Integrated sustainability assessment of Dunaliella-based algae biorefinery concepts

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Heidelberg, November 2017

Acknowledgements

The authors would like to thank all D-FACTORY partners sincerely for the provision of the data, which forms the basis of the sustainability assessment.

This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no. 613870 (THE MICRO ALGAE BIOREFINERY, "D-FACTORY").

Suggested citation:

Keller, H., Reinhardt, G., Gärtner, S., Rettenmaier, N., Goacher, P., Mitchell, R., Peñaloza, D., Stahl, S., Harvey, P. (2017): Integrated sustainability assessment of Dunaliella-based algae biorefinery concepts. In: D-Factory project reports, supported by the EU's FP7 under GA No. 613870, IFEU - Institute for Energy and Environmental Research Heidelberg, Heidelberg, Germany, available at www.ifeu.de/algae

Integrated sustainability assessment of *Dunaliella*-based algae biorefinery concepts

This report was produced as Deliverable 7.8 within Work Package 7 "Integrated assessment of sustainability" of the EU-funded project D-Factory ("The Micro Algae Biorefinery")

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Heidelberg, November 2017

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1 Executive Summary

The EU funded project D-Factory "*The micro algae biorefinery*" seeks to demonstrate a sustainable CO_2 algae biorefinery based on the cultivation and processing of the alga *Dunaliella salina* for natural products and potentially multiple markets. So far, *Dunaliella salina*, which grows in highly concentrated saltwater, is cultivated only for β-carotene production and sold as capsules containing unprocessed dried algae powder. This project aims at generating additional value by separating individual high-value carotenoids and their isomers present in the powder to be able to serve customers according to their specific needs. Furthermore, lower value biomass fractions are put into use as new co-products.

An integrated sustainability assessment led by IFEU – Institute for Energy and Environmental Research Heidelberg, Germany, analyses the sustainability impacts of the newly devised processes (see chapter 4 for a description). It is based on scenarios for 2025 to support decisions to be made during the implementation process. The assessment joins detailed analyses of technological, environmental, economic and social aspects (see chapters 5.1-0 for summaries) into an overall picture and derives common conclusions and recommendations (chapters 5.5 and 6). Most important insights are summarised below:

Sustainability of *Dunaliella* cultivation and harvesting

Any algae biomass production requires substantial energy and material inputs. Algae-based products are therefore not intrinsically sustainable. Instead, their production must be carefully optimised, as is the case for all other products. *Dunaliella* cultivation is already established in Israel, for example, but its energy and material efficiency can still be increased further. Moreover, production at other sites requires extensive adaptations.

The further development of *Dunaliella* production technologies and concepts in this project has revealed enormous optimisation potentials. If these potentials are realised instead of merely implementing transferable elements of the Israeli concept under different conditions, environmental burdens of each tonne of produced algae biomass can be reduced by up to 90%, for example. New algae cultivation medium recycling methods, aided by membrane pre-concentration, and harvesting intact algae cells by means of innovative spiral-plate centrifuges will be decisive to achieving the improvements. These technologies have been developed further in the project, but still need to achieve their potential in industrial-scale *Dunaliella* production. Moreover, the energy for algae cultivation should be supplied by renewables, for example by on-site solar power generation, in particular because the power demand and generation profiles generally match well.

The effects of these improvements on economic and social sustainability are also positive, although to different extents. For example, the conversion of waste streams to feeds and glycerol as new co-products causes substantial reductions in environmental impacts, but only marginal 0.4% improvement in profit margin. Medium recycling, in contrast, saves both costs and environmental burdens, and also makes it easier to comply with regulatory constraints.

Sustainability of *Dunaliella* processing

The dried algae biomass can continue to be sold directly as a β-carotene source as in existing businesses. However, this does not put a value on all other contained substances. In this project, new processes were therefore designed with which high value carotenoids and their isomers such as zeaxanthin or *9-cis* β-carotene can be separated and converted to additional products. A novel pharmaceutical active ingredient against cardiovascular disease may have been created with the production of pure *9-cis* β-carotene. Its production at the achieved purity was demonstrated for the first time in this project.

In a first step, a new extraction method employing supercritical CO_2 was introduced, producing a defatted powder containing constituents such as carbohydrates and proteins. This leads to the creation of further high value feed as a co-product, which can deliver substantial reductions in environmental burdens by substituting conventional feeds.

Further steps fractionate the carotenoid extract and thus generate more high value co-products in addition to *9-cis* β-carotene, but require a lot of energy and solvents to achieve this. However, if initial indications that *9-cis* ß-carotene extract displays similar efficacy to the pure substance are confirmed, this fractionation would not be necessary. To what degree it improves overall sustainability, is a question of perspective:

- The highest profitability at comparatively low investment costs occur if the final and most complex step is left out and one product less (α-carotene) is therefore produced.
- This scenario also shows the lowest social risks.
- Up to 50 times lower, but nevertheless substantial, environmental burdens are caused if fractionation is dispensed with completely and 6 products are instead produced by existing conventional processes. This also requires the lowest investment.

If a novel health benefit is provided in this way in a future *Dunaliella*-based algae biorefinery, social acceptance of the sustainability impacts is highly probable, assuming they are not excessive or avoidable. Also in response to this result, a new modular high-performance countercurrent chromatography (HPCCC) system was developed within this project that is expected to increase resource efficiency and reduce environmental impacts profoundly. The adequacy of improvements remains to be confirmed e.g. in a follow-up sustainability assessment once sufficient experience is gained for reliable quantitative modelling. As a fallback option, assuming *9-cis* β-carotene is also efficacious in the extract, fractionation could be reduced as far as possible or eliminated. If the whole process chain is thoroughly optimised, also the fallback option can be highly profitable.

Conclusions and recommendations: lessons learned

<u>Dunaliella cultivation and processing requires high expenditures.</u>

- Processes need to be and can be optimised.
- Sustainability assessment helps to identify suitable measures.

<u>Whether *9-cis* β-carotene provides a new health benefit or not determines degree of required optimisations. Sustainability impacts seem acceptable for a new pharmaceutical unless avoidable or excessive but for ‘only’ a natural nutraceutical higher expectations regarding sustainability should be fulfilled.</u>

- Verify the novel medical value of *9-cis* β-carotene in an adequate clinical trial.
- Test not only the pure substance but also *9-cis* β-carotene in mixtures.

In the analysed scenarios, downstream processing causes by far highest burdens, risks and costs.

- The modular high-performance countercurrent chromatography (HPCCC) system newly devised within this project should be realised in a relevant environment and evaluated for sustainability impacts.
- As a fallback option, if *9-cis* β-carotene shows sufficient pharmaceutical efficacy already in extracts, they should not be purified further to avoid environmental burdens and social risks.

Site selection is crucial in particular for *Dunaliella* cultivation.

- Integrate with existing salt activities.
- Flue gas needs to be, and waste heat should preferably be, available e.g. from a power plant.
- Do not use arable land (exceptions subject to conditions).
- Guarantee sufficient availability of freshwater.

Social risks need to be managed

- High social risks are not a no-go but entail obligations. E.g. closely monitor situation to avoid negative social impacts.
- Select suppliers according to social reporting standards such as GRI.

Solar power can make a big difference.

- Use as much of own renewable energy, in particular photovoltaics, as possible for algae cultivation.

Feed production makes some money and enormously improves land use related environmental burdens.

- Continue to establish defatted powder as chicken/fish feed.
- Research feed value of all other lower value biomass streams.
- Convert all algae constituents to products.
- Continue to research use of defatted powder in novel foods as substitute of fish-based ingredients.

Boundary conditions are important for sustainability.

- Support approval processes as required because regulatory barriers may prevent realisation by SMEs.
- In the future, solar power may compete for land and CCU/CCS may compete for remaining CO_2 sources. Therefore, a coordination of policies is required.

Perspectives

The production of *9-cis* β-carotene together with more or fewer co-products in a *Dunaliella*-based algae biorefinery represents a highly promising concept. This study has shown the steps needed to achieve acceptable production sustainability. Here, it is important to always keep the entire value-added chain in view. If production conditions of inputs are not otherwise generally defined, in contrast to grid power generation, for example, influence as a customer can and should be applied. Social risks in the supply chain need not result in social problems if they are appropriately managed. The environmental impacts of some inputs can also be reduced by actively selecting suppliers from an environmental point of view. This should always be taken into consideration in addition to reducing the required quantity of materials. Detailed recommendations to businesses, science, policymakers and consumers on how to address all these issues can be found in this report.

