Area $[ha]^{-0.2}$	(i)
Lifetime paddlewheels	year	20.00	(i)
Cost mixer	$EUR \cdot m^{-3}$	0.099 Capacity $[m^3]^{-0.2}$	(i)

Lifetime mixer	year	20.00	(i)
Cost inoculum production system	EUR·t^{-1}	99,452 Capacity [tonnes]$^{-0.2}$	(f)
Lifetime inoculum production system	year	20.00	(f)
Land cost	EUR·m^{-2}	2.77	(j)
Cost PBR	EUR·m^{-3}	20,302 Capacity [m^3]$^{-0.2}$	(g)
Lifetime PBR	year	10.00	(g)
Cost Blower	EUR·m^{-3}	839 Capacity [m^3]$^{-0.2}$	(g)
Lifetime blower	year	10.00	(g)
Cost medium preparation unit	EUR·m^{-3}·h	5,865 Capacity [m^3·h^{-1}]$^{-0.2}$	(g)
Lifetime medium preparation unit	year	10	(g)
Cost CO_2 supply unit	EUR·kg^{-1}·h	489 Capacity [kg·h^{-1}]$^{-0.2}$	(g)
Lifetime CO_2 supply unit	year	15.00	(g)
Cost heat exchanger titanium	EUR·m^{-3}	28.78 Capacity [m^3]$^{-0.2}$	(k)
Cost heat exchanger incoloy	EUR·m^{-3}	22.49 Capacity [m^3]$^{-0.2}$	(l)
Lifetime heat exchanger	year	15.00	(m)
Membrane filtration			
Cost Membrane modules	EUR	2,297 Capacity [m^3·h^{-1}]$^{0.99}$	(n)
Lifetime Membrane modules	year	3.00	(n)
Cost Membrane installation	EUR	2,232 Capacity [m^3·h^{-1}]+ 184,917	(n)
Lifetime Membrane installation	year	10.00	(n)
Harvesting			
Centrifuge	EUR·l^{-1}·h	122 Capacity [l·h^{-1}]$^{-0.20}$	(o)
Lifetime centrifuge	year	10.00	(a)
Washing			
Cost tank	EUR·m^{-3}	4457 Input [m^3]$^{-0.2}$	(g)
Lifetime tank	year	10.00	(g)

Cost mixer	EUR·kg^{-1} DW·year^{-1}	82 Capacity [kg DW·year^{-1}]$^{-0.51}$	(i)
Lifetime mixer	year	20.00	(i)
Centrifuge	EUR·l^{-1}·h	122 Capacity [l·h^{-1}]$^{-0.2}$	(o)
Lifetime centrifuge	year	10.00	(a)
Drying			
Dryer	EUR	28,872 Capacity [l$_{\text{water removed}}$·h^{-1}]$^{0.6918}$	(p)
Lifetime dryer	year	15.00	(a)
Disruption			
Bead mill	EUR·l^{-1}·h	2,115 Capacity [l·h^{-1}]$^{-0.4}$	(q)
Life time bead mill	year	10.00	(a)
Extraction			
Cost tank	EUR·m^{-3}	4,457 Input [m^{3}]$^{-0.2}$	(g)
Lifetime tank	year	10.00	(g)
Cost mixer	EUR·kg DW^{-1}·year	82 Capacity [kg DW·year^{-1}]$^{-0.51}$	(i)
Lifetime mixer	year	20.00	(i)
Filtration			
Filter	EUR·kg dried sludge^{-1}·h	860 Capacity [kg dried sludge·h^{-1}]$^{-0.4}$	(r)
Lifetime filter	year	1.00	(a)
Evaporation			
Evaporator	EUR·l^{-1}	1,986 Input [l]$^{-0.46}$	(s)
Lifetime evaporator	year	10.00	(a)
Vacuum distillation			
Distiller	EUR·l^{-1}	1,986 Input [l]$^{-0.46}$	(s)
Lifetime distillatory	year	10.00	(a)
Additional			
Pumps	EUR·kg^{-1}·day	13,807 Capacity [kg·day^{-1}]$^{-0.67}$	(i)
Lifetime pumps	year	20.00	(i)

Operational costs			
Working rate personnel	$EUR\cdot h^{-1}$	39.10	(t)
Working hours/day	$h\cdot day^{-1}$	8.00	(a)
Working days	day	250.00	(a)
Personnel on site ponds	person	3+Area [ha]/30	(a)
Personnel on site PBR	person	3+Area [ha]/10	(a)
Electricity costs	$EUR\cdot MWh^{-1}$	130.90	(t)
Natural gas cost	$EUR\cdot MWh^{-1}$	35.40	(t)
Insurance cost	$\%I_0$	1.00	(u)
Repair/maintenance cost	$\%I_0$	7.00	(u)
Water purchase cost	$EUR\cdot m^{-3}$	3.39	(v)
Water disposal cost	$EUR\cdot m^{-3}$	2.43	(v)
Operation rate	%	70.00	(a)
Salt price	$EUR\cdot t^{-1}$	68.53	(w)
CO_2 price	$EUR\cdot t^{-1}$	225.00	(q)
Hexane price	$EUR\cdot t^{-1}$	379.45	(x)
KNO_3 price	$EUR\cdot t^{-1}$	1,632.30	(y)
$NaHCO_3$ price	$EUR\cdot t^{-1}$	672.24	(z)
KH_2PO_4	$EUR\cdot t^{-1}$	2,040.37	(y)
$FeCl_3.6H_2O$	$EUR\cdot t^{-1}$	601.91	(r)
$MgSO_4$	$EUR\cdot t^{-1}$	816.15	(y)
Revenues			
Sale fertilizer	$EUR\cdot kg^{-1}$	0.39	(q)
Sale β-carotene	$EUR\cdot kg^{-1}$	1182.50	(aa)
Sale astaxanthin	$EUR\cdot kg^{-1}$	5112.78	(ab)

(a) Assumption; (b) (Caputo, Palumbo, Pelagagge, & Scacchia, 2005); (c) (M. Michiels, 2013); (d) (National Bank of

Belgium); (e) (European Commission, 2015); (f) (R. E. Davis et al., 2014); (g) (Acién et al., 2012); (h) (ANL; NREL; PNNL, 2012) ; (i) (J. N. Rogers et al., 2014); (j) (Peeters, Schreurs, & Van Passel, 2015); (k) (AZALP Pahlen Aqua Mex compleet 70 kW - Titanium); (l) (AZALP Pahlen Aqua Mex compleet 70 kW - Incoloy) ; (m) (De Minister van Economische Zaken, 2013); (n) Vito estimate; (o) (J. Li, Zhu, Niu, Shen, & Wang, 2011); (p) (Olafsson, 2013); (q) Personnel communication with supplier; (r) Commercial source; (s) (LLC); (t) (Eurostat); (u) (Peters et al., 2003) ; (v) (VMM); (w) (U.S. Geological Survey, 2015); (x) (Koutinas, Chatzifragkou, Kopsahelis, Papanikolaou, & Kookos, 2014); (y) (MBFerts); (z)(Intra Laboratories); (aa) (Brennan & Owende, 2010); (ab) (Pacheco et al., 2015).

Growth curves TEA case study

Figure A1.1, A1.2 and A1.3 provide the growth curves for the four scenarios. The underlying growth parameters can be found in Table A1.3.

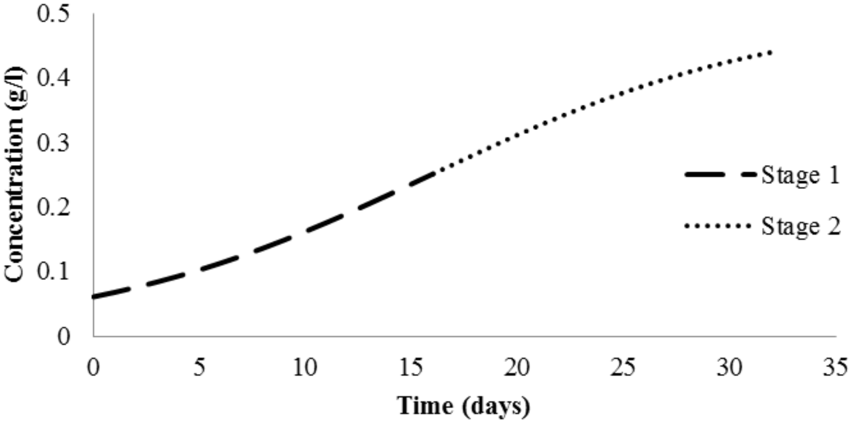

Figure A1.1. Growth curve for both stages of cultivation in the basic and intermediate scenario

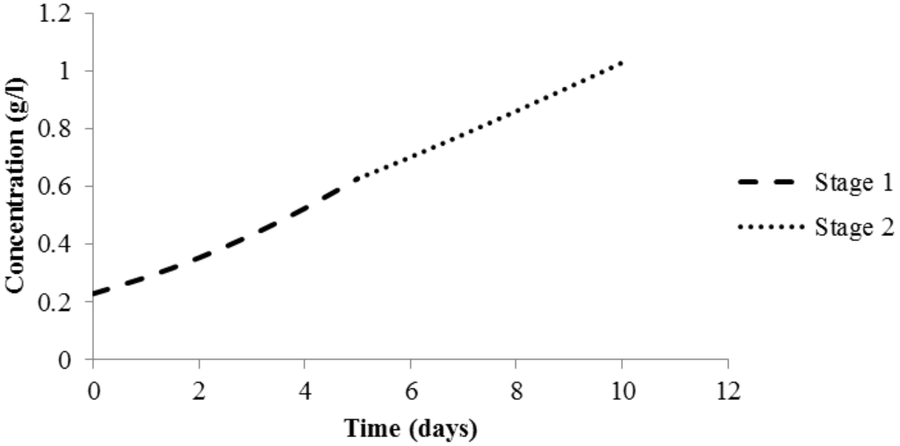

Figure A1.2. Growth curve PBR in the advanced scenario

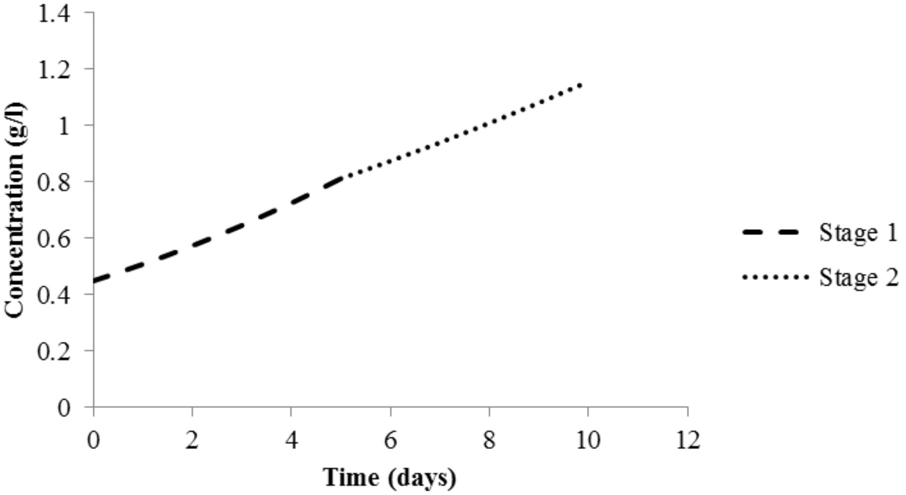

Figure A1.3. Growth curve *Haematococcus pluvialis* in the alternative scenario

Table A1.3. Main growth parameters

	Unit	Basic	Intermediate	Advanced	Alternative
K	$g\cdot l^{-1}$	0.500	0.500	2.000	4.100
N_0	$g\cdot l^{-1}$	0.061	0.061	0.230	0.450
$r_{stage\ 1}$	day^{-1}	0.124	0.124	0.252	0.139
$r_{stage\ 2}$	day^{-1}	0.083	0.083	0.168	0.093

Appendix 2. Supplementary information chapter 4

Technological data ETEA case study

Table A2.1 gives an overview of all technological input data with their corresponding references which have been used in the ETEA model. The data is grouped according to the different production process steps.

Table A2.1. Technological input parameters

Parameter	**Unit**	**Value**	**Reference**
Biological (Dunaliella salina)			
Molecular weight	pg·cell^{-1}	153.00	(a)
Optimal salinity	M	2	(b)
Stress stage salinity	M	2.5	(b)
KNO_3 requirement	mM	5	(b)
Stress stage KNO_3 requirement	mM	0.1	(b)
$NaHCO_3$ requirement	mM	2	(c)
$MgSO_4$ requirement	mM	2	(b)
KH_2PO_4 requirement	mM	0.1	(b)
$FeCl_3.6H_2O$ requirement	mM	0.01	(b)
CO_2 requirement	g·g biomass^{-1}	1.83	(d)
Optimal temperature	°C	25	(c)
Stress stage β-carotene	%	8.8	(a,c,e)
Geographical			

Solar irradiation Belgium	$kWh \cdot m^{-2}$	1040.00	(f)
Solar irradiation India	$kWh \cdot m^{-2}$	2100.00	(f)
Ambient temperature Belgium March-November	°C	12.86	(g)
Ambient temperature India	°C	27.9	(f)
Precipitation Belgium	$l \cdot m^{-2} \cdot yr^{-1}$	641	(h)
Precipitation India	$l \cdot m^{-2} \cdot yr^{-1}$	1019	(h)
Average wind speed Belgium	$m \cdot s^{-1}$	2.24	(i)
Average wind speed Oonayiur	$m \cdot s^{-1}$	3.04	(i)
Maximum humidity ratio Belgium	$kg \cdot kg^{-1}$	0.008	(j)
Maximum humidity ratio India	$kg \cdot kg^{-1}$	0.024	(j)
Average humidity Belgium	%	80.00	(k)
Average humidity India (Bangalore)	%	65.000	(k)
Process: General			
Operation rate Belgium	%	70.00	
Operation rate India	%	90.00	
Algae farm occupation factor	%	150.00	(l)
Process: Cultivation 1st stage			
Salinity seawater	$g \cdot l^{-1}$	35.00	(m)
CO_2 fixation efficiency open pond	%	41.23	(n,o)
CO_2 fixation efficiency PBR	%	71.00	(p,q)
N_2O emission open pond	% N-fertilizer	0.002	(r)
N_2O emission PBR	% N-fertilizer	0.39	(r)
NH_3 emission	% N-fertilizer	4.88	(s)
O_2 emission open pond	$g \cdot g$ biomass^{-1}	1.07	(d)
Fugitive emissions pump	$kg \cdot h^{-1}$	0.0199	(t)
Pumps in medium supply unit	#	4.00	(u)

Fugitive emission tank	$kg\cdot h^{-1}$	0.082	(t)
Tanks in medium supply unit	#	3.00	(u)
Fugitive emission open ended line	$kg\cdot h^{-1}$	0.0017	(t)
CO_2 injection energy	$kWh\cdot t\ CO_2^{-1}$	22.20	(v)
Mixing energy open pond	$W\cdot m^{-3}$	3.72	(w)
Mixing energy PBR	$W\cdot m^{-3}$	2500.00	(w)
Medium preparation energy	$W\cdot m^{-3}\cdot h$	275.00	(p)
Activity coefficient water	%	0.92	(y)
Heat loss PBR	%	5.00	
Additional heating solar irradiation	°C	5.00	
Hours of mixing	$h\cdot day^{-1}$	10.00	(w)
Hours of medium preparation	$h\cdot day^{-1}$	6.00	(p)
Height pond	m	0.15	(b)
Cooling PBR	$kW\cdot m^{-3}$	0.05	(u)
Hours of cooling	$h\cdot year^{-1}$	1,680.00	(u)
Volume surface ratio PBR	$m^3\cdot m^{-2}$	0.07	(p)
Process: Preharvesting			
End concentration	$g\ DW\cdot l^{-1}$	10.00	(z)
Energy consumption after open pond	$kWh\cdot m^{-3}$	0.24	(z)
Energy consumption after PBR	$kWh\cdot m^{-3}$	0.26	(z)
Maximum recycling ratio	%	100.00	(z)
Process: Cultivation 2nd stage			
CO_2 fixation efficiency open pond	%	41.23	(n,o)
CO_2 fixation efficiency PBR	%	71.00	(p,q)
N_2O emission open pond	% N-fertilizer	0.002	(r)
N_2O emission PBR	% N-fertilizer	0.39	(r)

NH_3 emission	% N-fertilizer	4.88	(s)
O2 emission open pond	g·g biomass^{-1}	1.07	(d)
Fugitive emissions pump	kg·h^{-1}	0.0199	(t)
Pumps in medium supply unit	#	4.00	(u)
Fugitive emission tank	kg·h^{-1}	0.082	(t)
Tanks in medium supply unit	#	3.00	(u)
Fugitive emission open ended line	kg·h^{-1}	0.0017	(t)
CO_2 injection energy	kWh·t CO_2^{-1}	22.20	(v)
Mixing energy open pond	W·m^{-3}	3.72	(w)
Mixing energy PBR	W·m^{-3}	2500.00	(x)
Medium preparation energy	W·m^{-3}·h	275.00	(p)
Activity coefficient water	%	0.92	(y)
Heat loss PBR	%	5.00	
Additional heating solar irradiation	°C	5.00	
Hours of mixing	h·day^{-1}	10.00	(w)
Hours of medium preparation	h·day^{-1}	6.00	(p)
Height pond	m	0.12	(b)
Cooling PBR	kW·m^{-3}	0.05	(u)
Hours of cooling	h·year^{-1}	1,680.00	(u)
Volume surface ratio PBR	m^{3}·m^{-2}	0.07	(p)
Process: Centrifuge			
Fugitive emissions pump	kg·h^{-1}	0.0199	(t)
Energy consumption	kWh·m^{-3}	1.40	(ab)
Maximum concentration	%	12.00	(ac)
Recovery	%	97.00	
Process: Washing			

Water consumption	$l\cdot l^{-1}$	30.00	
Mixing time	h	1.00	
Energy consumption mixing	$kWh\cdot h\cdot t^{-1}\cdot year\cdot l^{-1}$	0.18 Capacity $[l]^{-0.33}$	(ad)
Energy consumtion centrifuge	$kWh\cdot m^{-3}$	1.40	(ab)
Maximum concentration	%	12.00	(ac)
Fugitive emissions pump	$kg\cdot h^{-1}$	0.0199	(t)
Fugitive emission mixer input 1	$g\cdot h^{-1}$	88.00	(t)
Fugitive emission mixer input 2	$g\cdot h^{-1}$	82.00	(t)
Fugitive emission mixer output 2	$g\cdot h^{-1}$	560.00	(t)
Recovery	%	97.00	
Process: Drying			
T_{inlet} air	°C	200.00	(ae)
T_{outlet} air	°C	110.00	(ae)
T_{outlet} biomass	°C	72.00	(af)
Solid content$_{outlet}$	%	94.72	(ae)
Biomass recovery	%	95.00	
Correction factor for energy consumption	%	2.90	(af)
Total energy consumption	$GJ\cdot t(\text{water removed})^{-1}$	5.20	
Process: Extraction			
Extraction time	$min\cdot step^{-1}$	60.00	
Carotenoid recovery	%	95.00	
Hexane concentration	$l\cdot l^{-1}$	1.00	(ag)
Extraction steps	#	6.00	(ag)
Energy consumption mixing	$kWh\cdot h\cdot t^{-1}\cdot year\cdot l^{-1}$	0.18 Capacity $[l]^{-0.33}$	(ad)
Hexane emission	$g\cdot kg^{-1}$	2.00	(ah)
Fugitive emission mixer input 1	$g\cdot h^{-1}$	88.00	(t)

Fugitive emission mixer input 2	g·h^{-1}	82.00	(t)
Fugitive emission mixer output 2	g·h^{-1}	560.00	(t)
Other components extracted	%	1.50	
Process: Filtration			
Energy consumption	kWh·t dry material^{-1}	10.00	(ad)
Fugitive emissions pump	kg·h^{-1}	0.0199	(t)
Solvent in residu	%	10.00	
Process: Evaporation			
Water evaporation	%	40.00	
Solvent evaporation	%	100.00	
Other components evaporation	%	1.00	
Fugitive emission normal distillation input	g·h^{-1}	36.00	(t)
Fugitive emission normal distillation output 1	g·h^{-1}	405.00	(t)
Fugitive emission normal distillation output 2	g·h^{-1}	217.00	(t)
Cooling water	m^{3}·kg waste solvent^{-1}	0.027	(ah)
Evaporation energy Belgium	kWh·t recycled^{-1}	1,153.83	
Evaporation energy India	kWh·t recycled^{-1}	1,049.70	
Energy efficiency	%	64.00	(ad)
Minimum reflux ratio	%	120.00	(ad)
Evaporation time	min	60.00	
Evaporation temperature	K	341.60	
Process: Vacuum distillation			
Distillation carotenoids	%	1.00	
Distillation other components	%	1.00	
Distillation water	%	40.00	
Distillation hexane	%	100.00	

Fugitive emission vacuum distillation input	$g\cdot h^{-1}$	0.00	(t)
Fugitive emission vacuum distillation output 1	$g\cdot h^{-1}$	239.00	(t)
Fugitive emission vacuum distillation output 2	$g\cdot h^{-1}$	139.00	(t)
Cooling water	$m^3\cdot kg$ waste solvent^{-1}	0.027	(ah)
Temperature	°C	30.00	(ai)
Steps		3.00	
Time	$min\cdot step^{-1}$	60.00	
Pressure	kPa	24.91	
Distillation energy Belgium	$kWh\cdot t$ recycled^{-1}	1,353.32	
Distillation energy India	$kWh\cdot t$ recycled^{-1}	1,314.21	
Energy efficiency	%	64.00	(ad)
Minimum reflux ratio	%	120.00	(ad)
Distribution: Packaging			
Plastic packaging fertilizer	$kg\cdot kg^{-1}$	0.002	(aj)
Steel packaging β-carotene	$kg\cdot kg^{-1}$	0.003	(aj)
Plastic packaging β-carotene	$kg\cdot kg^{-1}$	0.012	(aj)
Paper packaging β-carotene	$kg\cdot kg^{-1}$	0.006	(aj)
Lorry transport fertilizer Be	km	193.00	(ak)
Train transport fertilizer Be	km	182.00	(al)
Lorry transport fertilizer In	km	148.50	(am)
Train transport fertilizer In	km	275.60	(am)
Inland waterways transport fertilizer In	km	46.60	(am)
Transoceanic ship transport fertilizer In	km	840.90	(am)
Lorry transport β-carotene Be	km	193.00	(ak)
Train transport β-carotene Be	km	182.00	(al)
Lorry transport β-carotene In	km	208.80	(am)

Train transport β-carotene In	km	309.10	(am)
Inland waterways transport β-carotene In	km	24.60	(am)
Transoceanic transport β-carotene In	km	599.00	(am)

(a) (Prieto et al., 2011); (b) (Tafreshi & Shariati, 2006); (c) (M. García-González et al., 2003); (d) (Buehner et al., 2009); (e) (Z. Wu et al., 2017); (f) (SolarGIS); (g) (Koninklijk Meteorologisch Instituut van België); (h) (The World Bank Group); (i) (Global Modeling and Assimilation Office (GMAO) (2015)); (j) (The Engineering Toolbox); (k) WMO data; (l) (M. Michiels, 2013); (m) (Zweng et al., 2013); (n) (Jiří Doucha et al., 2005); (o) (Ramanan et al., 2010); (p) (Acién et al., 2012); (q) (Mazzuca Sobczuk et al., 2000); (r) (Fagerstone, Quinn, Bradley, De Long, & Marchese, 2011); (s) (Yuan et al., 2015); (t) (Hassim, Pérez, & Hurme, 2010); (u) (Tredici, Rodolfi, Biondi, Bassi, & Sampietro, 2016); (v) (Kadam, 2001); (w) (Jorquera et al., 2010); (x) (Sierra et al., 2008); (y) (Salhotra, Adams, & Harleman, 1985); (z) VITO estimate; (ab) (Milledge & Heaven, 2011); (ac) (Molina Grima et al., 2003); (ad) (Piccinno et al., 2016); (ae) (Leach et al., 1998); (af) Course "Sproeidrogen", Technotrans BV(2001); (ag) (Cerón et al., 2008); (ah) (Lardon et al., 2009); (ah) (Capello, Hellweg, Badertscher, & Hungerbühler, 2005); (ai) (C.-C. Hu et al., 2008); (aj) (B. P. Weidema et al., 2013); (ak) (Eurostat); (al) (Eurostat); (am) (Wernet et al., 2016).