2 Goals of the project and of this report

2.1 Goal of the project

The EU funded project D-Factory "*The micro algae biorefinery*" seeks to demonstrate a sustainable CO_2 algae biorefinery based on the cultivation and processing of the alga *Dunaliella salina* for natural products and potentially multiple markets. So far, *Dunaliella salina*, which grows in highly concentrated saltwater, is cultivated only for β-carotene production and sold as capsules containing unprocessed dried algae powder. This project aims at generating additional value by separating individual high-value carotenoids and their isomers present in the powder to be able to serve customers according to their specific needs. Furthermore, lower value biomass fractions are put into use as new co-products.

This project includes an integrated sustainability assessment. It analyses the implications for sustainability associated with D-Factory systems, shows optimisation potentials and identifies the options that are the most sustainable for delivering value from the chosen alga, *Dunaliella salina* in an industrial setting.

2.2 Goal of this report

This report analyses all relevant sustainability impacts of potential future value chains according to the D-Factory concept. The overall sustainability assessment in this study is based on a life cycle approach. It takes into account the entire life cycle from “cradle” (= algae cultivation) to “grave” (e.g. end-of-life treatment) including the use of co-products (Figure 2-1). The analysis of the life cycles within D-Factory follows the integrated life cycle sustainability assessment (ILCSA) methodology [Keller et al. 2015]. The methodology builds upon and extends existing frameworks and standards [Andrews et al. 2009; ISO 2006a; b; JRC-IES 2012; Swarr et al. 2011] (see chapter 3 for details). This report joins the detailed anal-

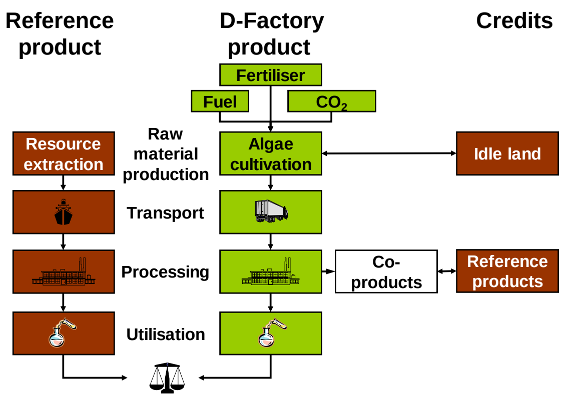


Figure 2-1: Schematic illustration of the life cycle comparison of the D-Factory plant (green) with conventional provision of products such as dietary supplements or chemicals (brown).

yses of technological, environmental, economic and social aspects [Harvey 2017a; Keller et al. 2017; Mitchell & Goacher 2017; Peñaloza & Stahl 2017] (see chapters 5.1 – 0 for summaries) into an overall picture (chapter 5.5).

This report answers the following key questions set out for the integrated assessment of sustainability:

- How does a future D-Factory plant, using mature technology, perform regarding environmental, economic and social impacts, compared to a conventional provision of equivalent products?
- How can the impacts of a future D-Factory plant be further improved?
  - Which unit processes determine the results significantly and what are the optimisation potentials?
  - Which is the best option for algae cultivation and harvesting?
  - Which downstream processes should proceed after algae harvesting, i.e. which product portfolio shows the best environmental, economic and social footprint?
  - Which of the technologies and applications studied in the D-Factory project, which could not be included into main quantitative sustainability assessment scenarios, have the potential to improve the environmental, economic and social impacts substantially if they should be included at a later stage?
- What is the influence of different uses and accounting methods for the main product *9-cis* β-carotene?
- Are there any constraints or bottlenecks that could hinder the large-scale deployment of D-Factory biorefineries?

3 Methodological approach

The sustainability analysis in D-Factory is based on common goal, scope, definitions and settings for the technological, environmental and socio-economic analyses. They are a prerequisite of an overall sustainability assessment and highly affect the assessment results. They are described in chapter 3.1. Specific definitions and settings that are only relevant for the technological, environmental, economic and social assessment are described in the respective reports [Harvey 2017a; Keller et al. 2017; Mitchell & Goacher 2017; Peñaloza & Stahl 2017].

3.1 ILCSA methodology

The analysis of the life cycles within D-Factory follows the integrated life cycle sustainability assessment (ILCSA) methodology (Figure 3-1). The methodology builds upon existing frameworks. It is based on international standards such as [ISO 2006a; b], the International Reference Life Cycle Data System (ILCD) guidelines [JRC-IES 2012], the SETAC code of practice for life cycle costing [Swarr et al. 2011] and the UNEP/SETAC guidelines for social life cycle assessment [Andrews et al. 2009]. ILCSA extends them with features for ex-ante assessments such as the identification of implementation barriers that increase the value for decision makers. This flexibility allows for focussing on those sustainability aspects relevant in the respective decision situation using the best available methodology for assessing each aspect within the overarching ILCSA. Furthermore, it introduces a structured discussion of results to derive concrete conclusions and recommendations. This includes a benchmarking procedure in which all scenarios are compared to a selected benchmark scenario. It is adapted to each decision context. See chapter 5.5.1 for details on the procedure selected in this study.

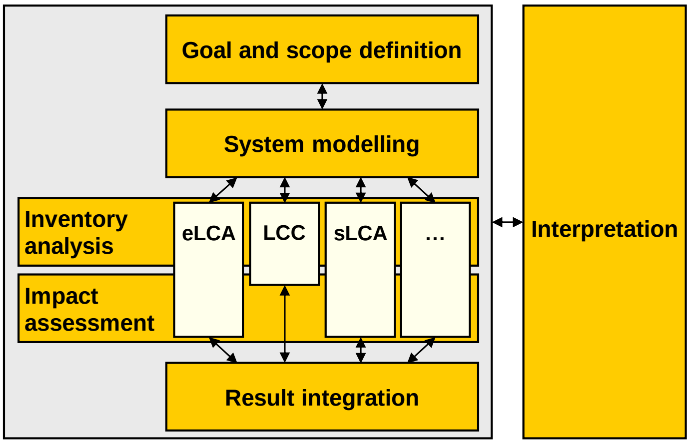


Figure 3-1: Schematic workflow of integrated life cycle sustainability assessment (ILCSA) [Keller et al. 2015]. It provides a framework to integrate several life cycle based assessments such as (environmental) life cycle assessment, (e)LCA, life cycle costing, LCC, social life cycle assessment, sLCA and analyses of other sustainability-relevant aspects.

3.2 Common definitions and settings

The analysis of the life cycles within D-Factory follows the ILCSA methodology [Keller et al. 2015]. It is based on international standards such as [ISO 2006a; b], the International Reference Life Cycle Data System (ILCD) guidelines [JRC-IES 2012], the SETAC code of practice for life cycle costing [Swarr et al. 2011] and the UNEP/SETAC guidelines for social life cycle assessment [Andrews et al. 2009]. The following common definitions and settings apply to all parts of the integrated sustainability assessment:

System boundaries

System boundaries specify which unit processes are part of the product system and thus included into the assessment, e.g. whether the entire or a partial life cycle will be analysed.

The sustainability assessment of the D-Factory system will take into account the **entire value chain (life cycle) from cradle to grave**, i.e. from algae cultivation to the distribution and usage of final products including land use change effects (Figure 2-1). Life cycle approaches avoid problem shifting from one life cycle stage to another, from one geographic area to another and from one environmental medium or protection target to another. In other words, no impact should escape.

Such shifting of burdens can also occur if impacts of **infrastructure** provision are significantly different between the compared pathways. The impacts of e.g. required roads may be less relevant and comparable between alternatives but infrastructure for algae cultivation is expected to be important, especially if photobioreactors are involved. To provide a balanced picture, infrastructure elements for algae cultivation and biorefinery are always taken into account for all pathways. Yet, only relevant infrastructure specific for the investigated processes is assessed explicitly. This in particular includes infrastructure for algae cultivation. Infrastructure that is used for other purposes as well (e.g. roads for transportation) or that is similar for the investigated scenarios and conventional reference systems (e.g. office buildings) is not assessed explicitly if the impact on the final results is negligible.

Technical reference

The technical reference describes the technology to be assessed in terms of development status/maturity. Scenarios of potential future D-Factory plants will be based on mature technology. Measured data (as far as available) from experiments and demo scale trials will only be used to validate the scenarios but will not be used directly for the assessment for two reasons:

1. It is not meaningful to compare immature processes with mature conventional processes producing the same products.
2. An assessment based on measured data requires routine operations for several years to average weather influences on cultivation. This is not possible because the project time does not allow this.