Economic data ETEA case study

Table A2.2 gives an overview of all economic input data with their corresponding references which have been used in the ETEA model. The data is grouped in general, investment, operational and revenue data.

Table A2.2. Economic input parameters

Parameter	**Unit**	**Value**	**Reference**
General			
Evaluation period	Years	10.00	
Site preparation	$\%I_0$	10.00	(a)
Nominal discount rate	%	15.00	(b)
Equity	%	20.00	
Interest loan Be	%	1.47	(c)
Interest loan In	%	7.85	(d)
Inflation rate Be	%	2.00	(e)
Inflation rate In	%	4.90	(e)
Tax rate Be	%	33.99	(f)
Tax rate Be	%	34.61	(g)
Investment costs			
Process: Cultivation			
Cost liners Be	$EUR \cdot ha^{-1}$	87,637	(h,i,j)
Cost liners In	$EUR \cdot ha^{-1}$	56,987	(h,i,j)
Lifetime liners	year	20.00	(k)
Cost landscaping Be	$EUR \cdot ha^{-1}$	8,760	(l)
Cost landscaping In	$EUR \cdot ha^{-1}$	5,696	(l)

Cost paddlewheels Be	EUR·ha^{-1}	11,728	(i,j,l)
Cost paddlewheels In	EUR·ha^{-1}	7,626	(i,j,l)
Lifetime paddlewheels	year	20.00	(l)
Cost inoculum production system Be	EUR·ha^{-1}	122,595 Capacity [ha]$^{-0.21}$	(h,m)
Cost inoculum production system In	EUR·ha^{-1}	79,719 Capacity [ha]$^{-0.21}$	(h,m)
Lifetime inoculum production system	year	20.00	(h)
Land cost Be	EUR·m^{-2}	2.62	(n)
Land cost In	EUR·m^{-2}	0.95	(o)
Cost PBR Be	EUR·m^{-3}	13,501 Capacity [m^3]$^{-0.07}$	(p,q)
Cost PBR In	EUR·m^{-3}	8,779 Capacity [m^3]$^{-0.07}$	(p,q)
Lifetime PBR	year	10.00	(p,q)
Cost Blower Be	EUR·m^{-3}	2,055 Capacity [m^3]$^{-0.6}$	(p,m)
Cost Blower In	EUR·m^{-3}	1,336 Capacity [m^3]$^{-0.6}$	(p,m)
Lifetime blower	year	20.00	(m)
Cost medium preparation unit Be	EUR·m^{-3}·h	6,954 Capacity [m^3 h^{-1}]$^{-0.51}$	(p,m)
Cost medium preparation unit In	EUR·m^{-3}·h	11,234 Capacity [m^3 h^{-1}]$^{-0.51}$	(p)
Lifetime medium preparation unit	year	10	(p)
Cost CO_2 supply unit Be	EUR·kg^{-1}·h	436	(p,i)
Cost CO_2 supply unit In	EUR·kg^{-1}·h	283	(p,i)
Lifetime CO_2 supply unit	year	10.00	(p)
Cost heat exchanger titanium Be	EUR·m^{-3}	429 Capacity [m^3]$^{-0.4}$	(r)
Cost heat exchanger titanium In	EUR·m^{-3}	279 Capacity [m^3]$^{-0.4}$	(r)
Lifetime heat exchanger	year	15.00	(s)
Process: Membrane filtration			
Total cost membrane 2 Be	EUR	6,702,213	
Total cost membrane 3 Be	EUR	1,329,654	

Total cost membrane 2 In	EUR	3,267,797	
Total cost membrane 3 In	EUR	864,612	
Process: Harvesting			
Centrifuge Be	EUR·l^{-1}·h	6,697 Capacity [l·h^{-1}]$^{-0.44}$	(q)
Centrifuge In	EUR·l^{-1}·h	4,410 Capacity [l·h^{-1}]$^{-0.44}$	(q)
Lifetime centrifuge	year	25.00	(m)
Process: Washing			
Cost tank Be	EUR·m^{-3}	2,417 Input [m^{3}]$^{-0.43}$	(p)
Cost tank In	EUR·m^{-3}	1,572 Input [m^{3}]$^{-0.43}$	(p)
Lifetime tank	year	10.00	(p)
Cost mixer Be	EUR·W^{-1}	436 Capacity [W]$^{-0.63}$	(q)
Cost mixer In	EUR·W^{-1}	284 Capacity [W]$^{-0.63}$	(q)
Lifetime mixer	year	10.00	
Centrifuge Be	EUR·l^{-1}·h	6,697 Capacity [l·h^{-1}]$^{-0.44}$	(q)
Centrifuge In	EUR·l^{-1}·h	4,410 Capacity [l·h^{-1}]$^{-0.44}$	(q)
Lifetime centrifuge	year	25.00	(m)
Process: Drying			
Dryer Be	EUR	188,458 Capacity [kg$_{\text{water removed}}$·h^{-1}]$^{-0.4}$	(q)
Dryer In	EUR	122,547 Capacity [kg$_{\text{water removed}}$·h^{-1}]$^{-0.4}$	(q)
Lifetime dryer	year	15.00	
Process: Extraction			
Cost tank Be	EUR·m^{-3}	2,417 Input [m^{3}]$^{-0.43}$	(p)
Cost tank In	EUR·m^{-3}	1,572 Input [m^{3}]$^{-0.43}$	(p)
Lifetime tank	year	10.00	(p)
Cost mixer Be	EUR·W^{-1}	436 Capacity [W]$^{-0.63}$	(q)
Cost mixer In	EUR·W^{-1}	284 Capacity [W]$^{-0.63}$	(q)

Lifetime mixer	year	10.00	
Process: Filtration			
Filter Be	EUR·m^{-2}	6,139 Capacity [m^2]$^{-0.54}$	(t,u)
Filter In	EUR·m^{-2}	3,992 Capacity [m^2]$^{-0.54}$	(t,u)
Lifetime filter	year	10.00	
Process: Evaporation			
Evaporator Be	EUR·l^{-1}	22,398 Input [l]$^{-0.69}$	(q)
Evaporator In	EUR·l^{-1}	14,565 Input [l]$^{-0.69}$	(q)
Lifetime evaporator	year	10.00	
Process: Vacuum distillation			
Evaporator Be	EUR·l^{-1}	22,398 Input [l]$^{-0.69}$	(q)
Evaporator In	EUR·l^{-1}	14,565 Input [l]$^{-0.69}$	(q)
Lifetime evaporator	year	10.00	
Operational costs			
Working rate personnel Be	EUR·h^{-1}	39.20	(v)
Working rate personnel In	EUR·h^{-1}	0.75	(w)
Working hours/day	h·day^{-1}	8.00	
Working days	day	241.00	
Personnel on site ponds	person	3+(Area [ha] 30^{-1})	
Personnel on site PBR	person	3+(Area [ha] 10^{-1})	
Electricity costs (<20,000 MWh yr^{-1}) Be	EUR·MWh^{-1}	117.50	(x)
Electricity costs (>20,000 MWh yr^{-1}) Be	EUR·MWh^{-1}	93.70	(x)
Electricity costs In	EUR·MWh^{-1}	67.22	(y)
Natural gas cost Be	EUR·MWh^{-1}	39.20	(z)
Insurance cost	%I_0	1.00	(aa)
Repair/maintenance cost	%I_0	7.00	(aa)

Water purchase cost Be	EUR·m^{-3}	3.39	(ab)
Water purchase cost In	EUR·m^{-3}	0.11	(ac)
Water disposal cost	EUR·m^{-3}	2.43	(ad)
Salt price Be	EUR·t^{-1}	75.57	(ae)
CO_2 price	EUR·t^{-1}	225.00	(q)
Hexane price	EUR·t^{-1}	393.21	(af)
KNO_3 price Be	EUR·t^{-1}	1,594.30	(ag)
KNO_3 price In	EUR·t^{-1}	1,815.25	(ag)
$NaHCO_3$ price Be	EUR·t^{-1}	869.51	(ah)
$NaHCO_3$ price In	EUR·t^{-1}	295.82	(ai)
KH_2PO_4 price Be	EUR·t^{-1}	1,992.81	(aj)
KH_2PO_4 price In	EUR·t^{-1}	1,976.60	(ak)
$FeCl_3.6H_2O$	EUR·t^{-1}	488.12	
$MgSO_4$ Be	EUR·t^{-1}	797.12	(al)
$MgSO_4$ In	EUR·t^{-1}	177.49	(am)
Revenues			
Sale fertilizer	EUR·kg^{-1}	0.39	(q)
Sale β-carotene	EUR·kg^{-1}	1000.00	(an,ao,ap,aq,ar)

(a) (Caputo et al., 2005); (b) (Mercken, 2004); (c) (National Bank of Belgium); (d) (Reserve Bank of India); (e) (World Bank); (f) (OECD); (g) (PWC, 2017); (h) (R. E. Davis et al., 2014); (i) (Lundquist et al., 2010); (j) (Norsker et al., 2011); (k) (ANL; NREL; PNNL, 2012); (l) (J. N. Rogers et al., 2014); (m) (Tredici et al., 2016); (n) (Peeters et al., 2015); (o) (Chakravorty, 2013); (p) (Acién et al., 2012); (q) price quote commercial source; (r) (AZALP Pahlen Aqua Mex compleet 70 kW - Titanium); (s) (De Minister van Economische Zaken, 2013); (t) (Sikder, Roy, Dey, & Pal, 2012); (u) (Vaňková et al., 2008); (v) (Eurostat); (w) (Government of India); (x) (Eurostat); (y) (Government of India); (z) (Eurostat); (aa) (Peters et al., 2003); (ab) (VMM); (ac) (ONGC & Global Compact Network India, 2016); (ad) (VMM); (ae) (U.S. Geological Survey, 2015); (af) (Global, 2016); (ag) (MBFerts); (ah) (Intra Laboratories); (ai) (Akshar Exim Company Private Limited); (aj) (MBFerts); (ak) (Indiamart); (al) (MBFerts); (am) (Chemie-Range); (an) (Brennan & Owende, 2010); (ao) (Guedes et al., 2011); (ap) (Hejazi & Wijffels, 2004); (aq) (Pharmacompass); (ar) (Richmond, 2004).

Environmental data ETEA case study

Table A2.3 gives an overview of all environmental input data with their corresponding references which have been used in the ETEA model. The data is grouped according to the different production process steps.

Table A2.3. Environmental input parameters

Parameter	**Inventory**	**Unit**		**Characterization factor in ecoinvent (Alloc Def, U)**	**Ref/C**
General					
Labour	Energy worker-hour^{-1}	MJ	39.00	Electricity, medium voltage {BE/IN}| market for	(a)
Factory	Sizing factor		0.60		
Factory				Chemical factory, organics {RER/RoW}| construction	
Water				Tap water {Europe without Switzerland/RoW}| market for	
Seawater				Inputs from nature: water (sea)	
Water disp. Be				Wastewater, average {Europe without Switzerland}| market for wastewater, average	
Water disp. In				Emissions to water: Waste water to ocean	
Water emission				Emissions to water: water	
Electricity				Electricity, medium voltage {BE/IN}| market for	
Heat				Heat, district or industrial, natural gas {RER}| market group for	
Land use				Inputs from nature: Occupation, bare area (non-use), BE/IN	
Process: Cultivation					
Salt				Sodium chloride, powder {GLO}| market for	(b)
CO_2				Carbon dioxide, liquid {RER/RoW}| market for	(b)
$NaHCO_3$	Na_2CO_3	$kg \cdot kg^{-1}$	0.66	Soda ash, dense {GLO}| market for	(c)
$NaHCO_3$	CO_2 emission	$kg \cdot kg^{-1}$	$2E^{-4}$	Emissions to air: Carbon dioxide	(d)
$NaHCO_3$	Water emission	$kg \cdot kg^{-1}$	$6E^{-4}$	Emissions to air: water	(d)
$NaHCO_3$	Na_2CO_3 emission	$kg \cdot kg^{-1}$	0.0013	Emissions to air: Sodium carbonate	(d)

$NaHCO_3$	CO_2 to water	kg·kg^{-1}	0.013	Emissions to water: Carbon dioxide	(d)
$NaHCO_3$	Water to water	kg·kg^{-1}	0.0054	Emissions to water: water	(d)
$NaHCO_3$	Na_2CO_3 to water	kg·kg^{-1}	0.014	Emissions to water: Sodium	(d)
$NaHCO_3$	Na_2CO_3 to water	kg·kg^{-1}	0.018	Emissions to water: Carbonate	(d)
$NaHCO_3$	Transport lorry	tkm·kg^{-1}	0.10	Transport, freight, lorry, unspecified {GLO}| market for	(e)
$NaHCO_3$	H_2O	kg·kg^{-1}	0.11	Tap water {Europe without Switzerland/RoW}| market for	(c)
$NaHCO_3$	CO_2	kg·kg^{-1}	0.28	See CO_2 Be/CO_2 In	(c)
$NaHCO_3$	Electricity	kWh·kg^{-1}	0.33	Electricity, medium voltage {BE/IN}| market for	(d,e)
$NaHCO_3$	Chemical factory	p·kg^{-1}	$4E^{-10}$	Chemical factory, organics {RER/RoW}| construction	(d)
$NaHCO_3$	Plastic packaging	kg·kg^{-1}	0.002	See Auxiliary: Plastic packaging Be/In	(f)
$NaHCO_3$	Transport train	tkm·kg^{-1}	0.60	Transport, freight train {Europe without Switzerland/GLO}| market for	(e)
KH_2PO_4	P_2O_5	kg·kg^{-1}	0.52	Phosphate fertiliser, as P2O5 {GLO}| market for	(g)
KH_2PO_4	K_2O	kg·kg^{-1}	0.34	Potassium fertiliser, as K2O {GLO}| market for	(g)
KH_2PO_4	Transport lorry	tkm·kg^{-1}	0.10	Transport, freight, lorry, unspecified {GLO}| market for	(e)
KH_2PO_4	Plastic packaging	kg·kg^{-1}	0.002	See Auxiliary: Plastic packaging Be/In	(f)
KH_2PO_4	Transport train	tkm·kg^{-1}	0.60	Transport, freight train {Europe without Switzerland/GLO}| market for	(e)
KNO_3				Potassium nitrate {GLO}| market for	(b)
$MgSO_4$				Magnesium sulfate {GLO}| market for	(b)
$FeCl_3.6H_2O$				Iron (III) chloride, without water, in 40% solution state {GLO}| market for	(b)
CO_2 em.				Emissions to water: Carbon dioxide	
N_2O em.				Emission to air: Dinitrogen monoxide	
NH_3 em.				Emissions to air: Ammonia	
O_2 em.				Emissions to air: Oxygen	
MPS	Tank	p·p^{-1}	1.00	1 p Hot water tank, 600l {CH/RoW}| production	(b)
MPS	Sizing factor		0.57		(i)
CO_2 supply	Pump	p·p^{-1}	1.00	Pump, 40W {CH/RoW}| production [a]	(b)
CO_2 supply	Sizing factor		0.62		(h)

Heat exch.	Capacity	kW·p^{-1}	70.00		(j)
Heat exch.	Sizing factor		0.60		(h)
Heat exch.	Transport, lorry	tkm·p^{-1}	0.88	Transport, freight, lorry, unspecified {GLO}| market for	(e)
Heat exch.	Titanium	kg·p^{-1}	8.80	Titanium, primary {GLO}| market for	(j)
Heat exch.	Titanium waste	kg·p^{-1}	8.80	See Auxiliary: Titanium waste Be/In	
Heat exch.	Packaging plastic	kg·p^{-1}	0.06	See Auxiliary: Plastic packaging Be/In	(f)
Heat exch.	Packaging paper	kg·p^{-1}	0.06	See Auxiliary: Paper packaging Be/In	(f)
Heat exch.	Transport, train	tkm·p^{-1}	5.28	Transport, freight train {Europe without Switzerland/GLO}| market for	(e)
IPS[§]					
Liner	Capacity	ha·p^{-1}	0.81		(k)
Liner	Sizing factor		1.00		(h)
Liner	Material		HDPE		(l)
Liner	Thickness	mil	40.00		(l)
Liner	Width	m	12.20		(k)
Liner	Additional height	m	0.05		
Liner*	Liner depth	m	0.15		(m)
Liner	Transport lorry	tkm·p^{-1}	8,792	Transport, freight, lorry, unspecified {GLO}| market for	(e)
Liner	HDPE	kg·p^{-1}	80,792	Polyethylene, high density, granulate {GLO}| market for	(b)
Liner	HDPE waste	kg·p^{-1}	80,792	See Auxiliary: HDPE waste Be/In	
Liner	Transport train	tkm·p^{-1}	48,475	Transport, freight train {Europe without Switzerland/GLO}| market for	(e)
PW	Capacity	ha·p^{-1}	0.81		(k)
PW	Sizing factor		1.00		(h)
PW	Paddle width	m·p^{-1}	12.20		(k)
PW	Paddle thickness	m·p^{-1}	0.01		
PW	Paddle radials	#·p^{-1}	8.00		(n)
PW*	Paddle depth	m·p^{-1}	15.00		(m)
PW	Paddle material		HDPE		(o)
PW	Motor material		Steel		(o)

PW	Transport lorry	tkm·p^{-1}	22.43	Transport, freight, lorry, unspecified {GLO}| market for	(e)
PW	HDPE production	kg·p^{-1}	141.31	Polyethylene, high density, granulate {GLO}| market for	(b)
PW	Steel production	kg·p^{-1}	83.00	Steel, chromium steel 18/8 {GLO}| market for	(b,p)
PW	HDPE waste	kg·p^{-1}	141.31	See Auxiliary: HDPE waste Be/In	
PW	Steel waste	kg·p^{-1}	83.00	See Auxiliary: Steel waste Be/In	
PW	Transport train	tkm·p^{-1}	134.58	Transport, freight train {Europe without Switzerland/GLO}| market for	(e)
PBR	Capacity	m³·p^{-1}	2.54		(q)
PBR	Int./ext. diam.	m·m^{-1}	0.88		(q)
PBR	Transport lorry	tkm·kg^{-1}	70.43	Transport, freight, lorry, unspecified {GLO}| market for	(e)
PBR	HDPE	kg·p^{-1}	704.26	Polyethylene, high density, granulate {GLO}| market for	(b)
PBR	HDPE waste	kg·p^{-1}	704.26	See Auxiliary: HDPE waste Be/In	
PBR	Transport train	tkm·kg^{-1}	422.56	Transport, freight train {Europe without Switzerland/GLO}| market for	(e)
Blower	Pump	p·p^{-1}	1.00	Pump, 40W {CH/RoW}| production [a]	(b)
Process: Membrane filtration					
IPC®	Capacity	m²·p^{-1}	1.00		
IPC®	Sizing factor		1.00		
IPC®	Water	l·m^{-2}	20.50	Tap water {Europe without Switzerland/RoW}| market for	
IPC®	Glycerine	g·m^{-2}	45.00	Glycerine {GLO}| market for	
IPC®	PES	g·m^{-2}	100.00	Polycarbonate {GLO}| market for	
IPC®	PVP	g·m^{-2}	50.00	See Auxiliary: PVP prod. Be/In	
IPC®	NaOCl	g·m^{-2}	5.00	Sodium hypochlorite, without water, in 15% solution state {GLO}| market for	
IPC®	NEP	kg·m^{-2}	6,944	N-methyl-2-pyrrolidone {GLO}| market for	
IPC®	Cl2 to air	g·m^{-2}	5.00	Emissions to air: Chlorine	
IPC®	AOX to water	g·m^{-2}	0.01	Emissions to water: AOX, Adsorbable Organic Halogen as Cl	
IPC®	NaOCl to water	g·m^{-2}	5.00	Emissions to water: Sodium hypochlorite	
IPC®	NEP to water	g·m^{-2}	305	Emissions to water: Organic compounds (unspecified)	
IPC®	Electricity	kWh·m^{-2}	1.11	Electricity, medium voltage {BE/IN}| market for	

IPC®	PVP to waste	g·m^{-2}	49.00	See Auxiliary: pl. pack. Waste Be/In	
IPC®	PES to waste	g·m^{-2}	5.00	See Auxiliary: pl. pack. Waste Be/In	
IPC®	Glycerine to waste	g·m^{-2}	45.00	Wastewater, average {Europe without Switzerland/RoW}| market for wastewater, average	
IPC®	Wastewater+NEP	l·m^{-2}	27.81	Wastewater, average {Europe without Switzerland/RoW}| market for wastewater, average	
Tanks	Tank	p·p^{-1}	1.00	1 p Hot water tank, 600l {CH/RoW}| production	(b)
Pumps	Pump	p·p^{-1}	1.00	Pump, 40W {CH/RoW}| production [a]	(b)
Control eq.	Sizing factor		1.00	Electronic component, passive, unspecified {GLO}| market for	
Laptop	Sizing factor		1.00	Computer, laptop {GLO}| market for	
Process: Harvesting					
Centrifuge	Sizing factor		0.56		(h)
Centrifuge	Capacity	l·h^{-1}	3,750		(r)
Centrifuge	Steel	kg·p^{-1}	3,750	Steel, chromium steel 18/8 {GLO}| market for	(b,r)
Centrifuge	Steel waste	kg·p^{-1}	3,750	See Auxiliary: Steel waste Be/In	(r)
Process: Washing					
Tank	Tank	p·p^{-1}	1.00	1 p Hot water tank, 600l {CH/RoW}| production	(b)
Mixer	Pump	p·p^{-1}	1.00	Pump, 40W {CH/RoW}| production [a]	(b)
Centrifuge	Centrifuge	p·p^{-1}	1.00	See Centrifuge of Process: Harvesting	
Process: Drying					
Spray dryer	Capacity	l·s^{-1}	1.00		(s)
Spray dryer	Sizing factor		0.60		(h)
Spray dryer	Transport lorry	tkm·unit^{-1}	29,895	Transport, freight, lorry, unspecified {GLO}| market for	(s)
Spray dryer	Steel	kg·p^{-1}	22,900	Steel, chromium steel 18/8 {GLO}| market for	(b,s)
Spray dryer	Glass fibre	kg·p^{-1}	96	Glass fibre {GLO}| market for	(b,s)
Spray dryer	Steel waste	kg·p^{-1}	22,900	See Auxiliary: Steel waste Be/In	(s)
Spray dryer	Glass fiber waste	kg·p^{-1}	96	See Auxiliary: Glass fibre waste Be/	(s)
Spray dryer	Electric welding	m·kg^{-1}	134	Welding, arc, steel {RER/RoW}| processing	(s)
Spray dryer	Rolling steel	kg·kg^{-1}	22,900	Sheet rolling, chromium steel {RER/RoW}| processing	(s)
Process: Extraction					

C_6H_{14}				Hexane {GLO}| market for	(b)
Em. C_6H_{14}				Emissions to air: Hexane	
Tank	Tank	$p\cdot p^{-1}$	1.00	1 p Hot water tank, 600l {CH/RoW}| production	(b)
Mixer	Pump	$p\cdot p^{-1}$	1.00	Pump, 40W {CH/RoW}| production [a]	(b)
Process: Filtration					
Membrane	Membrane	$p\cdot p^{-1}$	1.00	See IPC®	
Process: Evaporation					
Ref. fert.	N-fertilizer	$kg\cdot kg^{-1}$	0.04	Nitrogen fertiliser, as N {GLO}| market for	(b,t)
Ref. fert.	P-fertilizer	$kg\cdot kg^{-1}$	0.001	Phosphate fertiliser, as P2O5 {GLO}| market for	(b,t)
Evaporator	Spray dryer	$p\cdot p^{-1}$	1.00	See Spray Dryer Process: Drying	(b)
Process: Vacuum distillation					
Distiller	Spray dryer	$p\cdot p^{-1}$	1.00	See Spray Dryer Process: Drying	(b)
Ref β-carotene					(u)
Process: Distribution					
Pl. pack.	Pl. pack.prod.	$kg\cdot kg^{-1}$	1.00	Packaging film, low density polyethylene {GLO}| market for	
Pl. pack.	Pl. pack. waste	$kg\cdot kg^{-1}$	1.00	See Auxiliary: plastic packaging waste Be/In	
Steel pack.	Steel	$kg\cdot kg$	1.00	Steel, chromium steel 18/8 {GLO}| market for	(b)
Steel pack.	Steel waste	$kg\cdot kg^{-1}$	1.00	See Auxiliary: Steel waste Be/In	
P. pack.	Pack. P. prod.	$kg\cdot kg^{-1}$	1.00	Kraft paper, unbleached {GLO}| market for	
P. pack.	Pack. P. waste	$kg\cdot kg^{-1}$	1.00	See Auxiliary: Paper pack. Waste Be & Paper pack. Waste In	
Lorry				Transport, freight, lorry, unspecified {GLO}| market for	
Train				Transport, freight train {Europe without Switzerland/GLO}| market for	
Inland barge				Transport, freight, inland waterways, barge {GLO}| market for	
Transoc. ship				Transport, freight, sea, transoceanic ship {GLO}| market for	
Auxiliary					
Pl. Waste	Transport lorry	$tkm\cdot kg^{-1}$	0.019	Transport, freight, lorry, unspecified {GLO}| market for	(v)
Pl. Waste	Transport train	$tkm\cdot kg^{-1}$	0.011	Transport, freight train {Europe without Switzerland/GLO}| market for	(v)
Pl. Waste Be	Recycled plastic	$kg\cdot kg^{-1}$	0.85	See Auxiliary: Plastic recycling Be	(w)

Pl. Waste Be	Incinerated plastic	$kg\cdot kg^{-1}$	0.11	Disposal, polyethylene, 0.4% water, to municipal incineration/CH	(w)
Pl. Waste Be	Landfilled plastic	$kg\cdot kg^{-1}$	0.05	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH	(w)
Pl. Waste In	Recyled plastic	$kg\cdot kg^{-1}$	0.47	See Auxiliary: Plastic recycling In	(x)
Pl. Waste In	Incinerated plastic	$kg\cdot kg^{-1}$	0.06	Disposal, polyethylene, 0.4% water, to municipal incineration/CH	(v)
Pl. Waste In	Landfilled plastic	$kg\cdot kg^{-1}$	0.47	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH	
Pl. recycl.	Replaced pl. (QF)	$kg\cdot kg^{-1}$	0.75	Packaging film, low density polyethylene {GLO}| market for	(y)
Pl. recycl.	Electricity	$kWh\cdot kg^{-1}$	0.60	Electricity, medium voltage {BE/IN}| market for	(z)
Tit. waste	Transport lorry	$tkm\cdot kg^{-1}$	0.019	Transport, freight, lorry, unspecified {GLO}| market for	(aa)
Tit. waste	Transport train	$tkm\cdot kg^{-1}$	0.011	Transport, freight train {Europe without Switzerland/GLO}| market for	(aa)
Tit. waste Be	Recycled tit.	$kg\cdot kg^{-1}$	0.9998	See Auxiliary: Tit. Recycle. In	(w)
Tit. waste Be	Landfilled tit.	$kg\cdot kg^{-1}$	0.0002	Disposal, inert waste, 5% water, to inert material landfill/CH U	(w)
Tit. waste In	Recycled tit.	$kg\cdot kg^{-1}$	0.25	See Auxiliary: Tit. Recycle. In	(ab)
Tit. waste In	Landfilled tit.	$kg\cdot kg^{-1}$	0.75	Disposal, inert waste, 5% water, to inert material landfill/CH U	(ab)
Tit. rec.	Replaced tit. (QF)	$kg\cdot kg^{-1}$	1.00	Titanium, primary {GLO}| market for	(y)
Tit. rec.	Electricity	$GJ\cdot kg^{-1}$	0.026	Electricity, medium voltage {BE/IN}| market for	(ac)
P. Waste	Transport, lorry	$tkm\cdot kg^{-1}$	0.019	Transport, freight, lorry, unspecified {GLO}| market for	(v)
P. Waste	Transport train	$tkm\cdot kg^{-1}$	0.011	Transport, freight train {Europe without Switzerland/GLO}| market for	(v)
P. Waste	Recycled paper	$kg\cdot kg^{-1}$	0.9994	Paper (waste treatment) {GLO}| recycling of paper	(w)
P. Waste	Incinerated paper	$kg\cdot kg^{-1}$	0.0005	Disposal, packaging paper, 13.7% water, to municipal incineration/CH U	(w)
P. Waste	Recycled paper	$kg\cdot kg^{-1}$	0.14	Paper (waste treatment) {GLO}| recycling of paper	
P. Waste	Landfilled paper	$kg\cdot kg^{-1}$	0.86	Disposal, packaging paper, 13.7% water, to sanitary landfill/CH U	
HDPE waste	Transport lorry	$tkm\cdot kg^{-1}$	0.019	Transport, freight, lorry, unspecified {GLO}| market for	(v)
HDPE waste	Transport train	$tkm\cdot kg^{-1}$	0.011	Transport, freight train {Europe without Switzerland}| market for	(v)
HDPE waste Be	Recycled HDPE	$kg\cdot kg^{-1}$	0.85	See Auxiliary: HDPE recycle. Be	(w)
HDPE waste Be	Incinerated HDPE	$kg\cdot kg^{-1}$	0.11	Disposal, polyethylene, 0.4% water, to municipal incineration/CH U	(w)
HDPE waste Be	Landfilled HDPE	$kg\cdot kg^{-1}$	0.05	Disposal, polyethylene, 0.4% water, to sanitary landfill/CH U	(w)

HDPE waste In	Recycled HDPE	kg·kg^{-1}	0.47	See Auxiliary: HDPE recycle. In	(x)
HDPE waste In	Landfilled HDPE	kg·kg^{-1}	0.53	Disposal, polyethylene, 0.4% water, to sanitary landfill/CH U	(x)
HDPE rec.	Electricity	kWh·kg^{-1}	0.60	Electricity, medium voltage {BE/IN}| market for	(z)
HDPE rec.	Replaced HDPE (QF)	kg·kg^{-1}	0.75	Polyethylene, high density, granulate {GLO}| market for	(b,y)
Steel waste	Transport lorry	tkm·kg^{-1}	0.0193	Transport, freight, lorry, unspecified {GLO}| market for	(aa)
Steel waste	Transport train	tkm·kg^{-1}	0.011	Transport, freight train {Europe without Switzerland/GO}| market for	(aa)
Steel waste Be	Recycled Steel	kg·kg^{-1}	0.9998	See Auxiliary: Recycle steel Be	(w)
Steel waste Be	Landfilled Steel	kg·kg^{-1}	0.0002	Scrap steel {CH}| treatment of, inert material landfill	(w)
Steel waste In	Recycled Steel	kg·kg^{-1}	0.25	See Auxiliary: Recycle steel In	(ab)
Steel waste In	Landfilled Steel	kg·kg^{-1}	0.75	Scrap steel {CH}| treatment of, inert material landfill	(ab)
Rec. Steel	Electricity	GJ·kg^{-1}	0.023	Electricity, medium voltage {BE/IN}| market for	(aa,ac)
Rec. Steel	Replaced steel (QF)	kg·kg^{-1}	1.00	Steel, chromium steel 18/8 {GLO}| market for	(b,y)
PVP prod.	1,4-butanediol	kg·kg^{-1}	0.80	Butane-1,4-diol {GLO}| market for	(ad)
PVP prod.	Acetylene	kg·kg^{-1}	0.23	Acetylene {GLO}| market for | Alloc Def, U	(ad)
PVP prod.	Hydrogen to air	kg·kg^{-1}	0.04	Emissions to air: Hydrogen	(ad)
PVP prod.	Water to water	kg·kg^{-1}	0.16	Emissions to water: water	(ad)
PVP prod.	Ammonia	kg·kg^{-1}	0.15	Ammonia, liquid {RER/RoW}| market for	(ad)
Gl. f. waste	Transport lorry	tkm·kg^{-1}	0.0193	Transport, freight, lorry, unspecified {GLO}| market for	(aa)
Gl. f. waste	Transport train	tkm·kg^{-1}	0.011	Transport, freight train {Europe without Switzerland/GLO}| market for	(aa)
Gl. f. waste Be	Recycled gl. f.	kg·kg^{-1}	0.94	See Auxiliary: Glass recycling Be	(w)
Gl. f. waste Be	Incinerated gl.f.	kg·kg^{-1}	0.01	Waste glass {Europe without Switzerland}| treatment of waste glass, municipal incineration	(w)
Gl. f. waste Be	Landfilled gl. f.	kg·kg^{-1}	0.05	Disposal, glass, 0% water, to inert material landfill/CH U	(w)
Gl. f. waste In	Landfilled gl. f.e	kg·kg^{-1}	1.00	Disposal, glass, 0% water, to inert material landfill/CH U	
Gl. f. rec. Be	Replaced gl. f. (QF)	kg·kg^{-1}	1.00	Glass fibre {GLO}| market for	(b,y)

(a) (T. W. Zhang & Dornfeld, 2007); (b) adapted to Belgian and Indian conditions; (c) stoichiometry with efficieny of 95%; (d) (Hischier et al., 2004); (e) (Frischknecht et al., 2004); (f) (B. P. Weidema et al., 2013); (g) (MBFerts); (h) economic regression function ; (i) (Peters et al., 2003); (j) (AZALP Pahlen Aqua

Mex compleet 70 kW - Titanium); (k) (J. N. Rogers et al., 2014); (l) (R. E. Davis et al., 2014); (m) (Tafreshi & Shariati, 2006); (n) (Lundquist et al., 2010); (o) (Collet et al., 2014); (p) (Rotary power); (q) (Acién et al., 2012); (r) (Flottweg); (s) (Ciesielski & Zbicinski, 2010); (t) (Greenwell, Laurens, Shields, Lovitt, & Flynn, 2009); (u) (Bauer, Köhler, Neumann, Poll, & Winkler, 2003; Bonrath, Kuenzi, & Aquino, 2010; Bonrath, Scheer, Tschumi, & Zenhaeusern, 2004; Drapal et al., 2001; Feng, Yin, Wang, Xie, & Jiang, 2012; Herbert, 1948; Isler, Lindlar, Montavon, Rüegg, & Zeller, 1956; Khusnutdinov, Bayguzina, & Aminov, 2016; Litzmann, Repke, Hanselmann, & Heyl, 2012; Markovich, 1998; Midland & Gallou, 2001; Newman & Vander Zwan, 1973; Patent, 2009b, 2012, 2014; Reardan & Combe, 2007; Reichart, Tekautz, & Kappe, 2012; Shahabuddin, Subhash, Manohar, & Mahadeo, 2011; Slotte, Metha, & Zevenhoven, 2015; Tang & Zhao, 2014; Urban & Bakshi, 2009; Vani, Chida, Srinivasan, Chandrasekharam, & Singh, 2006; W. Weiss, Dawidowski, Pleyer, & KRÜCKEL, 2005; 印俊, 2004); (v) Waste polyethylene {Europe without Switzerland/RoW}| market for waste polyethylene; (w) (Eurostat); (x) (Mutha, Patel, & Premnath, 2006); (y) (Gala, Raugei, & Fullana-i-Palmer, 2015); (z) PE (waste treatment) {GLO}| recycling of PE; (aa) Scrap steel {Europe without Switzerland}| market for scrap steel (ab) (Darabshaw, 2015); (ac) (Johnson, Reck, Wang, & Graedel, 2008); (ad) (Pourzahedi & Eckelman, 2015). Abbreviations: Ref/C = Reference/Comment; pack. = packaging; rec. = recycling; pl. = plastic; QF = quality factor; em. = emission; exc. = exchanger; tit. = titanium; p. = paper; prod. = production; PW: paddlewheel; eq. = equipment; transf. = transformation; MPS = medium preparation system; fr. = fraction; sep. = separation; SSP = single superphosphate; TSP = triple superphosphate; Int./ext. diam. = internal/external diameter; disp. = disposal; transoc. = transoceanic; [§] IPS = Inoculum production system; the impact of the first cultivation stage of the third scenario is scaled to produce the corresponding amount of inoculum; * In second cultivation stage: height = 12 m.

Growth parameters ETEA case study

A logistic curve as defined in Equation 1 was used to model the growth of *Dunaliella salina.*

$$N(t) = \frac{K}{1+\left(\frac{K}{N_0}-1\right)x\ e^{-rt}} \qquad (1)$$

In this equation, K is the maximum biomass concentration, N(t) is the biomass concentration at time t_o, r is the maximum specific growth rate, and N_0 is the initial biomass concentration. The used values for this parameters are based on the cultivation experiments of Prieto et al. (2011), Tafreshi and Shariati (2006), (M. García-González et al., 2003), Z. Wu et al. (2017) and Mercedes García-González et al. (2005). The algae were grown in the first stage until they reached 70% of the maximum concentration. In the Belgian open pond scenario, a correction factor equaling the ratio of the solar irradiation was used to lower the specific growth rate. In the second stage, the cultivation time (t) was six days in open ponds and five days in the PBR. The main growth parameters are summarized in Table A2.4. The growth curves for the different scenarios are illustrated in Figure A2.1.

Table A2.4. Main growth parameters

	Unit	1 Be	2 Be	3 Be	1 In	2 In	3 In
K	$g{\cdot}l^{-1}$	0.5	0.5	2	0.5	0.5	2
N_0	$g{\cdot}l^{-1}$	0.06	0.06	0.23	0.06	0.06	0.23
$r_{stage\ 1}$	day^{-1}	0.12	0.12	0.35	0.25	0.25	0.35
$r_{stage\ 2}$	day^{-1}	0.08	0.08	0.23	0.17	0.17	0.23
$t_{stage\ 1}$	days	23	23	9	12	12	9
$t_{stage\ 1}$	days	6	6	5	6	6	5