Time frame

The D-Factory system must be described not only in space but also in time. The time frame of the assessment determines e.g. the development status of biorefinery technology. Likewise, the environmental impact associated with conventional products changes over time (hopefully decreasing), e.g. greenhouse gas emissions associated with electricity generation.

The D-Factory project intends to install and operate a demo plant by its conclusion in 2017. Optimised routine operations of this unit will take a few seasons to be established. A mature technology bigger scale plant could thus be operational around 2025, which is set as a reference year.

Geographical coverage

Geography plays a crucial role in many sustainability assessments, determining e.g. productivity of algae cultivation, transport systems and electricity generation. In this study, the location of the demo site in Monzón, Spain, is taken as a blueprint setting. To be able to derive conclusions valid for further plants according to the D-Factory concept in suitable locations elsewhere in Europe, generalised European background data is used as far as possible.

Functional unit, co-product handling and reference units

The functional unit is a key element of integrated life cycle sustainability assessment (ILCSA). It is a reference to which the environmental, social and economic effects of the studied system are related. It quantifies the function (i.e. utility) of the product(s) provided by the investigated system.

A central characteristic of a biorefinery, as it is assessed in D-Factory, is the provision of several products with different functions. These are each compared to a conventional equivalent product on the basis of a functional unit which is specific for each comparison. As an exception, all standard scenarios of this study produce the novel product *9-cis* β-carotene as the main product. This is based on the scenario setting that a novel health effect of purified *9-cis* β-carotene as a pharmaceutical will be demonstrated in a clinical trial to come. All pharmaceuticals that are currently used in conditions targeted by *9-cis* β-carotene will result in other health benefits. Thus, *9-cis* β-carotene adds a new benefit (or function in terms of a life cycle comparison), which cannot be compared to any existing product. This leads to the following procedure for life cycle comparisons in scenarios that produce purified *9-cis* β-carotene for the pharma market: 1 tonne of purified *9-cis* β-carotene will be defined as functional unit and all co-products will receive credits according to the burdens that are avoided by replacing conventional equivalent products (substitution approach). The resulting remaining burdens are attributed to purified *9-cis* β-carotene.

4 Analysed systems

This chapter gives an overview of the processes studied in the D-Factory project (chapter 4.1), the scenarios depicting potential future D-Factory value chains (chapter 4.2) and the products produced in these scenarios as well as the conventional reference products they compete with (chapter 4.3). For further details please refer to the original report this chapter summarises [Harvey 2017b].

4.1 Overview of processes

Figure 4-1 describes the nature of processes that have been studied in the D-Factory project and might feasibly deliver the 14 products described for an industrial-scale D-Factory biorefinery. The scenarios described in chapter 4.2 each depict a subset of the partially mutually exclusive options shown here, which are partially used in a sequence deviating from this overview chart. Please refer to schemes of final scenarios in the annex for details (chapter 7.3).

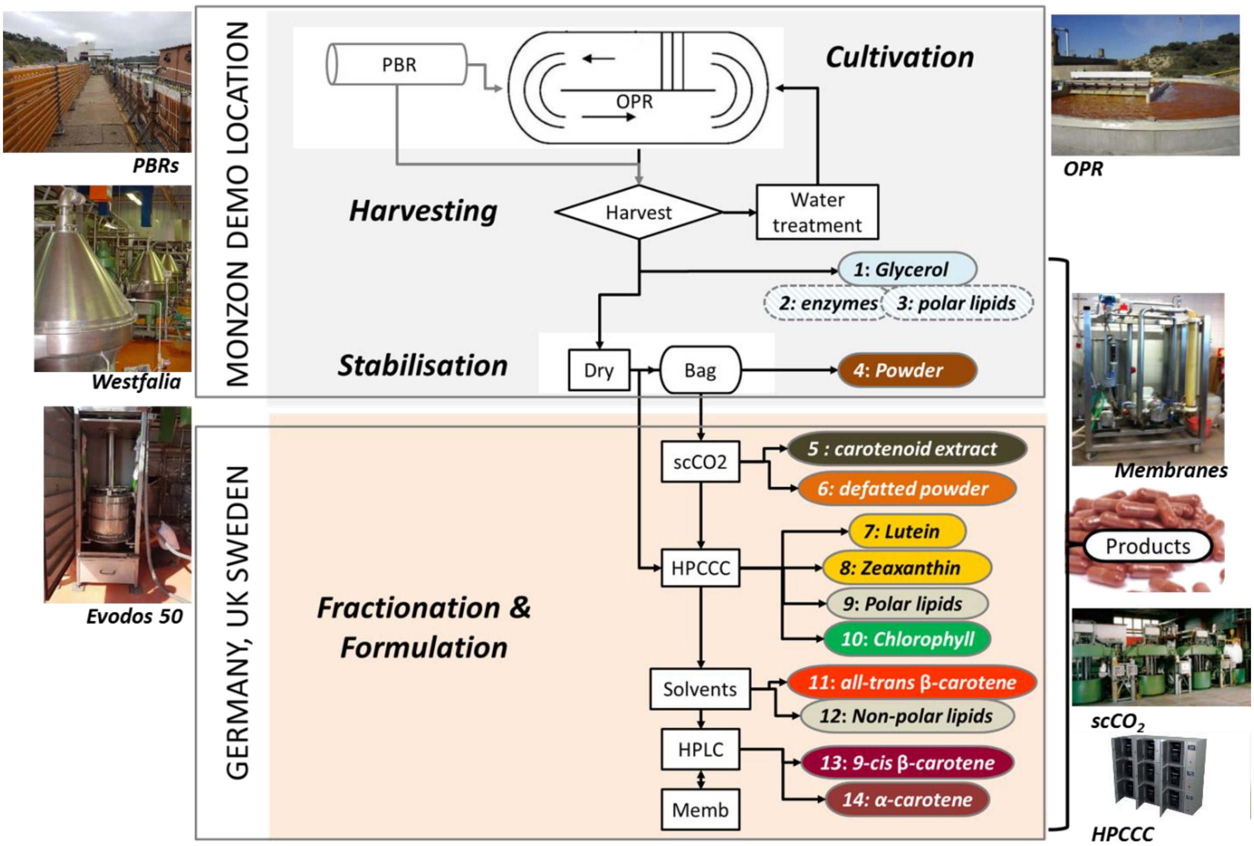


Figure 4-1: Schematic to summarise products and processes studied within the D-Factory project.

Algae cultivation

Algae are cultivated in hypersaline media using open raceways with paddle wheels. Algae are harvested by partially or completely draining the raceways. Inoculation is done by stepwise dilution of cultures from several sizes of smaller raceways. Alternatively, closed photobioreactors may be used for inoculation to protect the inoculum from contaminations and thus to restart cultures faster after a possible collapse.

Central biorefinery processes

In brief, after culture in raceways, with or without inoculation using photobioreactors (PBRs), there is a series of processes which for convenience are grouped in blocks as follows (Figure 4-1):

BLOCK 1*:* Biomass is harvested using spiral-plate centrifuge (such as provided by the project partner Evodos) or a conventional disc-stack centrifuge. These centrifuges are not equivalent: spiral-plate systems aim at harvesting cells intact in preparation for subsequent controlled cell rupture for **GLYCEROL** (Product 1), **ENZYMES** (Product 2), **POLAR LIPOPOLYSACCHARIDES** (Product 3), whereas disc-stack systems aim to concentrate cells but cause cell rupture and release these water-soluble components to the effluent stream for subsequent waste management before recycle or discharge.

The recovery and analysis of cytosolic enzymes and lipids from spiral-plate-harvested material under conditions of controlled cell rupture requires verification, hence in Figure 4-1 these products are shown in hatch. Membrane pre-concentration is used in some scenarios to remove large parts of the medium before centrifugation.

BLOCK 2*:* The water-insoluble lipophilic biomass collected at the centrifuge is stabilised by drying to a **POWDER** (Product 4), with or without prior washing to remove salt. Dryers are either spray-driers or lyophilisers. These are also not equivalent: Spray-drying involves use of a hot drying gas, which can denature enzymes and produces a fine (100-300µm) free-flowing powder. This is suitable for processing with chemical petroleum solvents but nevertheless unsuited for processing with supercritical CO_2 (scCO2), whereas lyophilisers use a combination of reduced pressure and enough heat for ice to sublime from pre-frozen material and the resultant powders are well-suited to $scCO_2$ processing.