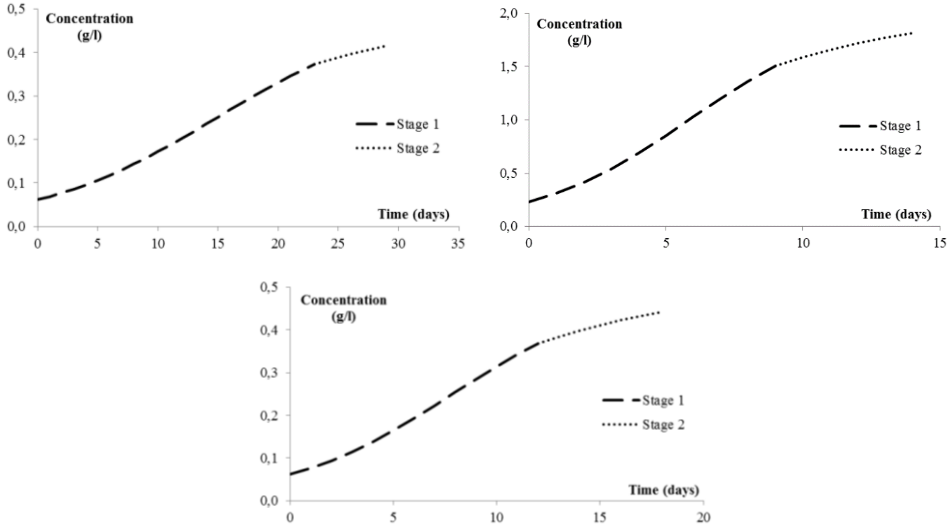

Figure A2.1 Growth curve scenario 1 Be and 2 Be; 1 In and 2 In; 3 Be and 3 In

Process flow diagrams ETEA case study

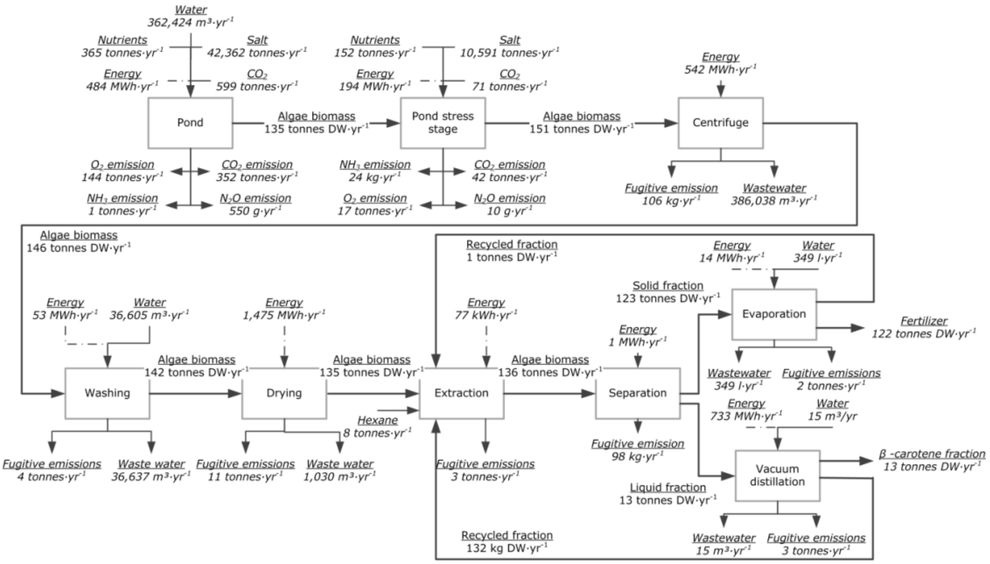

Figure A2.2. PFD scenario 1 Be

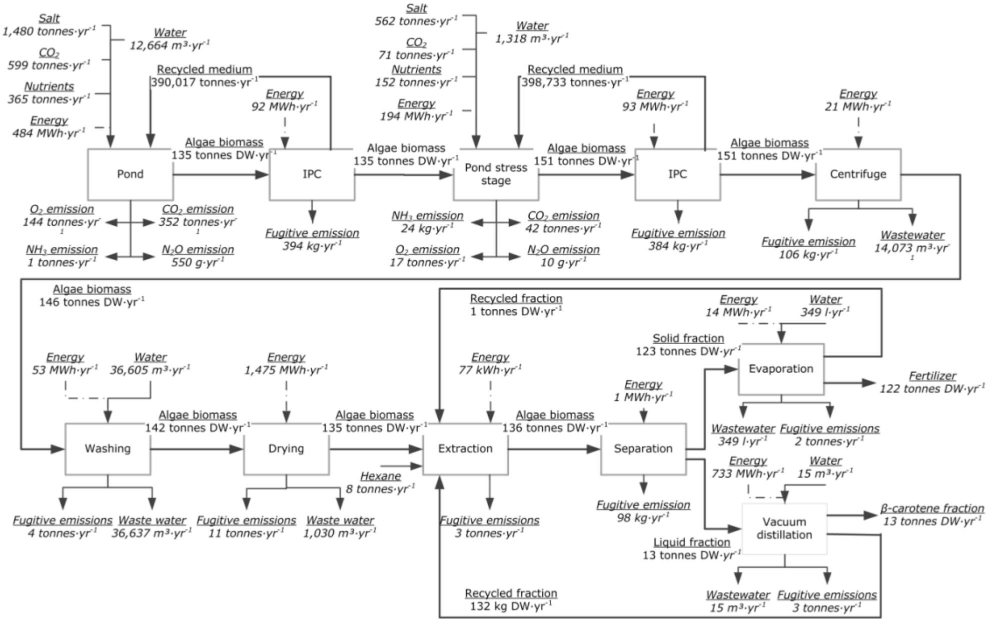

Figure A2.3. PFD scenario 2 Be

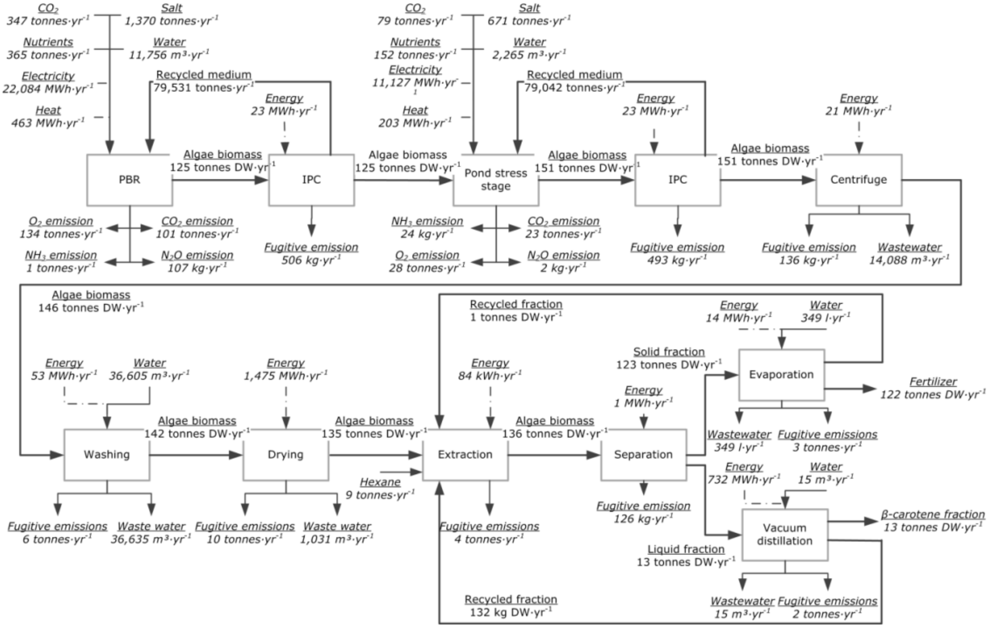

Figure A2.4. PFD scenario 3 Be

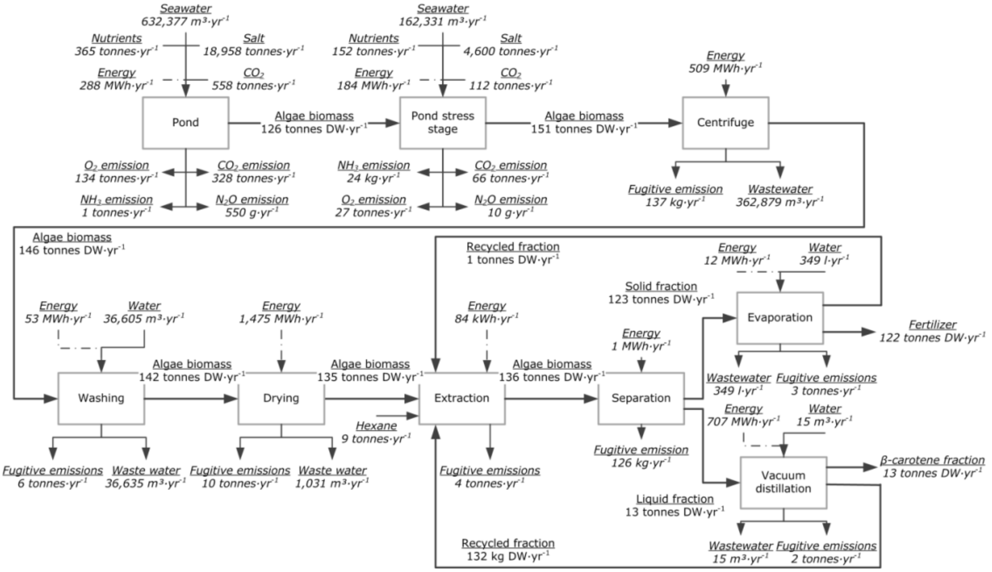

Figure A2.5. PFD scenario 1 In

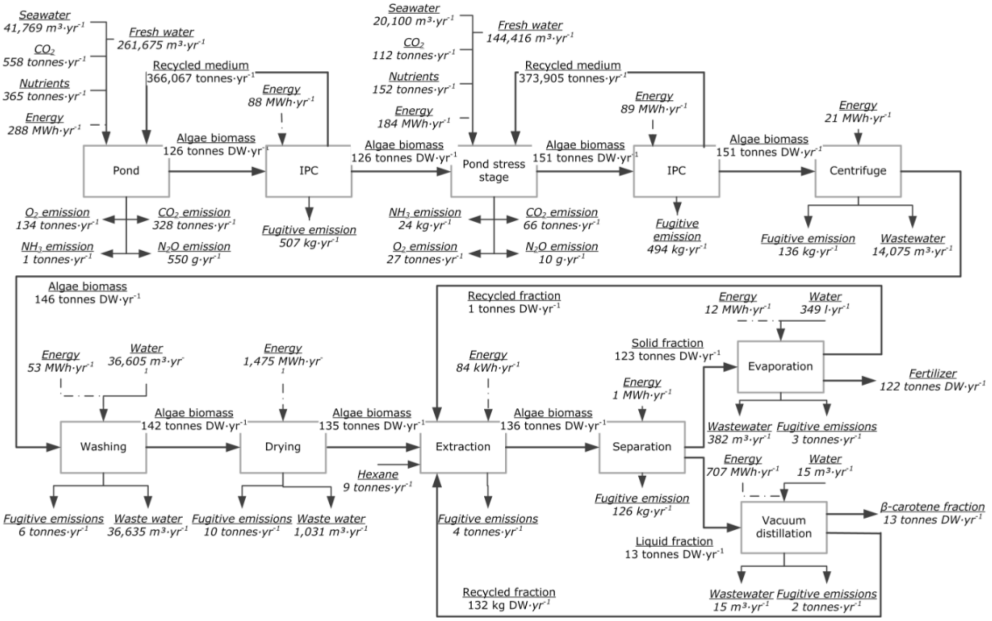

Figure A2.6. PFD scenario 2 In

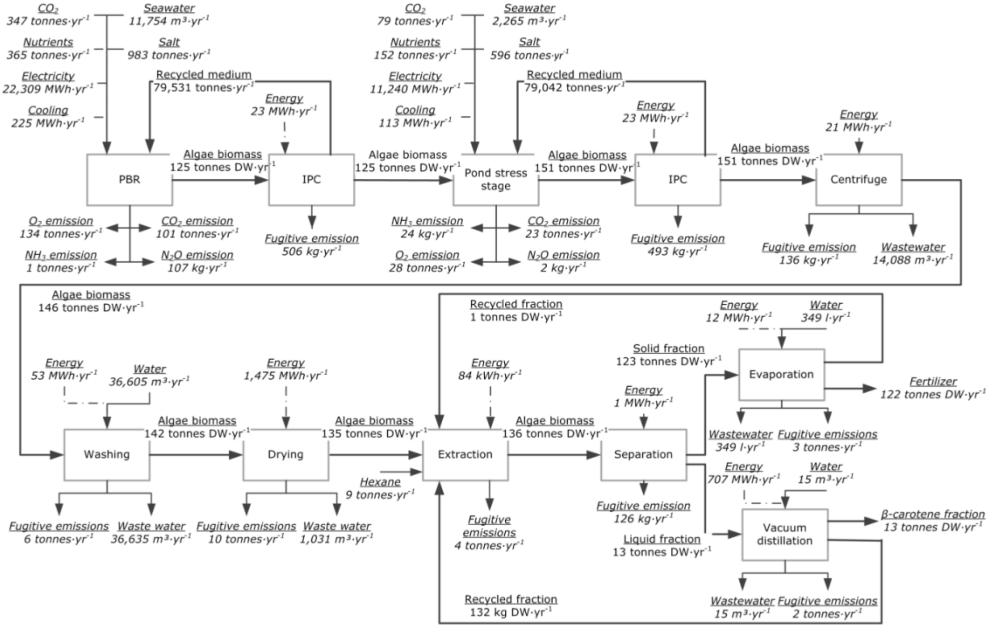

Figure A2.7. PFD scenario 3 In

Sensitivity analysis other environmental impact indicators ETEA case study

Table A2.5. Sensitivity analysis scenario other environmental impact indicators [%]

Scenario 1 Be	ODP	IRP	HOFP	EOFP	FEP	TETP	FETP	METP	HTPc	HTPnc	LOP	SOP	WCP
Max. conc.[a] [g·l^{-1}]		-18	-17	-18	-18	-17	-16	-17	-18	-16	-17	-17	
r[b] [day^{-1}]		-12	-10	-10	-10		-10	-10	-11	-10	-10	-10	
Sal. stress[c] [M]		+20	+23	+22	+22	+24	+23	+23	+22	+24	+23	+23	
Salt [imp.·kg^{-1}][d]		+19	+22	+22	+22	+23	+24	+23	+20	+24	+22	+23	+10
Solar irr.[e] [%]		-10	-10	-10	-10				-10			-10	
Water [imp.·kg^{-1}][d]													+26
W. disp.[f] [imp. ·m^{-3}][d]													+23
KNO_3 [g·g^{-1}]	+28												
KNO_3 [imp.·kg^{-1}][d]	+30												
Scenario 2 Be	**ODP**	**IRP**	**HOFP**	**EOFP**	**FEP**	**TETP**	**FETP**	**METP**	**HTPc**	**HTPnc**	**LOP**	**SOP**	**WCP**
Max. conc.[a] [g·l^{-1}]	-23		-21	-19	-14	-10	-15	-14	-15	-13	-12	-14	
r[b] [day^{-1}]	-13		-12	-11									
Sal. stress[c] [M]					+11		+11	+11		+14		+11	
Salt [imp.·kg^{-1}][d]					+20	+15	+21	+21	+17	+25		+19	
Solar irr.[e] [%]	-13		-12	-11									
Water [imp.·kg^{-1}][d]													+33
W. disp.[f] [imp.·m^{-3}][d]													+27
IPC® conc.[g] [g·l^{-1}]										-10			

El.[h] [imp.·kWh^{-1}][d]		+38									+25		
KNO_3 [imp.·kg^{-1}][d]	+30												
CO_2 upt.[i] [%]						-16							
$CO_{2\ req.}$[j] [g·g^{-1}]						+15							
Scenario 3 Be	ODP	IRP	HOFP	EOFP	FEP	TETP	FETP	METP	HTPc	HTPnc	LOP	SOP	WCP
Max. conc.[a] [g·l^{-1}]		-20	-21	-21	-21	-20	-21	-21	-21	-20	-20	-21	-19
El.[h] [imp.·kWh^{-1}][d]		+22	+23	+21	+22	+20	+23	+23	+22	+20	+23	+22	+19
Mix. Cul.[k] [W·m^{-3}]		+18	+17	+18	+18	+17	+17	+18	+18	+17	+18	+18	+16
Mix. Cul.[k] [h]		+19	+18	+18	+18	+17	+18	+18	+18	+18	+19	+19	+16
KNO_3 [g·g^{-1}]	+27												
KNO_3 [imp. kg^{-1}][d]	+25												
Scenario 1 In	ODP	IRP	HOFP	EOFP	FEP	TETP	FETP	METP	HTPc	HTPnc	LOP	SOP	WCP
Max. conc.[a] [g·l^{-1}]		-13	-16	-16	-16	-13	-15	-15	-15	-14	-14	-13	-32
r[b] [day^{-1}]													-11
Salt [imp.·kg^{-1}][d]		+20	+14	+14	+14	+19	+19		+18	+19	+19	+19	
Solar irr.[e] [%]								+19					
Cultivation [days]		-10				-10	-10	-10	-10	-10	-10	-10	
Sal. water[c] [g·l^{-1}]		-23	-15	-15	-16	-22	-22	-22	-20	-21	-22	-22	
Water [imp.·kg^{-1}][d]													+29
KNO_3 [g·g^{-1}]	+41												
KNO_3 [imp.·kg^{-1}][d]	+40												
Scenario 2 In	ODP	IRP	HOFP	EOFP	FEP	TETP	FETP	METP	HTPc	HTPnc	LOP	SOP	WCP

Max. conc.[a] [g·l^{-1}]		-12					-11	-10	-12			-16	-18
El.[f] [imp.·kWh^{-1}][d]		+29	+42	+40	+45		+32	+31	+26	+33	+40		
Water [imp.·kg^{-1}][d]													+17
Op. rate[l] [%]												-17	-17
Evap.[m] [m³·m^{-2}]													+12
CO_2 [imp.·kg^{-1}][d]						+26							
CO_2 upt.[i] [%]						-25							
$CO_{2\ req.}$[j] [g·g^{-1}]						+25							
W. conc.[n] [g·l^{-1}]			-12	-12	-12					-10	-11		
KNO_3 [g·g^{-1}]	+43												
KNO_3 [imp.·kg^{-1}][d]	+43												
Drying E.[o] [GJ·t^{-1}]			+11	+10	+11								
Scenario 3 In	ODP	IRP	HOFP	EOFP	FEP	TETP	FETP	METP	HTPc	HTPnc	LOP	SOP	WCP
Max. conc.[a] [g·l^{-1}]	-13	-21	-21	-21	-21	-20	-22	-20	-20	-21	-20	-21	-21
El.[f] [imp.·kWh][d]	+13	+22	+23	+22	+29	+23	+22	+23	+23	+23	+23	+19	+21
Mix. Cul.[k] [h]	+12	+20	+20	+20	+19	+18	+19	+20	+20	+20	+19	+17	+18
Mix. Cul.[k] [W·m^{-3}]	+11	+19	+19	+19	+19	+18	+18	+18	+19	+19	+19	+16	+19
KNO_3 [g·g^{-1}]	+20												
KNO_3 [imp.·kg^{-1}][d]	+16												

[a] Max. conc. = Maximum microalgae concentration during cultivation; [b] r = maximum specific growth rate; [c] Sal. = salinity; [d] imp. = impact; [e] Solar irr. = Solar irradiation correction factor; [f] W. disp. = water disposal; [g] IPC® conc. = IPC® membrane end concentration; [h] El. = Electricity; [i] CO_2 upt. = CO_2 uptake rate; [j] $CO_{2\ req.}$ = CO_2 requirement biomass; [k] Mix. Cul. = Mixing during cultivation; [l] Op. rate = operational rate; [m] Evap. = water evaporation; [n] W. conc. = biomass concentration after washing step; [o] E. = Energy.

Environmental impact different functional units and allocation assumptions ETEA case study

Table A2.6. Environmental results alternative functional units

Functional unit = 1 kg β-carotene, mass allocation

Parameter[a]	Unit	1 Be	2 Be	3 Be	1 In	2 In	3 In	Ref Be	Ref In
GWP	10^{2} kg CO_2-eq	10	2	11	9	5	38	23	24
ODP	10^{-4} kg CFC_{11}-eq	14	6	19	12	10	18	63	63
IRP	10^{1} kBq Co-60-eq	41	9	117	14	2	10	8	6
HOFP	10^{-1} kg NOx-eq	27	4	17	23	13	98	38	39
PMFP	10^{-1} kg PM2.5-eq	16	2	9	41	33	306	27	31
EOFP	10^{-1} kg NOx-eq	28	4	18	24	14	99	39	40
TAP	10^{-1} kg SO_2-eq	46	7	28	47	30	219	208	213
FEP	10^{-2} kg P-eq	66	8	29	55	31	232	56	56
TETP	10^{-1} kg 1,4-DCB-eq	25	4	9	14	5	10	10	10
FETP	10^{1} kg 1,4-DCB-eq	8	1	4	5	2	8	3	3
METP	10^{1} kg 1,4-DCB-eq	12	2	5	7	3	11	5	5
HTPc	10^{1} kg 1,4-DCB-eq	8	1	3	5	3	13	5	5
HTPnc	10^{4} kg 1,4-DCB-eq	10	1	3	6	2	8	3	3
LOP	10^{1} m²·yr	9	1	12	4	1	7	3	2
SOP	10^{0} kg Cu-eq	13	2	7	6	2	3	6	6
FFP	10^{1} kg oil-eq	26	5	31	20	11	79	56	53
WCP	10^{0}m³ water-eq	24	3	13	72	41	24	34	33

Functional unit = 1 € β-carotene, € allocation

Parameter[a]	Unit	1 Be	2 Be	3 Be	1 In	2 In	3 In	Ref Be	Ref In
GWP	10^{-1} kg CO_2-eq	13	4	11	11	7	47	23	24
ODP	10^{-6} kg CFC_{11}-eq	2	1	2	1	1	2	6	6
IRP	10^{-2} kBq Co-60-eq	50	16	120	17	2	13	8	6
HOFP	10^{-4} kg NOx-eq	33	7	18	29	16	122	38	39
PMFP	10^{-4} kg PM2.5-eq	20	4	9	49	39	380	27	31
EOFP	10^{-4} kg NOx-eq	34	8	19	29	17	123	39	40
TAP	10^{-3} kg SO_2-eq	6	1	3	6	4	27	21	21
FEP	10^{-4}kg P-eq	8	2	3	7	4	29	6	6
TETP	10^{-4} kg 1,4-DCB-eq	31	7	9	17	6	12	10	10
FETP	10^{-2} kg 1,4-DCB-eq	11	2	4	6	2	10	3	3
METP	10^{-2} kg 1,4-DCB-eq	15	3	5	9	3	14	5	5
HTPc	10^{-2} kg 1,4-DCB-eq	10	2	3	6	3	16	5	5
HTPnc	10^{1} kg 1,4-DCB-eq	12	2	3	7	2	10	3	3
LOP	10^{-2} m²· yr	11	3	13	5	2	9	3	2
SOP	10^{-3} kg Cu-eq	16	3	7	8	2	3	6	6
FFP	10^{-2} kg oil-eq	33	9	32	25	14	98	56	53
WCP	10^{-3} m³ water-eq	29	6	14	89	51	30	34	33

Appendix 3. Supplementary Information chapter 5

Technological data MOO case study

Table A3.1 gives an overview of all technological input data with their corresponding references which have been used in the MOO model. The data is grouped according to the different production process steps.