BLOCK 3*:* Product 4 POWDER is extracted with $scCO_2$ or sequentially with solvents of increasing polarity to give **CAROTENOID EXTRACTS** enriched in lipophilic carotenoids, chlorophyll and lipids (Product 5). Residual biomass, namely **DEFATTED POWDER** (Product 6) after solvent/scCO2 extraction may contain salt in addition to organic matter if pastes are not washed prior to drying. If solvent is used the defatted powder needs to be desolventized.

BLOCK 4*:* Further processing of carotenoid extracts using polar solvents generates fractions enriched in **POLAR LIPIDS** (product 9), the xanthophylls **LUTEIN** (product 7) and **ZEAXANTHIN** (product 8) and **CHLOROPHYLLS** (product 10), which are separated using HPCCC.

BLOCK 5*:* Processing of the remainder extract with non-polar solvents will deliver a fraction enriched in non-polar lipids and mixtures of carotenes which are separated from each other using a combination of temperature- or solvent-dependent precipitation followed by HPLC. Products 11-14 are **ALL-TRANS β-CAROTENE, 9-CIS β-CAROTENE, α-CAROTENE** and **NON-POLAR LIPID**

BLOCK 6*:* Solvents are removed from all final products using membranes and reused by recycling within the process itself using solvent resistant membranes specific for the solvents used. The chemical petroleum solvents primarily used for first extraction are Acetone and Heptane, followed eventually by Ethanol. The solvents used for HPCCC separation (BLOCK 4) include Heptane, Water, Methanol/Ethanol and may include small quantities of Ethyl Acetate or another solvent in order to prepare the biphasic partitioning system.

At the end of the processing steps, all solvents are recovered using a combination of solvent-resistant membranes and evaporation/condensation.

Utility provision, wastewater management

In standard scenarios, power is provided by the grid. Alternatively, on-site solar power can be generated with photovoltaics installations.

Brine for preparation of hypersaline algae growth medium is provided in standard scenarios by infusing freshwater through wells into underground salt deposits, which are relatively close to the surface. The brine pumped from these wells has to be supplemented with magnesium to reach magnesium concentrations similar to seawater. Alternatively, brine from existing seawater desalination plants for freshwater production can be used depending on the location. As a further alternative, mined rock salt can be dissolved in freshwater.

The amount and degree of contamination of wastewater varies strongly between scenarios. Outputs have in common that they contain high loads of salt, which may make it unsuitable for treatment in municipal wastewater systems. In the scenarios analysed here, hypersaline wastewater to be disposed is treated by aerobic wastewater treatment on site to largely eliminate organic matter. Depending on the location, it is then either injected into underground caverns left over after exploitation of salt deposits or discharged to the sea following local regulation.

4.2 Scenarios on algae cultivation and use

Table 4-1 and Figure 4-2 give and overview of the scenarios analysed in this study. Detailed process schemes for each scenario can be found in chapter 7.3 in the annex. These scenarios were selected for detailed analysis from a much bigger set of scenarios. Additional information and further scenarios can be found in [Harvey 2017b][1].

Table 4-1: Overview of the analysed scenarios

No.	Short description
1	Initial configuration: 1. Disruptive algae harvesting with disc-stack centrifuge without membrane pre-concentration including wash to remove salt. 2. Biomass is dried - drying step uses spray drying 3. Supercritical CO_2 and organic solvents to fractionate extracts into increasingly pure preparations of high-value compounds.
2	Membrane pre-concentration: scenario 1 with membrane technology as a pre-concentration step for harvesting cells to lower energy costs and permit effluent recycle.
3	Whole cell harvesting: scenario 2 with Evodos-type spiral plate centrifuge for harvesting intact whole cells and controlled cell rupture using water, which also washes biomass to remove salt.
4	Glycerol recovery: scenario 3 with recovery of glycerol after controlled cell rupture using water. Electrodialysis introduced to recover glycerol.
5	Shorter downstream processing: scenario 3 without separation of carotenes into α-carotene and *9-cis* β-carotene.
6	No carotenoid separation: scenario 3 without separation of carotenoid extract into seven products including *9-cis* β-carotene.

[1] Correspondence of scenario numbers to the original set of scenarios: 1 = 1d, 2 = 1c, 3 = 1 base case, 4 = 1f, 5 = 1h, 6 = 1g.

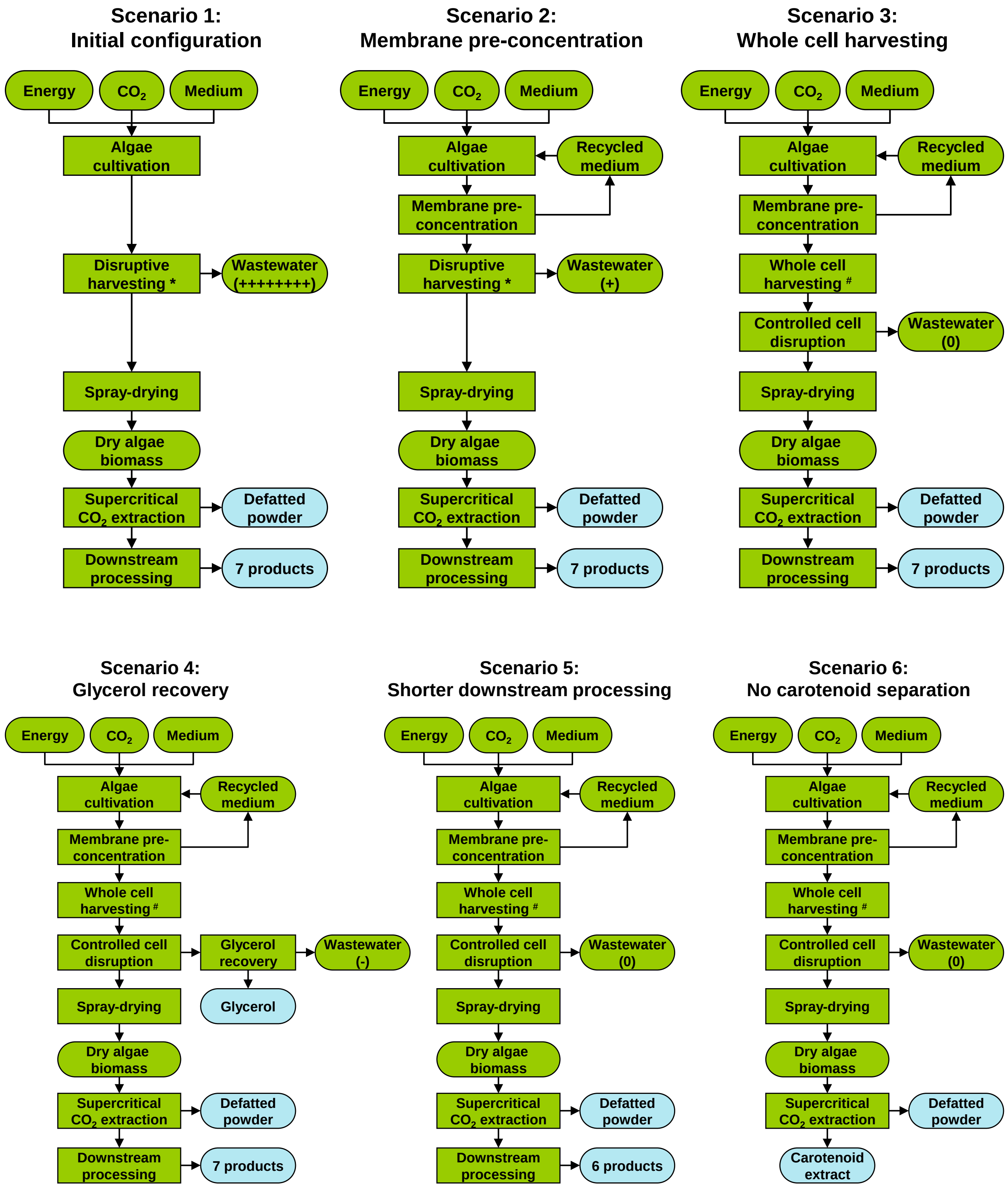


Figure 4-2: Overview schemes on the scenarios analysed in this study. *: by disc-stack centrifuge; #: by spiral-plate centrifuge; amounts and organic loads of wastewater are delineated by symbols +/0/-.

4.3 Products and reference products

Table 4-2 summarises all products that are produced in the analysed scenarios. For details, please see chapter 4.2. Each product is compared to a reference product of equivalent function. If a novel health benefit is confirmed for *9-cis* β-carotene in clinical trials, it cannot be compared to any existing product (see chapter 3.2 for methodological details). This is the case in all standard scenarios. In a sensitivity analysis, the other case without a novel benefit is analysed.

Table 4-2: Overview of products and reference products

Products	Market	Reference product
Polar-lipids, non-polar lipids, free fatty acids	Specialist animal feed Surfactants	Rapeseed oil
Defatted powder	Feed	Soy + cereals
Lutein	Nutraceutical	Lutein purified from marigold
Zeaxanthin	Nutraceutical	Zeaxanthin purified from marigold
Chlorophyll	Food colorant	Extracts from green plants such as spinach
All trans β-carotene	Food colorant	Synthetic all trans beta carotene
9-cis β-carotene*	Pharmaceutical Sensitivity: Nutraceutical	Standard: none (novel product) Sensitivity: like all-trans β-carotene
α-carotene	Nutraceutical	Like all-trans β-carotene
Glycerol	Multiple	Generic substituted chemicals

*: In some scenarios, mixtures containing *9-cis* β-carotene are not separated further (carotenoid extract resulting from supercritical CO_2 extraction and carotene extract resulting from HPCCC). They are only used for providing *9-cis* β-carotene. They are thus set not to replace e. g. other lutein products even if the mixture contains lutein because the consumer would not take lutein capsules instead.

5 Results and conclusions

As a basis for further analyses, this chapter contains summaries of the assessments of individual sustainability aspects (chapter 5.1-5.4). The results from these individual assessments are combined, extended and jointly assessed in the results chapter on the integrated assessment (chapter 5.5). For methodological details and settings see chapter 3.

5.1 Summary: technological assessment

This assessment by the project partner University of Greenwich (UOG), UK; analysed all technological aspects that could have an impact on sustainability. For details, further results and images cited in this summary please refer to the original technological assessment report [Harvey 2017a].

Methodological approach

The aim of the technology assessment task was to provide a complete system description and conclusive evaluation of all technological aspects in preparation for the Integrated Assessment of Sustainability.

The objectives included

1. Delivery of an updated technological system description.
2. The updated selection of suitable technological indicators based on these descriptions.
3. A score for potential biorefinery configurations based on scenarios described in chapter 4.2.

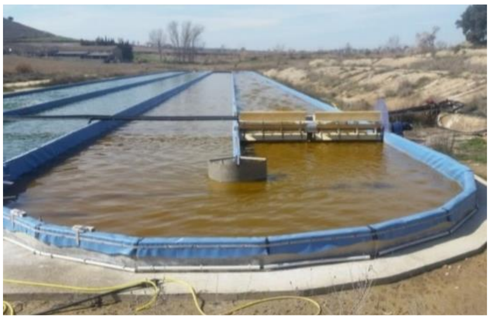


Figure 5-1: Raceways of Monzón Biotech, Spain.

Figure 5-2: Closed flat-panel GW photobioreactors from A4F growing carotene-rich Dunaliella at the Monzón Biotech production unit in Spain.

Technology assessments are difficult if not impossible to carry out in an objective manner since subjective decisions and value judgments have to be made regarding a number of complex issues such as (a) the boundaries of the analysis (b) the selection of appropriate indicators of potential positive and negative consequences of the new technology.

To minimise the tendency for bias by values of the most powerful stakeholders, i.e. the developers and proponents of the new technologies under consideration, the D-Factory partners held a workshop in October 2017 to review technology status and evaluate findings to date, which were made available in draft form. All partners were offered the chance to score technologies in an anonymous way using templates. This also provides the opportunity for new technologies to be brought forward.

Summary of results and conclusions

The current suite of technologies already in routine use at Monzón and NBT for cultivating *Dunaliella* (Figure 5-1) using inoculation with minipond raceways followed by harvest with a Westfalia disc-stack centrifuge, without membrane pre-concentration and then spray- or freeze-dry stabilisation of biomass after chitosan wash will be suitable for delivering the first stage of cultivation harvesting and drying necessary for an algal biorefinery. Green wall (GW)-type PBR technology is also highly suited to provide *Dunaliella* inoculum (Figure 5-2).

Figure 5-3: Membrane unit for harvesting

Successful application of cultivation technologies for delivering carotenogenic *Dunaliella* is dependent on many factors, particularly seasonality, influence of light and the 'art' of understanding how to impose nitrogen stress. Yields are also dependent on a balance between supply of CO_2 and level of applied salinity to control predators and optimise carotenogenesis. The art is not well formulated since it is highly location-dependent. By 2025, the 'art' may be better developed and applied by trained phycologists.

Figure 5-4: Evodos T50 in situ at NBT, Eilat

Effluent/spent culture medium from cultivation and harvesting currently requires intensive treatment to meet current legislation. By 2025, recycling technologies are likely to be better implemented, especially if membrane pre-concentration before centrifugation (Figure 5-3) can be successfully developed from TRL 5 to TRL 9 to harvest cells intact and more especially if Evodos spiral plate centrifugation technology (Figure 5-4) can reach a sufficient maturity from current TRL5/6 to replace disc-stack centrifugation, and harvest cells intact without damage to carotenoids.

Figure 5-5: Industrial plant HD12 for $scCO_2$-extraction of algae biomass at NATECO

Subsequent processing of powders with $scCO_2$ is a sufficiently mature technology, also in routine use and commercially available and does not require further development (Figure 5-5). Successful scale-up applied to *Dunaliella* powders has been demonstrated. The technology will deliver extracts of carotenoid, chlorophyll and lipid.

Whilst the technology associated with the use of solvents to extract powders and process extracts using HPCCC is reasonably well-defined, the application of these technologies to process *Dunaliella* is currently not yet validated in the laboratory: active research and development has been initiated and analytical and laboratory studies to physically validate analytical predictions are underway (TRL2-3). The technologies are far from having been actually proven to perform the required separations to deliver highly enriched individual preparations of carotenes, lutein, zeaxanthin, chlorophyll, polar lipid, and non-polar lipid. Preparative HPLC will separate carotene isomers but several sustainability aspects including profitability still require optimisation, as outlined in chapters 5.3 and 5.5. This suite of downstream technology innovations is likely to develop at a rate set by market demand for the enriched extracts.

5.2 Summary: environmental assessment

This assessment by the project partner IFEU – Institute for Energy and Environmental Research Heidelberg, Germany, analysed all environmental implications of the scenarios described in chapter 4.2. For details and further results please refer to the original environmental assessment report [Keller et al. 2017].

The most important results and insights are summarised in the following.

Dunaliella **algae cultivation and processing require substantial resources in addition to sunlight and** CO_2 **and are therefore not intrinsically environmentally friendly.**

The extraction of valuable substances such as carotenoids from *Dunaliella* algae, produced with the aid of sunlight and abundantly available CO_2, is a very promising concept. However, if algae are to be cultivated and harvested in sufficient concentrations, substantial energy and material inputs will be needed (Figure 5-6). Overall, algae cultivation – similar to traditional agriculture – is not possible without the input of limited resources and without significant environmental burdens. Algae-based products are therefore not intrinsically environmentally friendly, nor do they necessarily contribute to mitigating climate change just because algae consume CO_2.

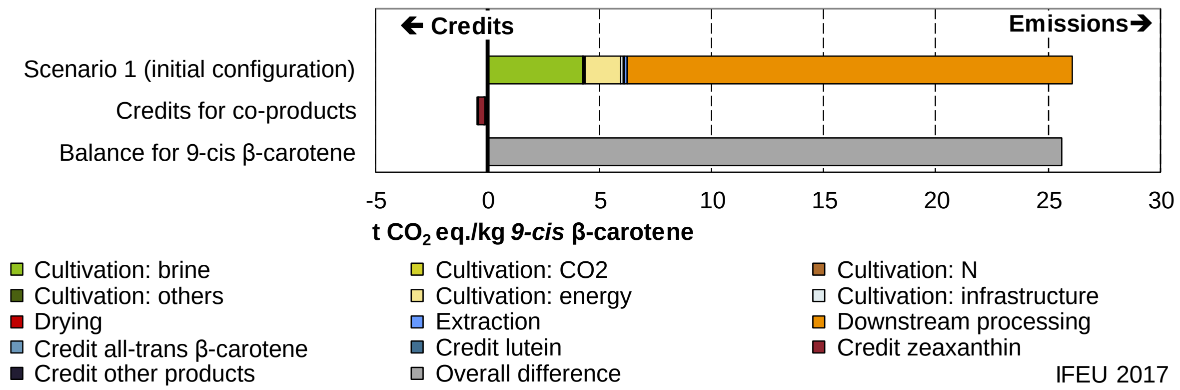


Figure 5-6: Contribution of inputs, processes and replaced reference products on the carbon footprint of the exemplary scenario 1 "initial configuration". Boundary conditions: Conservative performance, power from the grid.