Table A3.1. Technological input parameters

Parameter	**Unit**	**Value**	**Reference**
General			
Algae farm occupation factor	%	150.00	(a)
Geographical			
Solar irradiation Belgium	$kWh \cdot m^{-2}$	1040.00	(b)
Solar irradiation Iran	$kWh \cdot m^{-2}$	2100.00	(b)
Solar irradiation Cadiz	$kWh \cdot m^{-2}$	1900.00	(b)
Solar irradiation Hawaii	$kWh \cdot m^{-2}$	1868.00	(b)
Solar irradiation Tucson	$kWh \cdot m^{-2}$	2147.00	(b)
Solar irradiation Uttar Pradesh	$kWh \cdot m^{-2}$	1722.00	(b)
Ambient temp. Belgium March-November	°C	12.86	(c)
Ambient pressure	kPa	100.00	
Algae species: General			
Molecular weight	$pg \cdot cell^{-1}$	153.00	(d)

KNO_3 req.	mM	5.00	(e)
Stress stage KNO_3 req.	mM	0.10	(e)
$NaHCO_3$ requirement	mM	2.00	(f)
$MgSO_4$ requirement	mM	2.00	(e)
KH_2PO_4 requirement	mM	0.10	(e)
$FeCl_3.6H_2O$ requirement	mM	0.01	(e)
CO_2 requirement	g·g biomass^{-1}	1.83	(g)
Percentage growth function	%	67.00	(h)
Percentage growth function stress	%	77.00	(h)
Correction factor stress growth	%	67.00	(h)
Algae species: Dunaliella salina			
Optimal salinity	M	2.00	(e)
Stress stage salinity	M	2.50	(e)
Optimal temperature	°C	25.00	(f)
Stress stage β-carotene content	%	8.8	(d,f,i)
Stress stage astaxanthin content	%	0.00	(h)
TAG content	%	10.00	(j,k)
Stress stage TAG content	%	25.87	(j,k)
Initial concentration pond	10^6 cell·ml^{-1}	0.40	(d)
Maximum concentration pond	g·l^{-1}	0.50	(d)
Maximum specific growth rate pond	day^{-1}	0.25	(e)
Initial concentration reactor	10^6 cell·ml^{-1}	1.50	(d)
Maximum concentration reactor	g·l^{-1}	2.00	(d)
Maximum specific growth rate reactor	day^{-1}	0.35	(d,l)
Initial concentration ProviApt	10^6 cell·ml^{-1}	1.50	(h)
Maximum concentration ProviApt	g·l^{-1}	2.00	(h)
Maximum specific growth rate ProviApt	day^{-1}	0.90	(h)

Algae species: Haematococcus pluvialis			
Optimal salinity	M	0.00	(h)
Stress stage salinity	M	0.00	(h)
Optimal temperature	°C	27.00	(m)
Stress stage β-carotene content	%	0.00	(h)
Stress stage astaxanthin content	%	2.90	(n)
TAG content	%	0.11	(p)
Stress stage TAG content	%	1.15	(p)
Initial concentration pond	10^{6} cell·ml^{-1}	0.40	(d)
Maximum concentration pond	g·l^{-1}	0.50	(d)
Maximum specific growth rate pond	day^{-1}	0.25	(e)
Initial concentration reactor	g·l^{-1}	0.50	(p)
Maximum concentration reactor	g·l^{-1}	4.10	(p)
Maximum specific growth rate reactor	day^{-1}	0.25	(n)
Initial concentration ProviApt	g·l^{-1}	0.50	(h)
Maximum concentration ProviApt	g·l^{-1}	4.10	(h)
Maximum specific growth rate ProviApt	day^{-1}	0.64	(h)
Algae species: Nannochloropsis species			
Optimal salinity	g·kg^{-1}	22	(q)
Stress stage salinity	g·kg^{-1}	34	(q)
Optimal temperature	°C	25.00	(q,r,s)
Stress stage β-carotene content	%	0.01	(az)
Stress stage astaxanthin content	%	0.03	(az)
TAG content	%	7.00	(t)
Stress stage TAG content	%	38.00	(t)

Initial concentration pond	$g \cdot l^{-1}$	0.20	(u)
Maximum concentration pond	$g \cdot l^{-1}$	1.00	(u)
Maximum specific growth rate pond	day^{-1}	0.17	(u,v)
Initial concentration reactor	$g \cdot l^{-1}$	0.25	(w)
Maximum concentration reactor	$g \cdot l^{-1}$	2.50	(x)
Maximum specific growth rate reactor	day^{-1}	0.41	(y)
Initial concentration ProviApt	$g \cdot l^{-1}$	0.25	(w)
Maximum concentration ProviApt	$g \cdot l^{-1}$	2.50	(x)
Maximum specific growth rate ProviApt	day^{-1}	1.05	(y)
Process: General			
Operation rate	%	70.00	(h)
Process Step: Cultivation 1st stage			
All options			
Pumps in medium supply unit	#	4.00	(z)
Tanks in medium supply unit	#	3.00	(z)
NH_3 emission	% N-fertilizer	4.86	(aa)
CO_2 injection energy	$kWh \cdot t\ CO_2^{-1}$	22.20	(ab)
Medium preparation energy	$W \cdot m^{-3} \cdot h$	275.00	(ac)
Hours of mixing	$h \cdot day^{-1}$	10.00	(ad)
Hours of medium preparation	$h \cdot day^{-1}$	6.00	(ac)
O_2 emission	$g \cdot g\ biomass^{-1}$	1.07	(g)
Cultivation area	% total	67.00	(x)
Option: Open pond			
CO_2 fixation efficiency	%	41.23	(ae,af)
N_2O emission	% N-fertilizer	0.002	(ag)
Mixing energy	$W \cdot m^{-3}$	3.72	(ad)

Height pond	m	0.15	(e)
Option: PBR			
CO_2 fixation efficiency	%	71.00	(ac,ah)
N_2O emission	% N-fertilizer	0.39	(ag)
Mixing energy	$W \cdot m^{-3}$	2500.00	(ai)
Heat loss	%	5.00	(h)
Additional heating solar irradiation	°C	5.00	(h)
Volume surface ratio	$m^3 \cdot m^{-2}$	0.07	(ac)
Option: ProviApt			
CO_2 fixation efficiency	%	71.00	(ac,ah)
N_2O emission	%·N-fertilizer	0.39	(ag)
Mixing energy	$W \cdot m^{-2}$	5.00	(x)
Heat loss	%	5.00	(h)
Additional heating solar irradiation	°C	5.00	(h)
Volume surface ratio	$l \cdot m^{-2}$	8.66	(r)
Process: Preharvesting			
Option: IPC®			
End concentration	$g\ DW \cdot l^{-1}$	10.00	(aj)
Energy consumption after open pond	$kWh \cdot m^{-3}$	0.24	(aj)
Energy consumption after reactor	$kWh \cdot m^{-3}$	0.26	(aj)
Maximum recycling ratio	%	100.00	(aj)
Process: Cultivation 2nd stage			
All options			
Pumps in medium supply unit	#	4.00	(z)
Tanks in medium supply unit	#	3.00	(z)

NH_3 emission	% N-fertilizer^{-1}	4.86	(aa)
CO_2 injection energy	kWh·t CO_2^{-1}	22.20	(ab)
Medium preparation energy	$W \cdot m^{-3} \cdot h$	275.00	(ac)
Hours of mixing	h·day^{-1}	10.00	(ad)
Hours of medium preparation	h·day^{-1}	6.00	(ac)
O_2 emission open pond?	g·g biomass^{-1}	1.07	(g)
Cultivation area	% total	67.00	(x)
Option: Open pond			
CO_2 fixation efficiency	%	41.23	(ae,af)
N_2O emission	% N-fertilizer^{-1}	0.002	(ag)
Mixing energy	$W \cdot m^{-3}$	3.72	(ad)
Height pond	m	0.12	(e)
Option: PBR			
CO_2 fixation efficiency	%	71.00	(ac,ah)
N_2O emission	% N-fertilizer^{-1}	0.39	(ag)
Mixing energy	$W \cdot m^{-3}$	2500.00	(ai)
Heat loss	%	5.00	(h)
Additional heating solar irradiation	°C	5.00	(h)
Volume surface ratio	$m^3 \cdot m^{-2}$	0.07	(ac)
Option: ProviApt			
CO_2 fixation efficiency	%	71.00	(ac,ah)
N_2O emission	% N-fertilizer^{-1}	0.39	(ag)
Mixing energy	$W \cdot m^{-2}$	5.00	(x)
Heat loss	%	5.00	(h)
Additional heating solar irradiation	°C	5.00	(h)
Volume surface ratio	$l \cdot m^{-2}$	8.66	(r)

Process: Harvesting			
Option: Centrifuge			
Energy consumption	$kWh \cdot m^{-3}$	1.40	(ak)
Maximum concentration	%	12.00	(al)
Recovery	%	97.00	(h)
Process: Washing			
End salt concentration	$g \cdot l^{-1}$	4.00	(h)
Mixing time	h	1.00	(h)
Energy consumption mixing	$kWh \cdot h \cdot t^{-1} \cdot year \cdot l^{-1}$	0.18 Capacity $[l]^{-0.33}$	(am)
Energy consumption centrifuge	$kWh \cdot m^{-3}$	1.40	(an)
Maximum concentration	%	12.00	(al)
Recovery	%	97.00	(h)
Process: Drying			
Option: Spray Drying			
T_{inlet} air	°C	200.00	(ao)
T_{outlet} air	°C	110.00	(ao)
T_{outlet} biomass	°C	72.00	(ap)
Solid $content_{outlet}$	%	94.72	(ao)
Biomass recovery	%	95.00	(h)
Correction factor for energy consumption	%	2.90	(ap)
Total energy consumption	$GJ \cdot t(water\ removed)^{-1}$	5.20	(h)
Option: Freeze Drying			
Solid $content_{outlet}$	%	93.60	(aq)
Biomass recovery	%	95.00	
Energy consumption	$kW \cdot kg^{-1}$	2.00	(ar)

Process: Disruption			
Option: Bead mill			
Energy consumption	kWh·kg^{-1}	2.82	(as)
Disruption time	h	7.00	(at)
Process: Extraction			
Option: Hexane extraction			
Extraction time	min·step^{-1}	60.00	(h)
Carotenoid recovery	%	95.00	(h)
TAG recovery	%	95.00	(h)
Hexane concentration	l·l^{-1}	1.00	(au)
Extraction steps	#	6.00	(au)
Energy consumption mixing	kWh·h·t^{-1}·year·l^{-1}	0.18 Capacity [l]$^{-0.33}$	(am)
Hexane emission	g·kg^{-1}	2.00	(av)
Other components extracted	%	1.50	(h)
Process: Filtration			
Energy consumption	kWh·t dry material^{-1}	10.00	(am)
Solvent in residual biomass	%	10.00	(h)
Process: Lipid purification			
Option: Vacuum distillation			
Distillation carotenoids	%	1.00	(h)
Distillation other components	%	1.00	(h)
Distillation water	%	40.00	(h)
Distillation hexane	%	100.00	(h)
Cooling water	m^3·kg waste solvent^{-1}	0.027	(aw)
Temperature	°C	30.00	(ax)
Steps		3.00	(h)

Time	min·step^{-1}	60.00	(h)
Pressure	kPa	24.91	
Distillation energy Belgium	kWh·t recycled^{-1}	1,353.32	(ay)
Distillation energy India	kWh·t recycled^{-1}	1,314.21	(ay)
Energy efficiency	%	64.00	(am)
Minimum reflux ratio	%	120.00	(am)
Process: Lipid processing			
Option: Transesterification			
Methanol	kg·kg oil^{-1}	0.12	(ba)
HCl	kg·kg oil^{-1}	0.04	(ba)
NaOH	kg·kg oil^{-1}	0.001	(ba)
Phosphoric acid	kg·kg oil^{-1}	0.0006	(ba)
Citric acid	kg·kg oil^{-1}	0.0007	(ba)
Water	kg·kg oil^{-1}	0.34	(ba)
Glycerol production	kg·kg oil^{-1}	0.12	(ba)
Biodiesel production	kg·kg oil^{-1}	1.01	(ba)
Wastewater	kg·kg oil^{-1}	0.048	(ba)
Natural gas	kWh·kg^{-1}	0.24	(ba)
Electricity	kWh·kg^{-1}	0.04	(ba)
Energy pump	J·kg^{-1}	55.00	(am)
Mxixing time	min	50.00	(h)
Decanter time	min	50.00	(h)
Equipment			(bb)
Option: Hydrotreating			
Hydrogen	kg·kg oil^{-1}	0.02	(bc)

Phosphoric acid	kg·kg oil^{-1}	0.0019	(bc)
Silica	kg·kg oil^{-1}	0.001	(bc)
Clay dosing	kg·kg oil^{-1}	0.002	(bc)
Water	kg·kg oil^{-1}	0.13	(bc)
CO_2 emission	kg·kg oil^{-1}	0.01	(bc)
Hydrogen recycling rate	%	89.00	(bc)
Renewable diesel production	kg·kg oil^{-1}	0.78	(bc)
Naphtha production	kg·kg oil^{-1}	0.02	(bc)
Gas production	kg·kg oil^{-1}	0.18	(bc)
Propane in gas	%	29.18	(bc)
CO_2 in gas	%	63.12	(bc)
H_2 in gas	%	3.83	(bc)
Waste stream	%	12.50	(bc)
Electricity hydrotreating	kWh·kg^{-1}	0.05	(bd)
Natural gas hydrotreating	kWh·kg^{-1}	0.05	(bd)
PSA energy	kWh·kg^{-1}	0.10	(bc)
Degumming energy	kWh·kg^{-1}	0.01	(bc)
Equipment			(be)
Process: Residue purification			
Option: Evaporation			
Water evaporation	%	40.00	(h)
Solvent evaporation	%	100.00	(h)
Other components evaporation	%	1.00	(h)
Cooling water	m^3·kg waste solvent^{-1}	0.027	(aw)
Evaporation energy	kWh·t recycled^{-1}	1,153.83	(ay)
Energy efficiency	%	64.00	(am)

Minimum reflux ratio	%	120.00	(am)
Evaporation time	min	60.00	(h)
Evaporation temperature	K	341.60	(h)
Process: Residue processing			
Option: Pyrolysis			
Biochar fraction	%	63.00	(bf)
Syngas fraction	%	13.00	(bf)
Liquid fraction	%	24.00	(bf)
CO_2 loss	%	9.00	(bf)
CH_4 loss	%	1.50	(bf)
CO loss	%	1.00	(bf)
C_2H_4 loss	%	0.30	(bf)
C_2H_6 loss	%	1.00	(bf)
H_2 loss	%	0.70	(bf)
Energy requirement	MJ·kg dry biomass^{-1}	1.24	(bg)
Energy requirement	MJ·kg water^{-1}	0.14	(bg)
HHV bio-oil	MJ·kg^{-1}	27.90	(bf)
HHV syngas	MJ·kg^{-1}	2.90	(bf)
HHV biochar	MJ·kg^{-1}	14.50	(bf)
Energy use fluid catalytic cracking	MJ·bbl	401.87	(bh)
Biocrude to biochar fluid catalytic cracking	%	19.00	(bh)
Energy use hydrotreating	MJ·bbl	446.59	(bh)
Biocrude to biochar hydrotreating	%	7.00	(bh)
Ratio diesel gasoline refining	%	52.00	(bi)
Hydrogen consumption	kg·kg^{-1}	0.12	(bj)

Option: Gasification			
Biochar fraction	%	58.00	(bk)
Syngas fraction	%	28.00	(bk)
Liquid fraction	%	14.00	(bk)
Energy requirement	MJ·kg dry biomass^{-1}	1.47	(bg)
Energy requirement	MJ·kg water^{-1}	0.27	(bg)
HHV bio-oil	MJ·kg^{-1}	34.10	(bk)
HHV syngas	MJ·kg^{-1}	32.90	(bk)
HHV biochar	MJ·kg^{-1}	17.50	(bk)
Energy use fluid catalytic cracking	MJ·bbl	401.87	(bh)
Biocrude to biochar fluid catalytic cracking	%	19.00	(bh)
Energy use hydrotreating	MJ·bbl	446.59	(bh)
Biocrude to biochar hydrotreating	%	7.00	(bh)
Ratio diesel gasoline refining	%	52.00	(bi)
Hydrogen consumption	kg·kg^{-1}	0.12	(bj)
Option: Torrefaction			
Biochar fraction	%	75.00	(bk)
Syngas fraction	%	7.00	(bk)
Liquid fraction	%	84.00	(bk)
Energy requirement	MJ·kg dry biomass^{-1}	1.05	(bg)
Energy requirement	MJ·kg water^{-1}	0.28	(bg)
HHV bio-oil	MJ·kg^{-1}	15.50	(bk)
HHV syngas	MJ·kg^{-1}	2.67	(bk)
HHV biochar	MJ·kg^{-1}	16.60	(bk)
Energy use fluid catalytic cracking	MJ·bbl	401.87	(bh)
Biocrude to biochar fluid catalytic cracking	%	19.00	(bh)

Energy use hydrotreating	MJ·bbl	446.59	(bh)
Biocrude to biochar hydrotreating	%	7.00	(bh)
Ratio diesel gasoline	%	52.00	(bi)
Hydrogen consumption refining	kg·kg^{-1}	0.12	(bj)
Option: HTL			
Pretreatment Temperature	°C	150.00	(bh)
Heat exchange efficiency	%	90.00	(bh)
Pretreatment energy	MJ·kg water^{-1}	0.58	(bh)
Biomass conversion temperature	°C	300.00	(bh)
Biomass conversion energy	MJ·kg water^{-1}	0.72	(bh)
Biocrude fraction	%	20.00	(bh)
Hexane	l·l biocrude^{-1}	0.75	(bh)
Energy extraction	MJ·l feed^{-1}	0.02	(bh)
Hexane recovery	%	99.50	(bh)
Hexane recovery energy	MJ·tonne biocrude^{-1}	2.10	(bh)
Biocrude recovery	%	90.00	(bh)
Nitrogen in raffinate	%	89.00	(bh)
Nitrogen in biomass	%	8.00	(bh)
Phosphorus in raffinate	%	94.00	(bh)
Phosphorus in biomass	%	1.00	(bh)
Nutrient recycle efficiency	%	12.50	(bh)
Gas conversion	%	3.00	(bh)
CO_2 in gas fraction	%	70.00	(bh)
CH_4 in gas fraction	%	30.00	(bh)
Solid waste	%	3.00	(bh)

Energy use fluid catalytic cracking	MJ·bbl	401.87	(bh)
Biocrude to biochar fluid catalytic cracking	%	19.00	(bh)
Energy use hydrotreating	MJ·bbl	446.59	(bh)
Biocrude to biochar hydrotreating	%	7.00	(bh)
Ratio diesel gasoline refining	%	52.00	(bi)
Hydrogen consumption	$kg \cdot kg^{-1}$	0.12	(bj)
Option: Anaerobic digestion			
Biogas production	m^3 CH_4	0.375	(bl)
Methane in biogas	%	70.00	(bl)
CO_2 in biogas	%	30.00	(bl)
Digestate	$m^3 \cdot kg^{-1}$	0.02	(bl)
Liquid digestate	% digestate	93.36	(bl)
N liquid digestate	$kg \cdot m^{-3}$	2.94	(bl)
P liquid digestate	$kg \cdot m^{-3}$	0.39	(bl)
K liquid digestate	$kg \cdot m^{-3}$	0.32	(bl)
N solid digestate	$kg \cdot m^{-3}$	4.50	(bl)
P solid digestate	$kg \cdot m^{-3}$	0.61	(bl)
K solid digestate	$kg \cdot m^{-3}$	0.50	(bl)
Water consumption	$m^3 \cdot kg^{-1}$	0.07	(bl)
Heat demand	$kWh \cdot kg^{-1}$	0.68	(bl)
Power demand	$kWh \cdot kg^{-1}$	0.22	(bl)
Volume per feed flow	$m^3 \cdot kg^{-1} \cdot h$	0.25	(bc)

(a) (M. Michiels, 2013); (b) (SolarGIS); (c) (Koninklijk Meteorologisch Instituut van België);(d) (Prieto et al., 2011); (e) (Tafreshi & Shariati, 2006); (f) (M. García-González et al., 2003); (g) (Buehner et al., 2009) ; (h) assumption; (i) (Z. Wu et al., 2017) ; (j) (Q. Hu et al., 2008); (k) (Takagi, Karseno, & Yoshida, 2006) ; (l) (Mercedes García-González et al., 2005); (m) (Evens et al., 2007) ; (n) (Olaizola, 2000); (o) (Campbell et al., 2014); (p) (J. Wang et al., 2013); (q) (Bartley, Boeing, Corcoran, Holguin, & Schaub, 2013); (r) (Taelman et al., 2013); (s) (San Pedro, González-López, Acién, & Molina-Grima, 2015); (t) (Simionato et al., 2013); (u)

(Crowe et al., 2012); (v) (Van Wagenen et al., 2012); (w) (Quinn et al., 2012); (x) (M. Michiels, 2013); (y) (Daniel & Srivastava, 2016); (z) (Tredici et al., 2016); (aa) (Yuan et al., 2015); (ab) (Kadam, 2001); (ac) (Acién et al., 2012); (ad) (Jorquera et al., 2010); (ae) (Jiří Doucha et al., 2005); (af) (Ramanan et al., 2010); (ag) (Fagerstone et al., 2011); (ah) (Mazzuca Sobczuk et al., 2000); (ai) (Sierra et al., 2008); (aj) estimate from Vito experts; (ak) (Milledge & Heaven, 2011); (al) (Molina Grima et al., 2003); (am) (Piccinno et al., 2016); (an) (Milledge & Heaven, 2011); (ao) (Leach et al., 1998); (ap) Course "Sproeidrogen", Technotrans BV(2001); (aq) (Y. Liu et al., 2008); (ar) (Cuddon Freeze dry); (as) (J. Doucha & Lívanský, 2008); (at) (Vaňková et al., 2008); (au) (Cerón et al., 2008); (av) (Lardon et al., 2009); (aw) (Capello et al., 2005); (ax) (C.-C. Hu et al., 2008); (ay) Calculation; (az) (Nobre et al., 2013); (ba) (Omni Tech International, 2010); (bb) (Pokoo-Aikins et al., 2009) ; (bc) (R. Davis et al., 2014); (bd) (Huo, Wang, Bloyd, & Putsche, 2008); (be) (L. Wu & Liu, 2016); (bf) (Grierson, Strezov, Ellem, McGregor, & Herbertson, 2009); (bg) based on L. Xu et al. (2011); (bh) (X. Liu et al., 2013); (bi) (Ou et al., 2015); (bj) (Thilakaratne et al., 2014) ; (bk) (Khoo et al., 2013); (bl) (Collet et al., 2011).

Economic data MOO case study

Table A3.2 gives an overview of all economic input data with their corresponding references which have been used in the MOO model. The data is grouped in general, investment, operational and revenue data.