The largest contributions to environmental burdens of algae cultivation and harvesting have been successfully reduced.

In itself, the extraction of valuable substances from *Dunaliella* algae in algae biorefineries causes practically no environmentally relevant emissions. They primarily arise from the provision of precursor products and the energy required by the biorefinery. Before optimisation, the environmental burdens of algae biomass production were dominated by the brine used to produce the medium and the electricity for algae cultivation and harvesting (Figure 5-6). The identified optimisation measures can reduce these contributions by 99% and 85% respectively. Overall, savings of up to 90% were achieved for most environmental impacts of algae biomass production (Figure 5-7).

- Efficient medium recycling was facilitated by the introduction of membrane pre-concentration. It may be possible to further improve recycling rates by the use of a new centrifugation technology, which can harvest algae cells essentially intact and thus reduces impurities in the extracted medium. In addition, the environmental burdens of brine provision can be considerably reduced by integration with salt production or seawater desalination facilities, depending on the site. Intensive cultivation of hypersaline algae involving low environmental burdens therefore requires a site-specific medium recycling concept and integration with existing salt processing facilities.
- Electricity use within the facility depends on numerous different parameters. It is possible to directly reduce this use by adopting membrane pre-concentration. Additional reductions per unit of product are possible by lowering product losses. Electricity provision can be considerably more environmentally friendly if solar electricity is generated on-site using photovoltaics, in particular because electricity demand and generation are both at their highest when solar irradiation is highest. Even though this partially negates the land use savings by other measures, from an environmental perspective as large a proportion of electricity use as possible should be covered by on-site solar electricity generation.

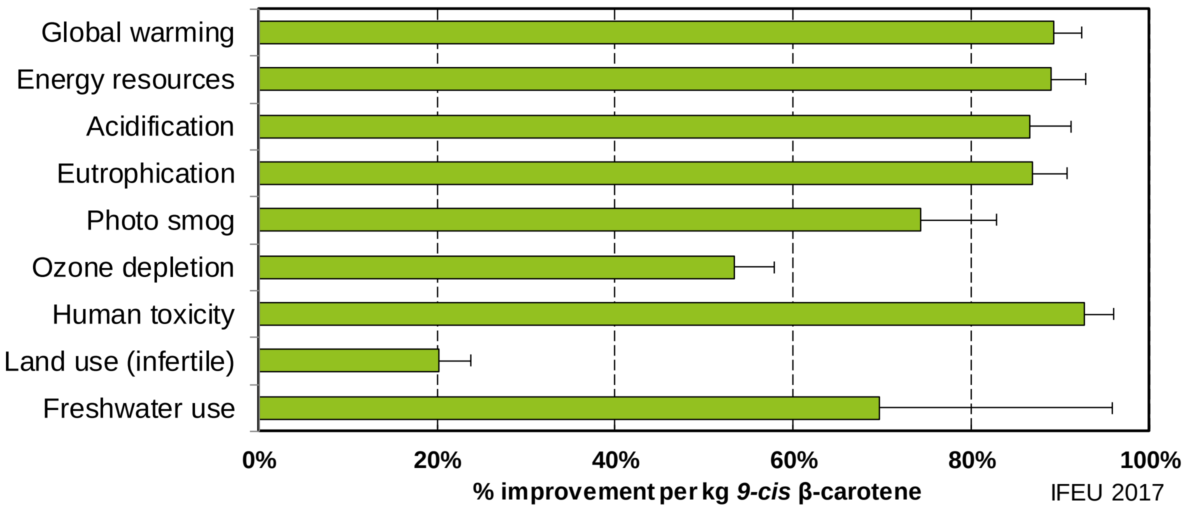


Figure 5-7: Reduction of emissions and expenditures of resources, respectively, of algae biomass production by all quantified optimisation measures (scenario 1 “initial configuration” vs. scenario 4 “glycerol recovery” with 80 % solar power and desalination brine use). Effects differ under optimistic and conservative conditions (see ranges indicated by thin lines).

The analysed version of downstream processing to separate algae extracts into several products was found to be environmentally harmful. In response, a new approach was found within the project that promises to be much more resource-efficient and environmentally friendly.

The environmental impacts over the entire life cycle of the assessed scenarios are undoubtedly dominated by the downstream processing energy and solvent demand. From an environmental perspective, the benefits of additional products do not balance the expenditures required for the purification method investigated here. Also in response to this result, a new modular high-performance countercurrent chromatography (HPCCC) system was developed within this project that is expected to increase resource efficiency and reduce environmental impacts profoundly. The adequacy of improvements remains to be confirmed e.g. in a follow-up environmental assessment once sufficient experience is gained for reliable quantitative modelling. As a fallback option, the unfractionated carotenoid extract could alternatively be marketed as main product.

Local ecological impacts of *Dunaliella* algae cultivation can be reduced by adopting appropriate concepts.

In addition to global and regional environmental impacts, which can be analysed and optimised using life cycle assessment, cultivating *Dunaliella* algae for algae biorefineries can also cause significant local environmental impacts on the environmental factors land, soil, water and biodiversity (Table 5-1). This particularly applies to:

- Freshwater use: On one side, it is possible to reduce the water-related impacts by the technical design of the facility – among other things by efficient medium recycling, the introduction of membrane pre-concentration and the use of a new centrifugation technology. If rigorously optimised, more water could even be saved by replacing products from irrigated agriculture with algae-based co-products than freshwater needed for algae cultivation. On the other side, sufficient local (blue) water availability must be guaranteed despite possible net water savings, in particular at inland sites. Existing water uses in a catchment area must be taken into consideration.
- Disposal of high salt content wastewater: here, an ecologically optimised saltwater disposal concept should be compiled, in particular for inland sites. The risk associated with saltwater disposal is expected to be lower at coastal sites.
- Quantitative and qualitative land use: the extent of land use can be reduced by the technical design of the facility, for example by minimising wastewater and thereby the area required for wastewater treatment. Because algae cultivation using raceways leads to complete ground sealing, the impacts of this qualitative alteration should be minimised, for example by utilising previously sealed disused industrial sites instead of agricultural land.

Table 5-1: Technology-related impacts expected from the implementation of the studied algae biorefinery scenarios and its competing reference systems, respectively. Impacts are ranked in five comparative categories; "A" is assigned to the best options concerning the factor, "E" is assigned to unfavourable options concerning the factor

	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Mari-gold	Soy-bean	Wheat	Spinach	Rape-seed
(Algal) biomass provision									
Impacts resulting from construction									
Construction works	C	C	C	C	C	C	C	C	C
Impacts related to the facility itself (F) and/or from operation (O)									
Soil sealing	E	D/E	D/E	D/E	n.a.	n.a.	n.a.	n.a.	n.a.
Soil erosion	n.a.	n.a.	n.a.	n.a.	D	D	C	D	D
Soil compaction	E	D/E	D/E	D/E	D	D	C	D	D
Loss of soil organic matter	n.a.	n.a.	n.a.	n.a.	D	C	D	D	C
Soil chemistry/fertiliser	n.a.	n.a.	n.a.	n.a.	E	D	D	E	D
Weed control/pesticides	n.a.	n.a.	n.a.	n.a.	E	E	E	E	E
Loss of habitat types	E	D/E	D/E	D/E	D	E	D	D	D
Loss of species	E	D/E	D/E	D/E	C	E	D	D	D
Barrier for migratory animals	E	E	E	E	n.a.	n.a.	n.a.	n.a.	n.a.
Loss of landscape elements	D	D	D	D	D	E	C	D	C
Risk for iLUC	C/E	C/E	C/E	C/E	D	E	D	D	D
Drain on water resources	E	D/E	D/E	D/E	E	D	C	E	D
Emission of nutrients (to water)	E	D/E	D	D	E	D	D	E	D
Emission of gases/fine dust (to air)	C	C	C	C	n.a.	n.a.	n.a.	n.a.	n.a.
Traffic (collision risk, emissions)	C	C	C	C	n.a.	n.a.	n.a.	n.a.	n.a.
Disposal of wastes/residues	D	C/D	C	C	n.a.	n.a.	n.a.	n.a.	n.a.
Accidents, explosions, fires, GMO	C	C	C	C	n.a.	E	n.a.	n.a.	n.a.
Downstream processing									
Impacts resulting from construction									
Construction works	C	C	C	C	C	C	C	C	C
Impacts related to the facility itself									
Buildings, infrastruct. & installations	C/E	C/E	C/E	C/E	C/E	C/E	C/E	C/E	C/E
Impacts resulting from operation									
Drain on water resources	C/E	C/E	C/E	C/E	C/E	C/E	C/E	C/E	C/E
Emission of nutrients (to water)	D	D	D	D	D	D	D	D	D
Emission of gases/fine dust (to air)	C	C	C	C	C	C	C	C	C
Traffic (collision risk, emissions)	C	C	C	C	C	C	C	C	C
Disposal of wastes/residues	C	C	C	C	C	C	C	C	C
Accidents, explosions, fires, GMO	C	C	C	C	C	C	C	C	C

Potential impacts

Likely significant impacts

Potentially significant impacts depending on the exact location and local surrounding of the facility

The number and quantity of marketable co-products from *Dunaliella* algae were successfully increased during the project. This can avoid environmental burdens elsewhere, if conventional products are substituted.

The project was based on an existing facility in Eilat, Israel, in which only β-carotene is marketed as a product and about half of the algae biomass is treated as wastewater. This waste fraction could be reduced to about 10% of the organic matter contained in algae biomass. Co-products such as extracted algae biomass generated as a result can e.g. be used as feeds. If these replace conventional feeds, the thus saved agricultural land may be up to 10 times the size of the land occupied by algae cultivation (Figure 5-8).

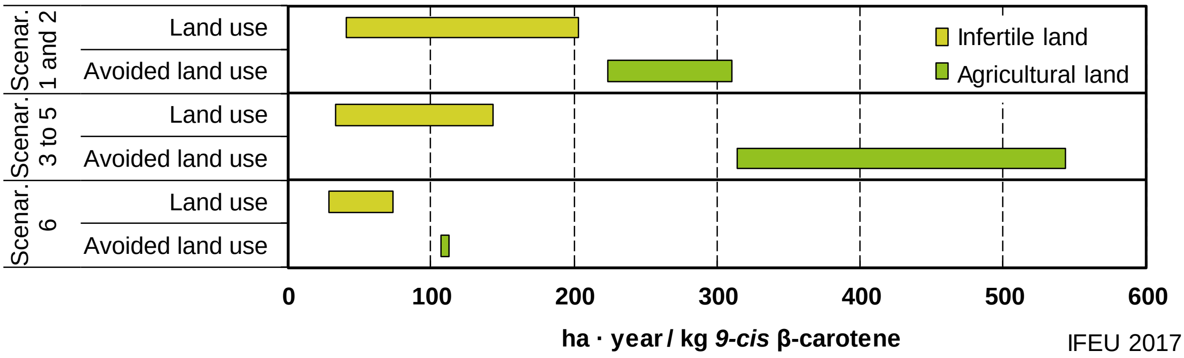


Figure 5-8: Ranges of land use impacts of *9-cis* β-carotene production in all analysed D-Factory scenarios. Infertile land is used and agricultural land use is avoided by co-product utilisation. Impacts of land use cannot be directly compared to impacts of avoided land use because the type of land is different.

A novel pharmaceutical active ingredient may have been created with the production of pure *9-cis* β-carotene. The health benefit to society cannot be scientifically balanced against the environmental burdens for its production. However, the environmental burdens can be within the range associated with different health-promoting natural substances.

Clinical tests to demonstrate the efficacy of *9-cis* β-carotene in cardiovascular disease are currently being initiated. If they are successful, *9-cis* β-carotene would clearly be the main product of a future algae biorefinery employing the D-Factory concept. This substance can only be produced in notable quantities using algae, specifically *Dunaliella salina*, at least at the moment. Its isolation from algae in the achieved purity was demonstrated for the first time in this project. Under these circumstances, a novel health benefit can be delivered by a future *Dunaliella*-based algae biorefinery. This valuable social asset cannot be evaluated in the context of an environmental assessment. However, because no exceptionally large environmental impact with clearly negative health impacts elsewhere is to be expected in particular if approaches for redesigning downstream processing can be realised (Figure 5-9), societal acceptance of caused environmental burdens is highly probable. If a D-Factory algae biorefinery is subsequently built, at least the most important identified environmental improvements should be implemented. These are rigorous recycling of the cultivation medium, utilisation of extracted biomass as a feed and providing a large proportion of the electricity demand by solar electricity generated on-site. In particular, the carotenoid extract should only be fractionated into all its constituents if the newly developed downstream processing technology is successful or if only pure *9-cis* ß-carotene turns out to be effective as a drug. The enormous environmental burdens caused by the quantitatively analysed version of downstream processing are disproportionate to the burdens that may be saved thanks to additional co-products.

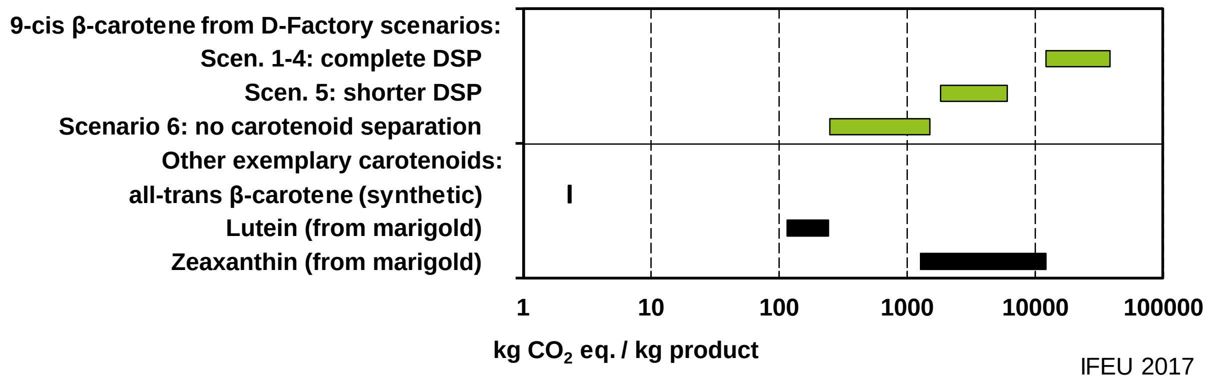


Figure 5-9: Relation of ranges of the carbon footprint of *9-cis* β-carotene production in selected D-Factory scenarios to carbon footprints of other carotenoids with different functions. Avoided environmental impacts of co-products were credited to the main product. Please note the logarithmic scale. DSP: downstream processing

If the efficacy of *9-cis* β-carotene cannot be confirmed in clinical tests, construction of a biorefinery exactly as described in the scenarios investigated in this study cannot be recommended from an environmental perspective. Instead, optimisations including the implementation of a new downstream processing technology would have to be realised at scale.

Based on current knowledge, it cannot be expected that an algae biorefinery adopting the process design quantitatively analysed in this study can contribute to an overall reduction in environmental burdens (Figure 5-10). This is only feasible if the downstream processing technology newly developed in this project can be implemented as expected and the rest of the value-added chain is highly optimised when established.

If co-products are efficiently utilised, algae biorefineries can indirectly release more land than they occupy. This can mitigate competition for land use.

Although algae cultivation does not require fertile land, it has certain limitations with regard to the availability of water, qualified personnel and access to supply networks. An additional strict limitation to infertile and unused land may represent a hurdle for large scale algae cultivation in Europe. Resorting to fertile land use instead would increase competition for agricultural land and exacerbate related problems such as the consequences of indirect land use change. In the worst case, this can lead to deforestation in other parts of the world. A similar effect is known from ground-mounted photovoltaic systems, the land use of which is limited by funding regulations in some EU member states. They additionally compete with algae for the same infertile land with high solar irradiation.