Table A3.2 Economic input parameters

Parameter	**Unit**	**Value**	**Reference**
General			
Evaluation period	Years	10.00	
Site preparation	%I_0	10.00	(a)
Nominal discount rate	%	15.00	(b)
Equity	%	20.00	
Interest loan	%	1.47	(c)
Inflation rate	%	2.00	(d)
Tax rate	%	33.99	(e)
Investment costs			
Process: Cultivation			
All options			
Cost inoculum production system	EUR·ha^{-1}	122,595 Capacity [ha]$^{-0.21}$	(f,g)
Lifetime inoculum production system	year	20.00	(f)
Land cost	EUR·m^{-2}	2.62	(h)
Cost medium preparation unit	EUR·m^{-3}·h	6,954 Capacity [m^3·h^{-1}]$^{-0.51}$	(i,g)
Lifetime medium preparation unit	year	10	(g)
Cost CO_2 supply unit	EUR·kg^{-1}·h	436	(i,j)

Lifetime CO_2 supply unit	year	10.00	(i)
Cost heat exchanger titanium	EUR·dam^{-3}	27,085 Capacity [dam^3]$^{-0.4}$	(k)
Cost heat exchanger incoloy	EUR·dam^{-3}	21,668 Capacity [dam^3]$^{-0.4}$	(l)
Lifetime heat exchanger	year	15.00	(m)
Option: Open pond			
Cost liners	EUR·ha^{-1}	87,637	(f,j,n)
Lifetime liners	year	20.00	(o)
Cost landscaping	EUR·ha^{-1}	8,760	(p)
Cost paddlewheels	EUR·ha^{-1}	11,728	(j,n,p)
Lifetime paddlewheels	year	20.00	(p)
Option: PBR			
Cost PBR	EUR·m^{-3}	13,501 Capacity [m^3]$^{-0.07}$	(i,q)
Lifetime PBR	year	10.00	(i)
Cost Blower	EUR·m^{-3}	2,055 Capacity [m^3]$^{-0.6}$	(i,g)
Lifetime blower	year	20.00	(g)
Option: ProviApt			
Reactor installed cost	EUR·ha^{-1}	143,231	(r)
Additional investment	EUR·ha^{-1}	492,500	(r)
Lifetime reactor	year	2.00	(r)
Process: Preharvesting			
Option: IPC®			
Total cost membrane scen Ns AF	10^6 EUR	180.20	
Total cost membrane scen Hp F	10^6 EUR	13.47	
Total cost membrane scen Ds F	10^6 EUR	6.90	
Total cost membrane scen Hp AD	10^6 EUR	13.47	

Total cost membrane scen Ds AD	10^6 EUR	6.90	
Total cost membrane scen Hp G	10^6 EUR	13.47	
Total cost membrane scen Ds G	10^6 EUR	6.90	
Total cost membrane scen Hp T	10^6 EUR	13.47	
Total cost membrane scen Ds T	10^6 EUR	6.90	
Process: Harvesting			
Option: Centrifuge			
Centrifuge	EUR·l^{-1}·h	318,225 Capacity $[m^3 \cdot h^{-1}]^{-0.44}$	(q)
Lifetime centrifuge	year	25.00	(g)
Process: Washing			
Cost tank	EUR·m^{-3}	2,417 Input $[m^3]^{-0.43}$	(i)
Lifetime tank	year	10.00	(i)
Cost mixer	EUR·W^{-1}	436 Capacity $[W]^{-0.63}$	(q)
Lifetime mixer	year	10.00	
Centrifuge	EUR·l^{-1}·h	318,225 Capacity $[m^3 \cdot h^{-1}]^{-0.44}$	(q)
Lifetime centrifuge	year	25.00	(g)
Process: Drying			
Option Spray Drying			
Spray dryer	EUR	188,458 Capacity $[kg_{\text{water removed}} \cdot h^{-1}]^{-0.4}$	(q)
Lifetime dryer	year	15.00	
Option Freeze Drying			
Freeze dryer	EUR·kg^{-1}·h	224,031 Capacity $[kg \cdot h^{-1}]^{-0.4}$	(s)
Lifetime freeze dryer	year	10	
Process: Disruption			
Option: Bead mill			
Bead mill	EUR·l^{-1}·h	5,161 Capacity $[l \cdot h^{-1}]^{-0.4}$	(q)

Lifetime bead mill	year	10	
Process: Extraction			
Option: Hexane extraction			
Cost tank	EUR·m^{-3}	2,417 Input [m^3]$^{-0.43}$	(i)
Lifetime tank	year	10.00	(i)
Cost mixer	EUR·W^{-1}	436 Capacity [W]$^{-0.63}$	(q)
Lifetime mixer	year	10.00	
Process: Filtration			
Filter	EUR·m^{-2}	6,139 Capacity [m^2]$^{-0.54}$	(t,u)
Lifetime filter	year	10.00	
Process: Lipid purification			
Option: Vacuum distillation			
Evaporator	EUR·m^{-3}	192,552 Input [m^3]$^{-0.69}$	(q)
Lifetime evaporator	year	10.00	
Process: Lipid processing			
Option: Transesterification			
Transesterification equipment	EUR·t^{-1}·h	1,874140 Capacity [t·h^{-1}]$^{-0.4}$	(v)
Lifetime equipment	year	10	
Option: Hydrotreating			
Hydrotreating unit	EUR·l^{-1}·m	2,212,987 Capacity [l·min^{-1}]$^{-0.5}$	(w)
Lifetime hydrotreating unit	year	30	(w)
Pressure swing adsorption (PSA) unit	EUR·l^{-1}·m	484,713 Capacity [l·min^{-1}]$^{-0.4}$	(w)
Lifetime PSA unit	year	30	(w)
Bleaching/degumming unit	EUR·l^{-1}·m	258,514 Capacity [l·min^{-1}]$^{-0.4}$	(w)
Lifetime bleaching/degumming unit	year	30	(w)

Process: Residue purification			
Option: Evaporation			
Evaporator	EUR·m^{-3}	192,552 Input $[m^3]^{-0.69}$	(q)
Lifetime evaporator	year	10.00	
Process: Residue processing			
Option: Pyrolysis			
Pyrolysis equipment	EUR·t^{-1}·h	19,387,234 Input $[t\cdot h^{-1}]^{-0.44}$	(x,y,z,aa)
Lifetime pyrolysis unit	year	30	(x)
Hydroprocessing unit	EUR·t^{-1}·day	717,314 Input $[t\cdot day^{-1}]^{-0.40}$	(aa)
Lifetime hydroprocessing unit	year	30	(aa)
Refining unit	EUR·t^{-1}·day	60,618 Input $[t\cdot day^{-1}]^{-0.40}$	(aa)
Lifetime refining unit	year	30	(aa)
Option: Gasification			
Gasificiation equipment	EUR·t^{-1}·h	19,387,234 Input $[t\cdot h^{-1}]^{-0.44}$	(ab)
Lifetime gasification unit	year	30	(ab)
Hydroprocessing unit	EUR·t^{-1}·day	717,314 Input $[t\cdot day^{-1}]^{-0.40}$	(aa)
Lifetime hydroprocessing unit	year	30	(aa)
Refining unit	EUR·t^{-1}·day	60,618 Input $[t\cdot day^{-1}]^{-0.40}$	(aa)
Lifetime refining unit	year	30	(aa)
Option: Torrefaction			
Torrefaction equipment	EUR·t^{-1}·h	19,387,234 Input $[t\cdot h^{-1}]^{-0.44}$	(ab)
Lifetime torrefaction unit	year	30	(ab)
Hydroprocessing unit	EUR·t^{-1}·day	717,314 Input $[t\cdot day^{-1}]^{-0.40}$	(aa)
Lifetime hydroprocessing unit	year	30	(aa)
Refining unit	EUR·t^{-1}·day	60,618 Input $[t\cdot day^{-1}]^{-0.40}$	(aa)
Lifetime refining unit	year	30	(aa)

Option: HTL			
HTL equipment	EUR·t^{-1}·h	19,387,234 Input [t·h^{-1}]$^{-0.44}$	(ab)
Lifetime HTL unit	year	30	(ab)
Hydroprocessing unit	EUR·t^{-1}·day	717,314 Input [t·day^{-1}]$^{-0.40}$	(aa)
Lifetime hydroprocessing unit	year	30	(aa)
Refining unit	EUR·t^{-1}·day	60,618 Input [t·day^{-1}]$^{-0.40}$	(aa)
Lifetime refining unit	year	30	(aa)
Option: Anaerobic digestion			
Digester	EUR·m^{-3}	9,257 Input [m^{-3}]$^{-0.40}$	(w)
Lifetime digester	year	30	(w)
Operational costs			
General			
Working rate personnel	EUR·h^{-1}	39.20	(ac)
Working hours/day	h·day^{-1}	8.00	
Working days	day	241.00	
Electricity costs (<20,000 MWh yr^{-1})	EUR·MWh^{-1}	117.50	(ad)
Electricity costs (>20,000 MWh yr^{-1})	EUR·MWh^{-1}	93.70	(ad)
Natural gas cost	EUR·MWh^{-1}	39.20	(ae)
Water purchase cost	EUR·m^{-3}	3.39	(af)
Water disposal cost	EUR·m^{-3}	2.43	(ag)
Insurance cost	%I_0	1.00	(ah)
Repair/maintenance cost	%I_0	7.00	(ah)
Process: Cultivation			
All Options			
Salt price	EUR·t^{-1}	75.57	(ai)

CO_2 price	EUR·t^{-1}	225.00	(q)
KNO_3 price	EUR·t^{-1}	1,594.30	(aj)
$NaHCO_3$ price	EUR·t^{-1}	869.51	(ak)
KH_2PO_4 price	EUR·t^{-1}	1,992.81	(al)
$FeCl_3.6H_2O$	EUR·t^{-1}	488.12	(am)
$MgSO_4$	EUR·t^{-1}	797.12	(an)
Option: Open pond			
Personnel on site ponds	person	3+(Area [ha] 30^{-1})	
Option: PBR			
Personnel on site PBR	person	3+(Area [ha] 10^{-1})	
Option: ProviApt			
Personnel on site ProviApt	person	3+(Area [ha] 1^{-1})	(ao)
Process: Extraction			
Option: Hexane extraction			
Hexane price	EUR·t^{-1}	393.21	(ap)
Process: Lipid processing			
Option: Transesterification			
Methanol	EUR·t^{-1}	380.00	(aq)
NaOH	EUR·t^{-1}	181.69	(ar)
HCl	EUR·t^{-1}	2,378.22	(as)
Phosphoric acid	EUR·t^{-1}	717.41	(w)
Citric acid	EUR·t^{-1}	2,531.20	(at)
Option: Hydrotreating			
Hydrogen	EUR·kg^{-1}	10.00	(au)
Phosphoric acid	EUR·t^{-1}	717.41	(w)
Silica	EUR·kg^{-1}	1.99	(w)

Clay	EUR·kg^{-1}	0.60	(w)
Process: Residue processing			
Option: Pyrolysis			
Hydrogen	EUR·kg^{-1}	10.00	(au)
Option: Gasification			
Hydrogen	EUR·kg^{-1}	(au)	(au)
Option: Torrefaction			
Hydrogen	EUR·kg^{-1}	10.00	(au)
Option: HTL			
Solid waste	EUR·t^{-1}	33.43	(aa)
Hydrogen	EUR·kg^{-1}	10.00	(au)
Revenues			
Sale fertilizer	EUR·kg^{-1}	0.39	(q)
Market fertilizer	t·yr^{-1}	17,000,000	(av)
Sale larval feed	EUR·kg^{-1}	318.00	(aw)
Market fish feed	t·yr^{-1}	67,000,000	(ax)
Market larval feed	t·yr^{-1}	67,000	
Sale β-carotene	EUR·kg^{-1}	1000.00	(am, ay, az, ba, bb, bc)
Market β-carotene	t·yr^{-1}	371.56	(bd)
Sale astaxanthin	EUR·kg^{-1}	5000.00	(be, bf, bg, bh, bi)
Market astaxanthin	t·yr^{-1}	280.00	(bj)
Sale biodiesel	EUR·l^{-1}	0.50	(bk)
Sale renewable diésel	EUR·l^{-1}	0.50	(bk)
Market volume diésel	10^6·t·year^{-1}	1,281.78	(bl)

Sale glycerol	EUR·t^{-1}	0.17	(v)
Market volume glycerol	ton·yr^{-1}	900,000.00	(bm)
Sale gasoline	EUR·l^{-1}	0.48	(bk)
Market volume gasoline	10^6 t·year^{-1}	1,125.69	(bl)
Sale naphtha	EUR·kg^{-1}	0.46	(bn)
Market volume naphtha	10^6 t·year^{-1}	270.70	(bo)

(a) Caputo et al., 2005); (b) (Mercken, 2004); (c) (National Bank of Belgium); (d) (World Bank); (e) (OECD); (f) (R. E. Davis et al., 2014); (g) (Tredici et al., 2016); (h) (Peeters et al., 2015), (i) (Acién et al., 2012); (j) (Lundquist et al., 2010); (k) (AZALP Pahlen Aqua Mex compleet 70 kW - Titanium); (l) (AZALP Pahlen Aqua Mex compleet 70 kW - Incoloy); (m) (De Minister van Economische Zaken, 2013); (n) (Norsker et al., 2011); (o) (ANL; NREL; PNNL, 2012); (p) (J. N. Rogers et al., 2014); (q) price quote commercial supplier; (r) (M. Michiels, 2013); (s) (Gong & You, 2014a); (t) (Sikder et al., 2012); (u) (Vaňková et al., 2008); (v) (Pokoo-Aikins et al., 2009); (w) (R. Davis et al., 2014) ; (x) (Thilakaratne et al., 2014); (y) (J. G. Rogers & Brammer, 2012); (z) (Bridgwater, 2012); (aa) (Ou et al., 2015); (ab) assumed the same as pyrolysis; (ac) (Eurostat); (ad) (Eurostat); (ae) (Eurostat); (af) (VMM); (ag) (VMM); (ah) (Peters et al., 2003); (ai) (U.S. Geological Survey, 2015); (aj) (MBFerts); (ak) (Intra Laboratories); (al) (MBFerts); (am) commercial sources; (an) (MBFerts); (ao) (M. Michiels, 2013); (ap) (Global, 2016); (aq) (Methanex, 2018); (ar) (Intratec, 2011); (as) (De Oplosmiddelspecialist, 2018); (at) (Schippers, 2018); (au) (Fraile, Lanoix, Patrick, Rangel, & Torres, 2015); (av) (Persistence Market Research, 2016); (aw) (Proviron, 2018); (ax) (Schalekamp, van den Hill, & Huisman, 2016); (ay) (Brennan & Owende, 2010); (az) (Guedes et al., 2011); (ba) (Hejazi & Wijffels, 2004); (bb) (Pharmacompass)); (bc) (Richmond, 2004); (bd) (Research and Markets, 2017); (be) (Pacheco et al., 2015); (bf) (Olaizola, 2000); (Markou & Nerantzis, 2013); (bg) (Raja, Hemaiswarya, Kumar, Sridhar, & Rengasamy, 2008); (bh) (Cuellar-Bermudez et al., 2015); (bi) (Spolaore et al., 2006); (bj) (Research and Markets, 2015); (bk) (EIA, 2018); (bl) (Marcacci, 2012); (bm) (Global Market Insights, 2016); (bn) (Marketinsider, 2018); (bo) (Grand View Research, 2015).

Environmental data MOO case study

Table A3.3 gives an overview of all environmental input data with their corresponding references which have been used in the MOO model. The data is grouped according to the different production process steps.

Table. A3.3. Environmental input parameters

Parameter	**Inventory**	**Unit**		**Characterization factor in ecoinvent (Alloc Def, U)**	**Ref/C**
General					
Labour	Energy worker-hour^{-1}	MJ	39.00	Electricity, medium voltage {BE}| market for	(a)
Factory	Sizing factor		0.60		
Factory				Chemical factory, organics {RER}| construction	
Water				Tap water {Europe without Switzerland}| market for	
Water disp.				Wastewater, average {Europe without Switzerland}| market for wastewater, average	
Water em.				Emissions to water: water	
Electricity				Electricity, medium voltage {BE}| market for	
Heat				Heat, district or industrial, natural gas {RER}| market group for	
Land use				Inputs from nature: Occupation, bare area (non-use), BE	
Process: Cultivation 1st stage					
All Options					
Salt				Sodium chloride, powder {GLO}| market for	(b)
CO_2				Carbon dioxide, liquid {RER}| market for	(b)
$NaHCO_3$	Na_2CO_3	$kg^{\cdot}kg^{-1}$	0.66	Soda ash, dense {GLO}| market for	(e)
$NaHCO_3$	CO_2 emission	$kg \cdot kg^{-1}$	2^{E-4}	Emissions to air: Carbon dioxide	(d)

$NaHCO_3$	Water emission	$kg \cdot kg^{-1}$	6^{E-4}	Emissions to air: water	(d)
$NaHCO_3$	Na_2CO_3 emission	$kg \cdot kg^{-1}$	0.0013	Emissions to air: Sodium carbonate	(d)
$NaHCO_3$	CO_2 to water	$kg \cdot kg^{-1}$	0.013	Emissions to water: Carbon dioxide	(d)
$NaHCO_3$	Water to water	$kg \cdot kg^{-1}$	0.0054	Emissions to water: water	(d)
$NaHCO_3$	Na_2CO_3 to water	$kg \cdot kg^{-1}$	0.014	Emissions to water: Sodium	(d)
$NaHCO_3$	Na_2CO_3 to water	$kg \cdot kg^{-1}$	0.018	Emissions to water: Carbonate	(d)
$NaHCO_3$	Transport lorry	$tkm \cdot kg^{-1}$	0.10	Transport, freight, lorry, unspecified {GLO}| market for	(e)
$NaHCO_3$	H_2O	$kg \cdot kg^{-1}$	0.11	Tap water {Europe without Switzerland}| market for	(e)
$NaHCO_3$	CO_2	$kg \cdot kg^{-1}$	0.28	See CO_2	(e)
$NaHCO_3$	Electricity	$kWh \cdot kg^{-1}$	0.33	Electricity, medium voltage {BE}| market for	(d,e)
$NaHCO_3$	Chemical factory	$p \cdot kg^{-1}$	4^{E-10}	Chemical factory, organics {RER}| construction	(d)
$NaHCO_3$	Plastic packaging	$kg \cdot kg^{-1}$	0.002	See Auxiliary: Plastic packaging	(f)
$NaHCO_3$	Transport train	$tkm \cdot kg^{-1}$	0.60	Transport, freight train {Europe without Switzerland/GLO}| market for	(e)
KH_2PO_4	P_2O_5	$kg \cdot kg^{-1}$	0.52	Phosphate fertilizer, as P2O5 {GLO}| market for	(g)
KH_2PO_4	K_2O	$kg \cdot kg^{-1}$	0.34	Potassium fertilizer, as K2O {GLO}| market for	(g)
KH_2PO_4	Transport lorry	$tkm \cdot kg^{-1}$	0.10	Transport, freight, lorry, unspecified {GLO}| market for	(e)
KH_2PO_4	Plastic packaging	$kg \cdot kg^{-1}$	0.002	See Auxiliary: Plastic packaging	(f)
KH_2PO_4	Transport train	$tkm \cdot kg^{-1}$	0.60	Transport, freight train {Europe without Switzerland}| market for	(e)
KNO_3				Potassium nitrate {GLO}| market for	(b)
$MgSO_4$				Magnesium sulfate {GLO}| market for	(b)
$FeCl_3.6H_2O$				Iron (III) chloride, without water, in 40% solution state {GLO}| market for	(b)
CO_2 em.				Emissions to water: Carbon dioxide	
N_2O em.				Emission to air: Dinitrogen monoxide	
NH_3 em.				Emissions to air: Ammonia	
O_2 em.				Emissions to air: Oxygen	
MPS	Tank	$p \cdot p^{-1}$	1.00	1 p Hot water tank, 600l {CH}| production	(b)
MPS	Sizing factor		0.57		(i)

CO$_2$ supply	Pump	p·p^{-1}	1.00	Pump, 40W {CH}| production [a]	(b)
CO$_2$ supply	Sizing factor		0.62		(h)
Heat exch.	Capacity	kW·p^{-1}	70.00		(j)
Heat exch.	Sizing factor		0.60		(h)
Heat exch.	Transport, lorry	tkm·p^{-1}	0.88	Transport, freight, lorry, unspecified {GLO}| market for	(e)
Heat exch.	Titanium	kg·p^{-1}	8.80	Titanium, primary {GLO}| market for	(j)
Heat exch.	Titanium waste	kg·p^{-1}	8.80	See Auxiliary: Titanium waste	
Heat exch.	Packaging plastic	kg·p^{-1}	0.06	See Auxiliary: Plastic packaging	(f)
Heat exch.	Packaging paper	kg·p^{-1}	0.06	See Auxiliary: Paper packaging	(f)
Heat exch.	Transport, train	tkm·p^{-1}	5.28	Transport, freight train {Europe without Switzerland}| market for	(e)
IPS§					
Option: Open pond					
Liner	Capacity	ha·p^{-1}	0.81		(k)
Liner	Sizing factor		1.00		(h)
Liner	Material		HDPE		(l)
Liner	Thickness	mil	40.00		(l)
Liner	Width	m	12.20		(k)
Liner	Additional height	m	0.05		
Liner*	Liner depth	m	0.15		(m)
Liner	Transport lorry	tkm·p^{-1}	8,792	Transport, freight, lorry, unspecified {GLO}| market for	(e)
Liner	HDPE	kg·p^{-1}	80,792	Polyethylene, high density, granulate {GLO}| market for	(b)
Liner	HDPE waste	kg·p^{-1}	80,792	See Auxiliary: HDPE waste	
Liner	Transport train	tkm·p^{-1}	48,475	Transport, freight train {Europe without Switzerland}| market for	(e)
PW	Capacity	ha·p^{-1}	0.81		(k)
PW	Sizing factor		1.00		(h)
PW	Paddle width	m·p^{-1}	12.20		(k)

PW	Paddle thickness	m·p^{-1}	0.01		
PW	Paddle radials	#·p^{-1}	8.00		(n)
PW*	Paddle depth	m·p^{-1}	15.00		(m)
PW	Paddle material		HDPE		(o)
PW	Motor material		Steel		(o)
PW	Transport lorry	tkm·p^{-1}	22.43	Transport, freight, lorry, unspecified {GLO}| market for	(e)
PW	HDPE production	kg·p^{-1}	141.31	Polyethylene, high density, granulate {GLO}| market for	(b)
PW	Steel production	kg·p^{-1}	83.00	Steel, chromium steel 18/8 {GLO}| market for	(b,p)
PW	HDPE waste	kg·p^{-1}	141.31	See Auxiliary: HDPE waste	
PW	Steel waste	kg·p^{-1}	83.00	See Auxiliary: Steel waste	
PW	Transport train	tkm·p^{-1}	134.58	Transport, freight train {Europe without Switzerland}| market for	(e)
Option: PBR					
PBR	Capacity	m^3·p^{-1}	2.54		(q)
PBR	Int./ext. diam.	m·m^{-1}	0.88		(q)
PBR	Transport lorry	tkm·kg^{-1}	70.43	Transport, freight, lorry, unspecified {GLO}| market for	(e)
PBR	HDPE	kg·p^{-1}	704.26	Polyethylene, high density, granulate {GLO}| market for	(b)
PBR	HDPE waste	kg·p^{-1}	704.26	See Auxiliary: HDPE waste	
PBR	Transport train	tkm·kg^{-1}	422.56	Transport, freight train {Europe without Switzerland}| market for	(e)
Blower	Pump	p·p^{-1}	1.00	Pump, 40W {CH}| production [a]	(b)
Option: ProviApt					
ProviApt	Width	m·p^{-1}	1.25		(ae)
ProviApt	Panels	#·p^{-1}	35.00		(ae)
ProviApt	Distance panels	m	0.25		(ae)
ProviApt	Heigth	m	0.50		(ae)
ProviApt	Thickness	m	180.00		(ae)
ProviApt	Diameter panels	m	0.02		(ae)
ProviApt	HDPE production	kg·p^{-1}	13.07	Polyethylene, high density, granulate {GLO}| market for	
ProviApt	HDPE waste	kg·p^{-1}	13.07	See Auxiliary: HDPE waste	

ProviApt	Transport, lorry	tkm·p^{-1}	1.31	Transport, freight train {Europe without Switzerland}| market for	(e)
ProviApt	Transport, train	tkm·p^{-1}	7.84	Transport, freight train {Europe without Switzerland}| market for	(e)
Process: Preharvesting					
Option: IPC®					
IPC®	Capacity	m^2·p^{-1}	1.00		
IPC®	Sizing factor		1.00		
IPC®	Water	l·m^{-2}	20.50	Tap water {Europe without Switzerland}/| market for	
IPC®	Glycerine	g·m^{-2}	45.00	Glycerine {GLO}| market for	
IPC®	PES	g·m^{-2}	100.00	Polycarbonate {GLO}| market for	
IPC®	PVP	g·m^{-2}	50.00	See Auxiliary: PVP prod.	
IPC®	NaOCl	g·m^{-2}	5.00	Sodium hypochlorite, without water, in 15% solution state {GLO}| market for	
IPC®	NEP	kg·m^{-2}	6,944	N-methyl-2-pyrrolidone {GLO}| market for	
IPC®	Cl2 to air	g·m^{-2}	5.00	Emissions to air: Chlorine	
IPC®	AOX to water	g·m^{-2}	0.01	Emissions to water: AOX, Adsorbable Organic Halogen as Cl	
IPC®	NaOCl to water	g·m^{-2}	5.00	Emissions to water: Sodium hypochlorite	
IPC®	NEP to water	g·m^{-2}	305	Emissions to water: Organic compounds (unspecified)	
IPC®	Electricity	kWh·m^{-2}	1.11	Electricity, medium voltage {BE}| market for	
IPC®	PVP to waste	g·m^{-2}	49.00	See Auxiliary: pl. pack. Waste	
IPC®	PES to waste	g·m^{-2}	5.00	See Auxiliary: pl. pack. Waste	
IPC®	Glycerine to waste	g·m^{-2}	45.00	Wastewater, average {Europe without Switzerland}| market for wastewater, average	
IPC®	Wastewater+NEP	l·m^{-2}	27.81	Wastewater, average {Europe without Switzerland}| market for wastewater, average	
Tanks	Tank	p·p^{-1}	1.00	1 p Hot water tank, 600l {CH}| production	(b)
Pumps	Pump	p·p^{-1}	1.00	Pump, 40W {CH}| production[a]	(b)

Control eq.	Sizing factor		1.00	Electronic component, passive, unspecified {GLO}| market for	
Laptop	Sizing factor		1.00	Computer, laptop {GLO}| market for	
Process: Harvesting					
Option: Centrifuge					
Centrifuge	Sizing factor		0.56		(h)
Centrifuge	Capacity	$l \cdot h^{-1}$	3,750		(r)
Centrifuge	Steel	$kg \cdot p^{-1}$	3,750	Steel, chromium steel 18/8 {GLO}| market for	(b,r)
Centrifuge	Steel waste	$kg \cdot p^{-1}$	3,750	See Auxiliary: Steel waste	(r)
Process: Washing					
Tank	Tank	$p \cdot p^{-1}$	1.00	1 p Hot water tank, 600l {CH}| production	(b)
Mixer	Pump	$p \cdot p^{-1}$	1.00	Pump, 40W {CH}| production[a]	(b)
Centrifuge	Centrifuge	$p \cdot p^{-1}$	1.00	See Centrifuge of Process: Harvesting	
Process: Drying					
Option: Spray dryer					
Spray dryer	Capacity	$l \cdot s^{-1}$	1.00		(s)
Spray dryer	Sizing factor		0.60		(h)
Spray dryer	Transport lorry	$tkm \cdot p^{-1}$	29,895	Transport, freight, lorry, unspecified {GLO}| market for	(s)
Spray dryer	Steel	$kg \cdot p^{-1}$	22,900	Steel, chromium steel 18/8 {GLO}| market for	(b,s)
Spray dryer	Glass fibre	$kg \cdot p^{-1}$	96	Glass fibre {GLO}| market for	(b,s)
Spray dryer	Steel waste	$kg \cdot p^{-1}$	22,900	See Auxiliary: Steel waste	(s)
Spray dryer	Glass fiber waste	$kg \cdot p^{-1}$	96	See Auxiliary: Glass fibre waste	(s)
Spray dryer	Electric welding	$m \cdot kg^{-1}$	134	Welding, arc, steel {RER}| processing	(s)
Spray dryer	Rolling steel	$kg \cdot kg^{-1}$	22,900	Sheet rolling, chromium steel {RER}| processing	(s)
Option: Freeze dryer					
Freeze dryer	Spray dryer	$p \cdot p^{-1}$	1.00	See Spray Dryer Process: Drying	(b)
Process: Disruption					
Option: Bead mill					
Bead mill	Capacity	$l \cdot h^{-1}$	500.00		(af)
Bead mill	Sizing factor		0.60		
Bead mill	Steel	$kg \cdot p^{-1}$	750.00	Steel, chromium steel 18/8 {GLO}| market for	(b,af)

Bead mill	Volume	l	16.50		(af)
Bead mill	Electric welding	$m \cdot kg^{-1}$	4.39	Welding, arc, steel {RER}| processing	(ag)
Bead mill	Rolling steel	$kg \cdot kg^{-1}$	750.00	Sheet rolling, chromium steel {RER}| processing	(ag)
Bead mill	Transport lorry	$tkm \cdot p^{-1}$	7,027.08	Transport, freight, lorry, unspecified {GLO}| market for	(ag)
Bead mill	Steel waste	$kg \cdot p^{-1}$	750.00	See Auxiliary: Steel waste	
Bead mill	ZrO_2 waste	$kg \cdot p^{-1}$	4,66.45	See Auxiliary: Steel waste	
Bead mill	Pump	kW	0.55	Pump, 40W {CH}| production[a]	(af)
Beads	Filling	%	85.00	Zirconium oxide {GLO}| market for	(ah)
Beads	Lifetime	h	1500.00		(af)
Process: Extraction					
Option: Hexane extraction					
C_6H_{14}				Hexane {GLO}| market for	(b)
Em. C_6H_{14}				Emissions to air: Hexane	
Tank	Tank	$p \cdot p^{-1}$	1.00	1 p Hot water tank, 600l {CH}| production	(b)
Mixer	Pump	$p \cdot p^{-1}$	1.00	Pump, 40W {CH}| production[a]	(b)
Process: Filtration					
Membrane	Membrane	$p \cdot p^{-1}$	1.00	See IPC®	
Process: Lipid purification					
Option: Vacuum distillation					
Distiller	Spray dryer	$p \cdot p^{-1}$	1.00	See Spray Dryer Process: Drying	(b)
Ref β-car.					(u)
Ref ast.					(an)
Process: Lipid processing					
Option: Transesterification					
Methanol				Methanol {GLO}| market for	
NaOH				Sodium hydroxide, without water, in 50% solution state {GLO}| market for	(b)
HCl				Hydrochloric acid, without water, in 30% solution state {RER}|	

				market for	
P_2O_5				Phosphate fertiliser, as P2O5 {GLO}| market for	
Ref. diesel				Diesel {Europe without Switzerland}| petroleum refinery operation	
Ref. glycerol				Glycerine {GLO}| market for	(am)
CHOH em.				Emissions to air: Methanol	
NaOH em.				Emissions to air: NaOH	
HCl em.				Emissions to air: HCl	
P_2O_5 em.				Emissions to air: P_2O_5	
TE unit	Pumps	#	9.00	Pump, 40W {CH}| production [a]	(b,ai)
TE unit	Tanks	#	7.00	1 p Hot water tank, 600l {CH}| production	(b,ai)
TE unit	Distiller	#	2.00	See Spray Dryer Process: Drying	(ai)
TE unit	Heat exchangers	#	11.00	See Heat exchanger Process: Cultivation	(ai)
TE unit	Sizing factor		0.60		
Option: Hydrotreating					
Hydrogen				Hydrogen, liquid {RER}| market for	
H_3PO_4				Phosphoric acid, industrial grade, without water, in 85% solution state {RER}| purification of wet-process phosphoric acid to industrial grade, product in 85% solution state	
Clay				Clay {RoW}| market for clay	
Silica				Silica sand {GLO}| market for	
Ref. Diesel				Diesel {Europe without Switzerland}| petroleum refinery operation	
Ref. Naphtha				Naphtha {Europe without Switzerland}| petroleum refinery operation	
H_2 em.				Emission to air: H2	
H_3PO_4 em.				Emission to air: Phosphoric acid	
HT unit	Reactors	#	5.00	1 p Hot water tank, 600l {CH}| production	(b,aj)
HT unit	Separators	#	4.00	See Spray Dryer Process: Drying	(aj)
HT unit	Pump	#	1.00	Pump, 40W {CH}| production [a]	(b,aj)

HT unit	Compressor	#	2.00	Pump, 40W {CH}| production [a]	(b,aj)
HT unit	Heat exchanger	#	1.00	See Heat exchanger Process: Cultivation	(aj)
HT unit	Sizing factor		0.60		
PSA	Tank	#	1.00	1 p Hot water tank, 600l {CH}| production	(b,aj)
PSA	Sizing factor		0.60		
Pur. Unit	Reactors	#	3.00	1 p Hot water tank, 600l {CH}| production	(b,aj)
Pur. Unit	Centrifuge	#	1.00	See Centrifuge Process: Harvesting	(aj)
Pur. Unit	Filters	#	2.00	See IPC®	(aj)
Pur. Unit	Sizing factor		0.6		
Process: Residue purification					
Option: Evaporation					
Ref. fert.	N-fertilizer	kg·kg^{-1}	0.04	Nitrogen fertiliser, as N {GLO}| market for	(b,t,am)
Ref. fert.	P-fertilizer	kg·kg^{-1}	0.001	Phosphate fertiliser, as P2O5 {GLO}| market for	(b,t,am)
Ref. ff	Electricity boat	MJ·kg^{-1}	2.34	Electricity, medium voltage {PE}| market for	(ak)
Ref. ff	Aluminium	kg·kg^{-1}	0.07	Aluminium, wrought alloy {GLO}| market for	(ak)
Ref. ff	Aluminium landfill	%	20.00	Disposal, inert waste, 5% water, to inert material landfill/CH U	(ak)
Ref. ff	Steel	kg·kg^{-1}	0.07	Steel, chromium steel 18/8 {GLO}| market for	(ak)
Ref. ff	Steel landfill	%	90.75	Scrap steel {CH}| treatment of, inert material landfill	(ak)
Ref. ff	Steel recycling	%	9.25	See Auxiliary: Recycling steel	(ak)
Ref. ff	Plastic	kg·kg^{-1}	0.03	Polyethylene, high density, granulate {GLO}| market for	(ak)
Ref. ff	Plastic landfill	%	100.00	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH U	(ak)
Ref. ff	Lead	g·kg^{-1}	10.45	Lead {GLO}| market for	(ak)
Ref. ff	Lead EoL	%	100.00	Lead concentrate {GLO}| market for	
Ref. ff	Diesel	MJ·kg^{-1}	8.09	Diesel, burned in agricultural machinery {GLO}| market for diesel, burned in agricultural machinery	(ak)
Ref. ff	Electricity processing	MJ·kg^{-1}	0.56	Electricity, medium voltage {PE}| market for	(ak)
Ref. ff	Fuel oil	MJ·kg^{-1}	10.99	Heavy fuel oil {RoW}| market for	(ak)

Ref. ff	COD to water	kg·kg^{-1}	0.22	Emission to air: COD	(ak)
Evaporator	Spray dryer	p·p^{-1}	1.00	See Spray Dryer Process: Drying	(b)
Process: Residue processing					
Option: Pyrolysis					
Pyr. Unit	Spray dryer	p·p^{-1}	1.00	See Spray Dryer Process: Drying	(b)
Pyr. Unit	Sizing factor		0.60		
Com. bioch.				Hard coal, burned in power plant/BE	(al)
Com. syngas				Natural gas, burned in power plant/BE	(al)
HP eq.	Hydrotreating unit	p·p^{-1}	1.00	See Hydrotreating unit Process: Hydrotreatment	
HP eq	PSA	p·p^{-1}	1.00	See PSA Process: Hydrotreatment	
HP eq	Purification unit	p·p^{-1}	1.00	See Purification unit Process: Hydrotreatment	
HP eq	Sizing facor		0.60		
Hydrogen				Hydrogen, liquid {RER}| market for	
Ref. gasol.				Petrol, unleaded {Europe without Switzerland}| petroleum refinery operation	
Ref. diesel				Diesel {Europe without Switzerland}| petroleum refinery operation	
Option: Gasification					
Gasif. Unit	Spray dryer	p·p^{-1}	1.00	See Spray Dryer Process: Drying	(b)
Gasif. Unit	Sizing factor		0.60		
Com. bioch.				Hard coal, burned in power plant/BE	(al)
Com. syngas				Natural gas, burned in power plant/BE	(al)
HP eq	Hydrotreating unit	p·p^{-1}	1.00	See Hydrotreating unit Process: Hydrotreatment	
HP eq	PSA	p·p^{-1}	1.00	See PSA Process: Hydrotreatment	
HP eq	Purification unit	p·p^{-1}	1.00	See Purification unit Process: Hydrotreatment	
HP eq	Sizing facor		0.60		
Hydrogen				Hydrogen, liquid {RER}| market for	
Ref. gasol.				Petrol, unleaded {Europe without Switzerland}| petroleum refinery operation	
Ref. diesel				Diesel {Europe without Switzerland}| petroleum refinery	

				operation	
Option: Torrefaction					
Tor. Unit	Spray dryer	$p \cdot p^{-1}$	1.00	See Spray Dryer Process: Drying	(b)
Tor. Unit	Sizing factor		0.60		
Com. bioch.				Hard coal, burned in power plant/BE	(al)
Com. syngas				Natural gas, burned in power plant/BE	(al)
HP eq	Hydrotreating unit	$p \cdot p^{-1}$	1.00	See Hydrotreating unit Process: Hydrotreatment	
HP eq	PSA	$p \cdot p^{-1}$	1.00	See PSA Process: Hydrotreatment	
HP eq	Purification unit	$p \cdot p^{-1}$	1.00	See Purification unit Process: Hydrotreatment	
HP eq	Sizing facor		0.60		
Hydrogen				Hydrogen, liquid {RER}| market for	
Ref. gasol.				Petrol, unleaded {Europe without Switzerland}| petroleum refinery operation	
Ref. diesel				Diesel {Europe without Switzerland}| petroleum refinery operation	
Option: HTL					
HTL unit	Spray dryer	$p \cdot p^{-1}$	1.00	See Spray Dryer Process: Drying	(b)
Hydrogen				Hydrogen, liquid {RER}| market for	
Solid waste				Final waste flow: solid waste	
Ref. gasol.				Petrol, unleaded {Europe without Switzerland}| petroleum refinery operation	
HTL unit	Sizing factor		0.60		
HP eq	Hydrotreating unit	$p \cdot p^{-1}$	1.00	See Hydrotreating unit Process: Hydrotreatment	
HP eq	PSA	$p \cdot p^{-1}$	1.00	See PSA Process: Hydrotreatment	
HP eq	Purification unit	$p \cdot p^{-1}$	1.00	See Purification unit Process: Hydrotreatment	
HP eq	Sizing facor		0.60		
Hydrogen				Hydrogen, liquid {RER}| market for	

Ref. gasol.				Petrol, unleaded {Europe without Switzerland}| petroleum refinery operation	
Ref. diesel				Diesel {Europe without Switzerland}| petroleum refinery operation	
Option: Anaerobic digestion					
Digester	Spray dryer	p·p^{-1}	1.00	See Spray Dryer Process: Drying	(b)
Ref. CO_2				Carbon dioxide, liquid {RER}| market for	(b)
Ref. CH_4				Methane, 96% by volume {GLO}| market for	
N-fertillizer				Nitrogen fertiliser, as N {GLO}| market for	
P-fertilizer	P to P_2O_5 ratio	kg·kg^{-1}	2.41	Phosphate fertiliser, as P2O5 {GLO}| market for	
K-fertilizer	K to K_2O ratio	kg·kg^{-1}	4.58	Potassium fertiliser, as K2O {GLO}| market for	
Digester	Sizing factor		0.60		
Auxiliary					
Pl. Waste	Transport lorry	tkm·kg^{-1}	0.019	Transport, freight, lorry, unspecified {GLO}| market for	(v)
Pl. Waste	Transport train	tkm·kg^{-1}	0.011	Transport, freight train {Europe without Switzerland}| market for	(v)
Pl. Waste	Recycled plastic	kg·kg^{-1}	0.85	See Auxiliary: Plastic recycling	(w)
Pl. Waste	Incinerated plastic	kg·kg^{-1}	0.11	Disposal, polyethylene, 0.4% water, to municipal incineration/CH	(w)
Pl. Waste	Landfilled plastic	kg·kg^{-1}	0.05	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH	(w)
Pl. recycl.	Replaced pl. (QF)	kg·kg^{-1}	0.75	Packaging film, low density polyethylene {GLO}| market for	(y)
Pl. recycl.	Electricity	kWh·kg^{-1}	0.60	Electricity, medium voltage {BE}| market for	(z)
Tit. waste	Transport lorry	tkm·kg^{-1}	0.019	Transport, freight, lorry, unspecified {GLO}| market for	(aa)
Tit. waste	Transport train	tkm·kg^{-1}	0.011	Transport, freight train {Europe without Switzerland}| market for	(aa)
Tit. waste	Recycled tit.	kg·kg^{-1}	0.9998	See Auxiliary: Tit. Recycle.	(w)
Tit. waste	Landfilled tit.	kg·kg^{-1}	0.0002	Disposal, inert waste, 5% water, to inert material landfill/CH U	(w)
Tit. rec.	Replaced tit. (QF)	kg·kg^{-1}	1.00	Titanium, primary {GLO}| market for	(y)
Tit. rec.	Electricity	GJ·kg^{-1}	0.026	Electricity, medium voltage {BE}| market for	(ac)

P. Waste	Transport, lorry	tkm·kg^{-1}	0.019	Transport, freight, lorry, unspecified {GLO}| market for	(v)
P. Waste	Transport train	tkm·kg^{-1}	0.011	Transport, freight train {Europe without Switzerland}| market for	(v)
P. Waste	Recycled paper	kg·kg^{-1}	0.9994	Paper (waste treatment) {GLO}| recycling of paper	(w)
P. Waste	Incinerated paper	kg·kg^{-1}	0.0005	Disposal, packaging paper, 13.7% water, to municipal incineration/CH U	(w)
P. Waste	Recycled paper	kg·kg^{-1}	0.14	Paper (waste treatment) {GLO}| recycling of paper	
P. Waste	Landfilled paper	kg·kg^{-1}	0.86	Disposal, packaging paper, 13.7% water, to sanitary landfill/CH U	
HDPE waste	Transport lorry	tkm·kg^{-1}	0.019	Transport, freight, lorry, unspecified {GLO}| market for	(v)
HDPE waste	Transport train	tkm·kg^{-1}	0.011	Transport, freight train {Europe without Switzerland}| market for	(v)
HDPE waste	Recycled HDPE	kg·kg^{-1}	0.85	See Auxiliary: HDPE recycle.	(w)
HDPE waste	Incinerated HDPE	kg·kg^{-1}	0.11	Disposal, polyethylene, 0.4% water, to municipal incineration/CH U	(w)
HDPE waste	Landfilled HDPE	kg·kg^{-1}	0.05	Disposal, polyethylene, 0.4% water, to sanitary landfill/CH U	(w)
HDPE rec.	Electricity	kWh·kg^{-1}	0.60	Electricity, medium voltage {BE}| market for	(z)
HDPE rec.	Replaced HDPE (QF)	kg·kg^{-1}	0.75	Polyethylene, high density, granulate {GLO}| market for	(b,y)
Steel waste	Transport lorry	tkm·kg^{-1}	0.0193	Transport, freight, lorry, unspecified {GLO}| market for	(aa)
Steel waste	Transport train	tkm·kg^{-1}	0.011	Transport, freight train {Europe without Switzerland}| market for	(aa)
Steel waste	Recycled Steel	kg·kg^{-1}	0.9998	See Auxiliary: Recycle steel	(w)
Steel waste	Landfilled Steel	kg·kg^{-1}	0.0002	Scrap steel {CH}| treatment of, inert material landfill	(w)
Rec. Steel	Electricity	GJ·kg^{-1}	0.023	Electricity, medium voltage {BE}| market for	(aa,ac)
Rec. Steel	Replaced steel (QF)	kg·kg^{-1}	1.00	Steel, chromium steel 18/8 {GLO}| market for	(b,y)
PVP prod.	1,4-butanediol	kg·kg^{-1}	0.80	Butane-1,4-diol {GLO}| market for	(ad)
PVP prod.	Acetylene	kg·kg^{-1}	0.23	Acetylene {GLO}| market for | Alloc Def, U	(ad)
PVP prod.	Hydrogen to air	kg·kg^{-1}	0.04	Emissions to air: Hydrogen	(ad)

PVP prod.	Water to water	kg·kg^{-1}	0.16	Emissions to water: water	(ad)
PVP prod.	Ammonia	kg·kg^{-1}	0.15	Ammonia, liquid {RER}| market for	(ad)
Gl. f. waste	Transport lorry	tkm·kg^{-1}	0.0193	Transport, freight, lorry, unspecified {GLO}| market for	(aa)
Gl. f. waste	Transport train	tkm·kg^{-1}	0.011	Transport, freight train {Europe without Switzerland}| market for	(aa)
Gl. f. waste	Recycled gl. f.	kg·kg^{-1}	0.94	See Auxiliary: Glass recycling	(w)
Gl. f. waste	Incinerated gl.f.	kg·kg^{-1}	0.01	Waste glass {Europe without Switzerland}| treatment of waste glass, municipal incineration	(w)
Gl. f. waste	Landfilled gl. f.	kg·kg^{-1}	0.05	Disposal, glass, 0% water, to inert material landfill/CH U	(w)
Gl. f. rec.	Replaced gl. f. (QF)	kg·kg^{-1}	1.00	Glass fibre {GLO}| market for	(b,y)

(a) (T. W. Zhang & Dornfeld, 2007); (b) adapted to Belgian conditions; (c) stoichiometry with efficieny of 95%; (d) (Hischier et al., 2004); (e) (Frischknecht et al., 2004); (f) (B. P. Weidema et al., 2013); (g) (MBFerts); (h) economic regression function; (i) (Peters et al., 2003); (j) (AZALP Pahlen Aqua Mex compleet 70 kW - Titanium); (k) (J. N. Rogers et al., 2014); (l) (R. E. Davis et al., 2014); (m) (Tafreshi & Shariati, 2006); (n) (Lundquist et al., 2010); (o) (Collet et al., 2014); (p) (Rotary power); (q) (Acién et al., 2012); (r) (Flottweg); (s) (Ciesielski & Zbicinski, 2010); (t) (Greenwell et al., 2009); (u) (Bauer et al., 2003; Bonrath et al., 2010; Bonrath et al., 2004; Drapal et al., 2001; Feng et al., 2012; Herbert, 1948; Isler et al., 1956; Khusnutdinov et al., 2016; Litzmann et al., 2012; Markovich, 1998; Midland & Gallou, 2001; Newman & Vander Zwan, 1973; Patent, 2009b, 2012, 2014; Reardan & Combe, 2007; Reichart et al., 2012; Shahabuddin et al., 2011; Slotte et al., 2015; Tang & Zhao, 2014; Urban & Bakshi, 2009; Vani et al., 2006; W. Weiss et al., 2005; 印俊, 2004); (v) Waste polyethylene {Europe without Switzerland}| market for waste polyethylene; (w) (Eurostat); (x) (Mutha et al., 2006); (y) (Gala et al., 2015); (z) PE (waste treatment) {GLO}| recycling of PE; (aa) Scrap steel {Europe without Switzerland}| market for scrap steel; (ab) (Darabshaw, 2015); (ac) (Johnson et al., 2008); (ad) (Pourzahedi & Eckelman, 2015); (ae) (de Vree, 2016); (af) Information supplier; (ag) adapted from spray dryer; (ah) (J. Doucha & Lívanský, 2008); (ai) (Pokoo-Aikins et al., 2009); (aj) (L. Wu & Liu, 2016); (ak) (Pelletier, 2006); (al) assumed same combustion process, input put at zero; (am) removed the transport emissions; (an) (Arndt, Henkelmann, Kindler, & Klass, 2002; Ding, Metiu, & Stucky, 2013; Ernst, 2002; Ernst, Dobler, Paust, & Rheude, 1995; Gummin, Haefele, & Noesberger, 2007; Hahn, Huthmacher, Hübner, & Krill, 1999; Lockwood et al., 2004; Nakayama, Hirso, & Yazawa, 1980; Nosberger & Vieth, 1994; Organic Syntheses, 1940; 2009a, 2014; Reichart et al., 2012; Shahabuddin et al., 2011; Volland et al., 2003; Wagner, 1986; Meng Wang et al., 2015; Wilfried Weiss & Dawidowski, 2004; Wittig & Bickelhaupt, 1958; Yamada et al., 2009; Yamahara, Kishimoto, Nakamura, Deguchi, & Takamatsu, 1973; Y. Zhang, Zhu, et al., 2013; 印俊, 2004). Abbreviations: Ref/C = Reference/Comment; pack. = packaging; rec. = recycling; pl. = plastic; QF = quality factor; em. = emission; exc. = exchanger; tit. = titanium; p. = paper; prod. = production; PW: paddlewheel; eq. = equipment; transf. = transformation; MPS = medium preparation system; fr. = fraction; sep. = separation; SSP = single superphosphate; TSP = triple superphosphate; Int./ext. diam. = internal/external diameter; Tor. = Torrefaction; Gas. = Gasification; Gasol.= Gasoline; Pyr. = Pyrolysis; TE = Transesterification; HP = Hydroprocessing; HT = Hydrotreatmen; eq = equipment; com = combustion; bioch. =biochar; ff = fish feed; pur. = purification. § IPS = Inoculum production system; the impact of the first cultivation stage of the PBR cultivation option is scaled to produce the corresponding amount of inoculum; * In second cultivation stage: height = 12 m.

Process flow diagrams MOO case study

Figure A3.1-A3.11 are the process flow diagrams of the Pareto-optimal scenarios of the MOO case study.

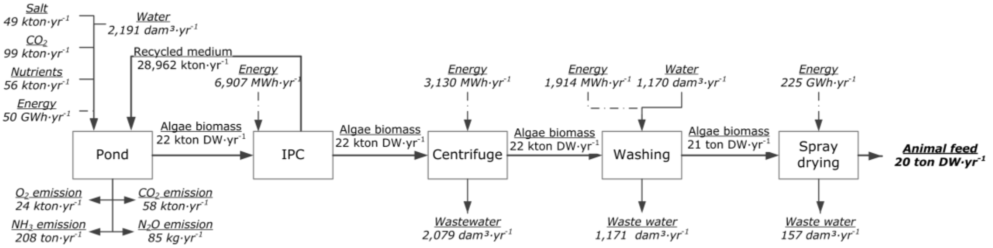

Figure A3.1. PFD Ns AF scenario

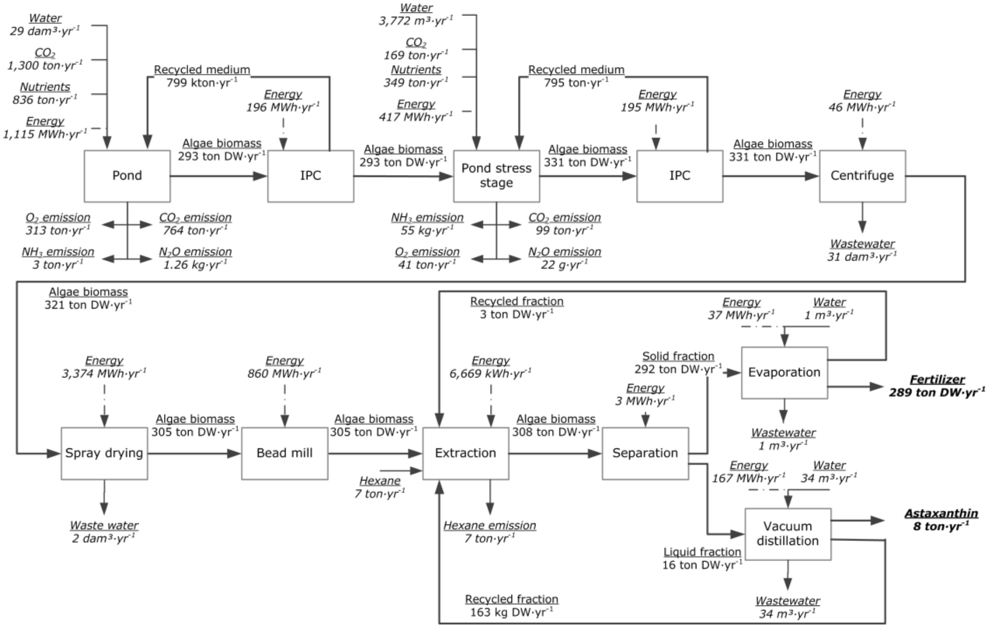

Figure A3.2. PFD Hp F scenario

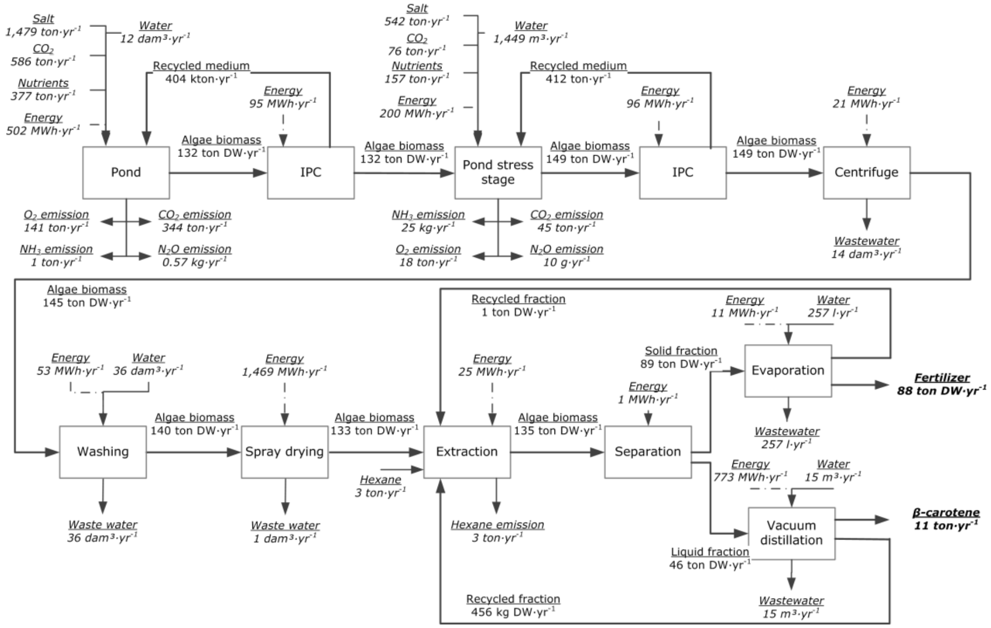

Figure A3.3. PFD Ds F scenario

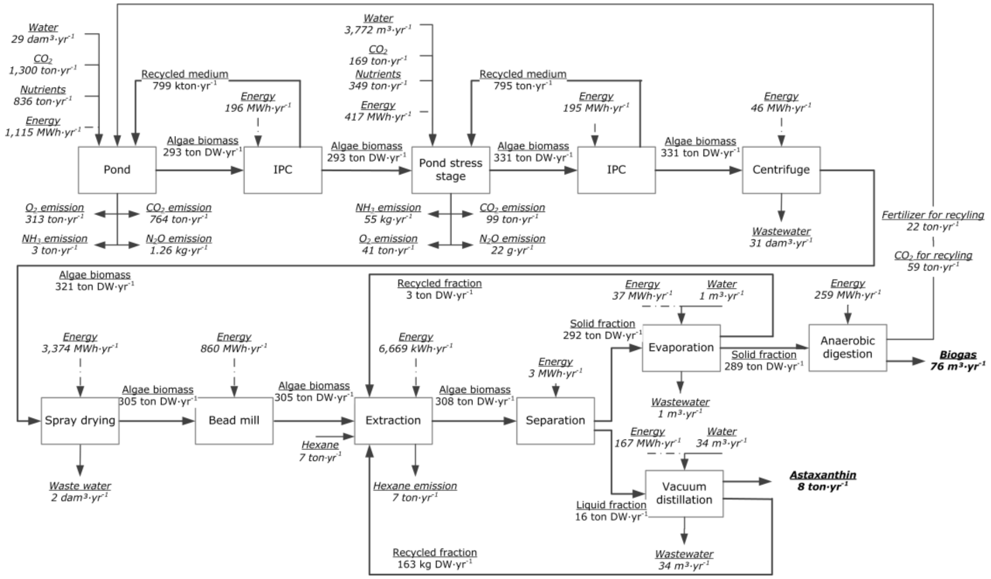

Figure A3.4. PFD Hp AD scenario

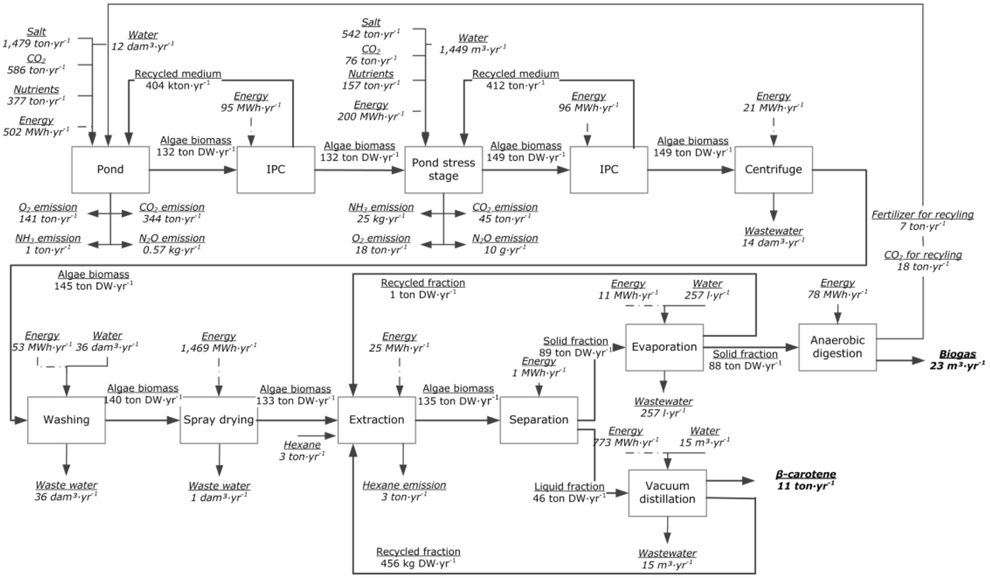

Figure A3.5. PFD Ds AD scenario

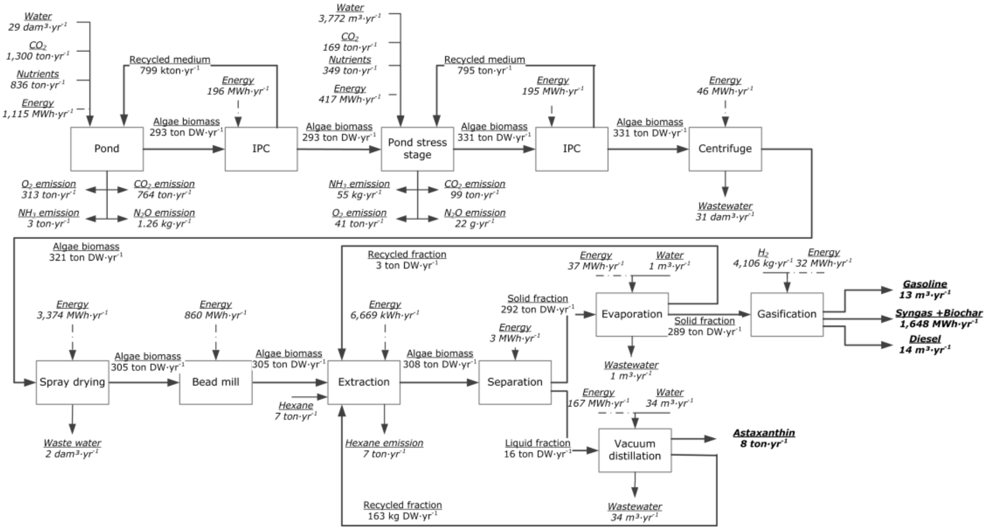

Figure A3.6. PFD Hp G scenario

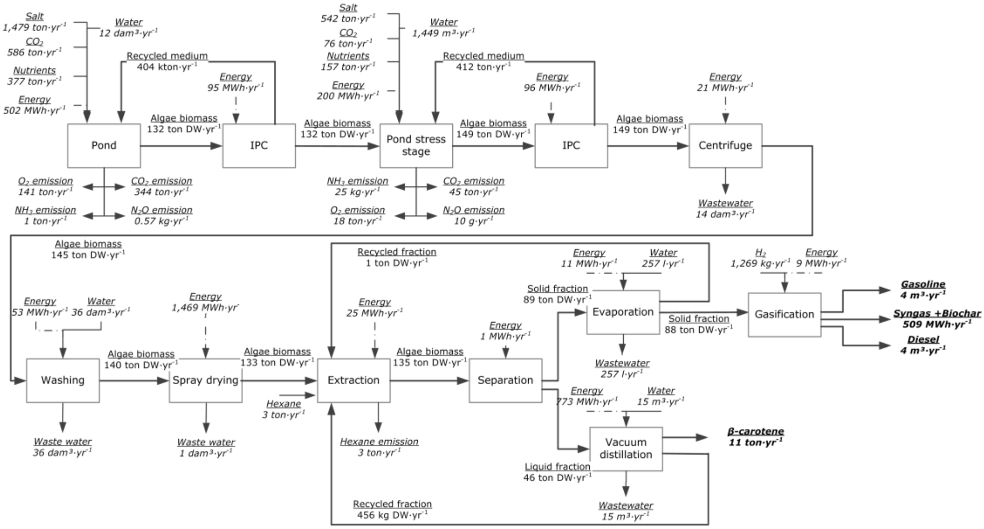

Figure A3.7. PFD Ds G scenario

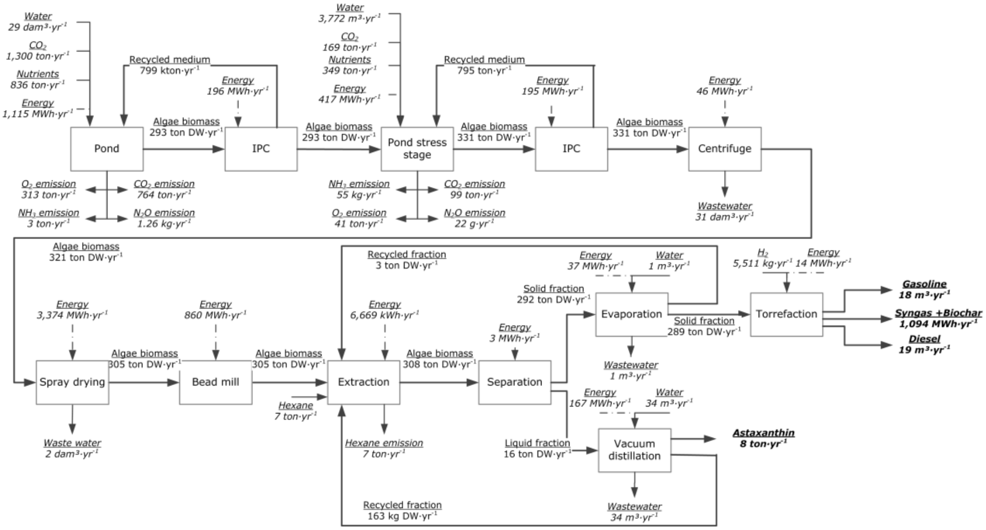

Figure A3.8. PFD Hp T scenario

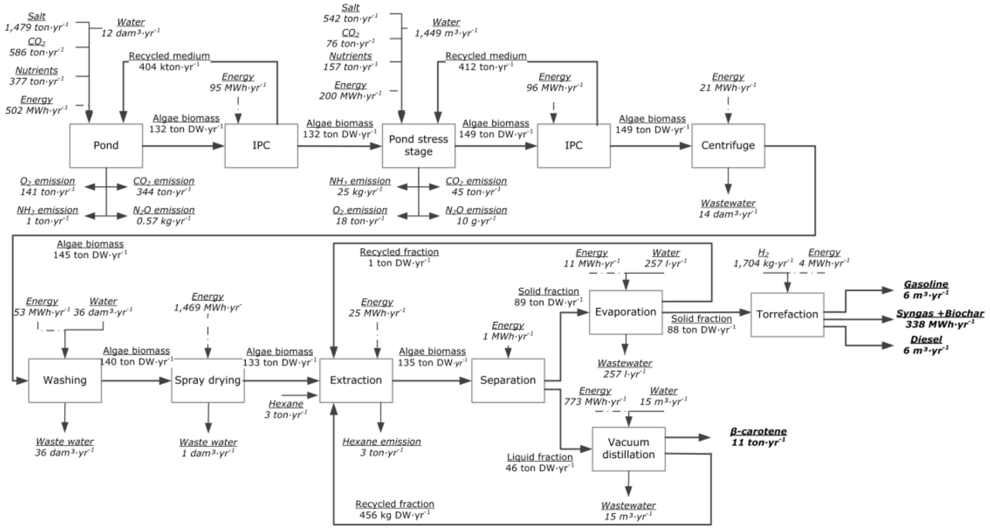

Figure A3.9. PFD Ds T scenario

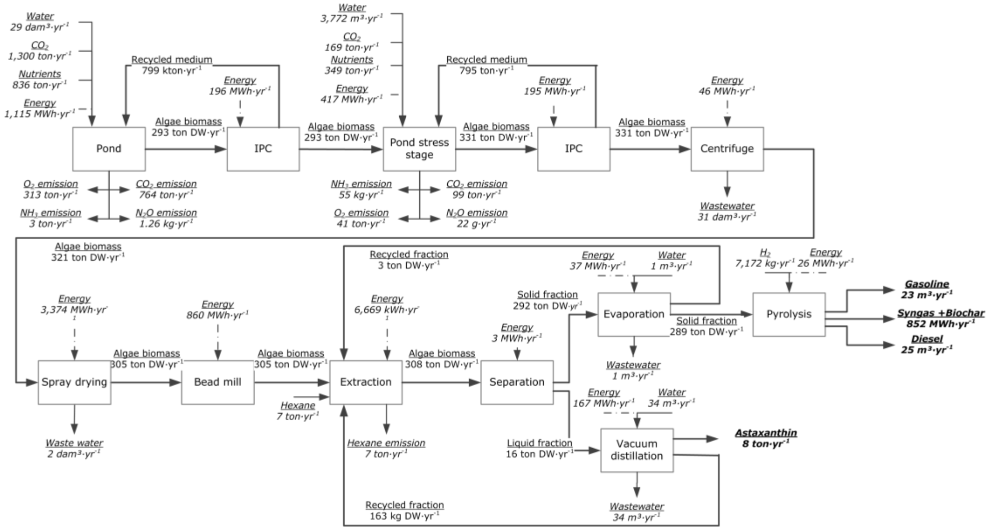

Figure A3.10. PFD Hp P scenario

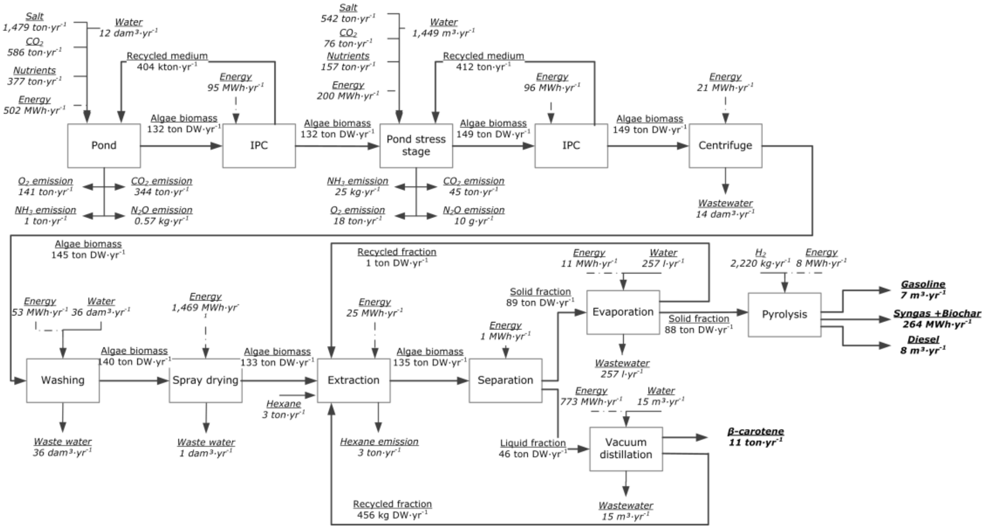

Figure A3.11. PFD Ds P scenario

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