However, in contrast to photovoltaics, co-products from algae cultivation, in particular feeds, may substitute for agricultural products. This can lead to agricultural land savings up to 10 times greater than the land needed for algae cultivation (Figure 5-8). If this was to help avoid the conversion of rainforest into new agricultural land, the greenhouse gas emissions saved in this way may, under some circumstances, even exceed the emissions from algae production. It is therefore vital that all algae biomass fractions are utilised. In this case, sealing of a small area for algae cultivation, with the associated local environmental disadvantages, could be justified if much more land becomes available and if part of that is used as an ecological compensation site. Despite potential restrictions to large scale algae cultivation in Europe, we urgently recommend the strict use of only infertile land for such cultivation facilities.

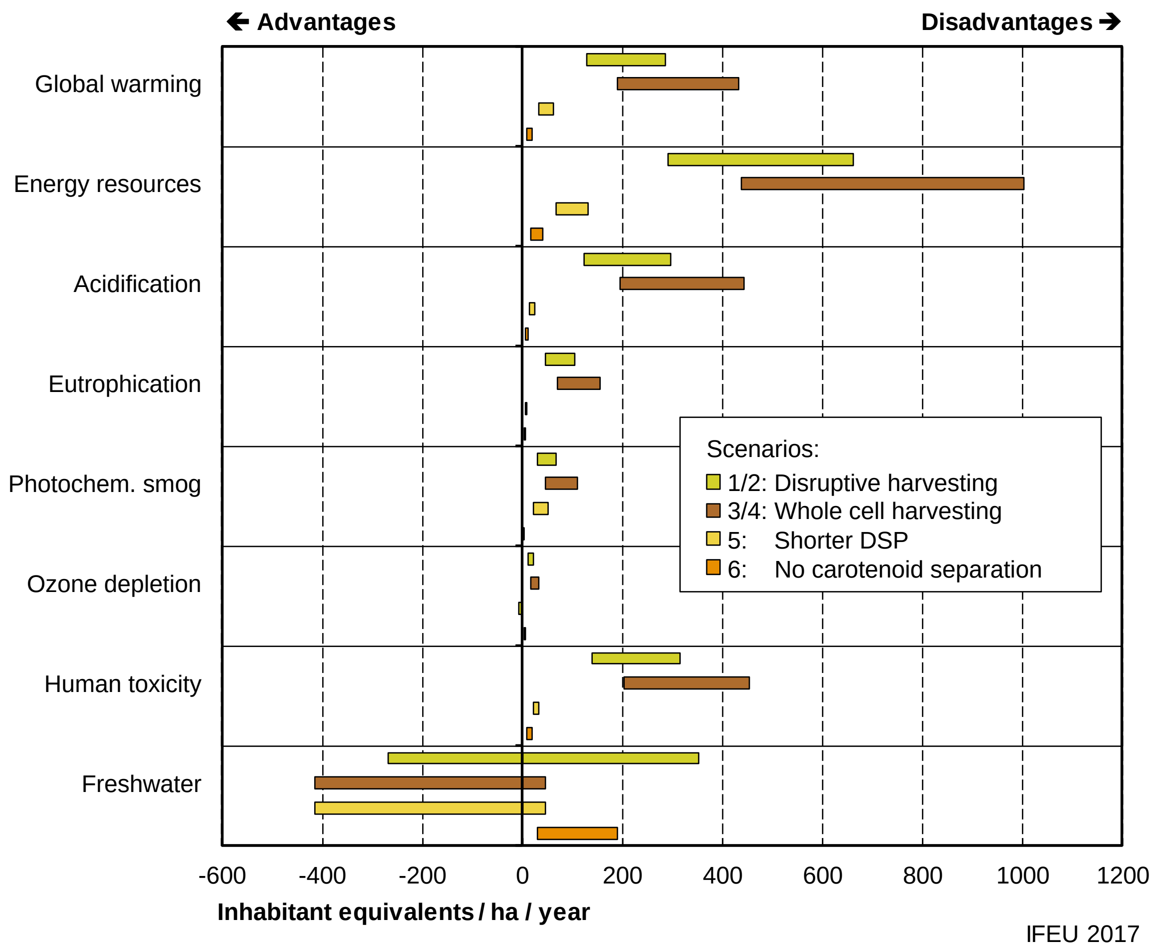


Figure 5-10: Ranges of environmental impacts of *9-cis* β-carotene production in all analysed D-Factory scenarios per hectare and year of land use. Avoided environmental impacts of co-products were credited to the main product. DSP: downstream processing

A focus on high-value algae-based products instead of mass products can mitigate potential future competition about CO_2.

If the decarbonisation of society is to be truly progressed such that the objectives of the Paris climate agreement are seriously pursued or achieved, only very few point sources of CO_2-containing exhaust gases such as cement factories or steel plants may remain within a few decades. In addition to algae facilities, there will be competition from other technologies such as power-to-X and carbon capture and storage (CCS). Therefore, algae cultivation priorities should focus on high-value products such as pharmaceuticals instead of mass production.

5.3 Summary: economic assessment

This assessment by the project partner Hafren Investments (HI), UK, analysed the profitability of the scenarios described in chapter 4.2. For details and further results please refer to the original economic assessment report [Mitchell & Goacher 2017].

The economic assessment methodology incorporates the UNEP/SETAC guidelines for life cycle costing and the assessment is not location specific. The data have been obtained from D-Factory partners and have been informed by the operating results of the pilot plant at Monzón, Spain, laboratory scale experiments and the expert knowledge of the partners. A limitation of these data is that no material and energy consumption of the solvent extraction processes was available from partners or literature.

The capital expenditure consists of investment in fixed assets and working capital. The capital expenditure for the algae production unit or 'farm' includes the construction of raceways and inoculation systems together with harvesting and biomass drying equipment. The Down Stream Processes (DSPs) include heptane/ethanol extraction, high performance countercurrent chromatography (HPCCC) units and high performance liquid chromatography (HPLC) units. The DSP infrastructure cost estimates have been determined based upon a scaled up laboratory design and operation. Working capital includes debtor, creditor and raw material costs.

Operating expenditure consists of direct or variable production costs, fixed production costs and general expenses. Direct production costs are the cost of inputs, which increase in usage as production increases. Fixed production costs are costs not directly required to produce the production output but are required in order for production to take place. General expenses include administration and general expenses.

Market research has identified that there are several potential products that might be targeted by the D-Factory biorefinery using Dunaliella salina algae including a range of lipophilic antioxidant carotenoids and water-soluble enzymes. It has not been possible to demonstrate the solvent extraction of all these target products at commercial scale and consequentially an estimate of the composition of the Dunaliella salina algal powders has been used to determine the product output of the D-Factory. Once commercial quantities are available the market demand and market value can be ascertained. Product prices have consequently been derived using the laboratory scale pricing for these products and using lutein, which is commercially available, as a benchmark product.

The economic performance of the plant is based upon the revenue generated through product sales and the cost of producing these products. The economic performance indicators used are the Net Present Value, the Internal Rate of Return, the Breakeven Revenue and the product contribution margin.

The economic assessment has been conducted for 6 design scenarios. Scenarios 1 to 4 are full design scenarios incorporating complete solvent extraction of the algal biomass into the identified constituent products. Scenario 5 is a design scenario in which the fractionation of an extract prepared using $scCO_2$ does not include HPLC separation and purification steps, but does include HPCCC separation and purification. Scenario 6 is a design scenario in which there is no solvent extraction apart from use of supercritical CO_2 ($scCO_2$). In scenarios 5 and 6 the β-carotene extract is not fully refined into its constituent products and an extract product is sold. Sensitivities have been run based upon "conservative" and "optimistic" productivity estimates.

The capital expenditure estimates for the full process design of scenarios 1 to 4 range between €51 - €53 million. The largest single element of this capital expenditure arises due to the capital expenditure requirement of the HPLC carotene separation steps of €49 million. Scenarios 5 and 6 were run in order to assess the impact of excluding this expenditure.

The product revenue in the “optimistic” design scenarios 1 to 4 range between €33.5 - €40.7 million per annum and is anticipated to predominantly arise from all-trans β-carotene (approx. 50%) and *9-cis* β-carotene (approx. 38%) revenue. The product revenue in “optimistic” scenario 5 is €33.6 million per annum and is anticipated to predominantly arise from all-trans β-carotene (approx. 63%) and the *9-cis* & α-carotene extract (approx. 33%). 99% of the product revenue in scenario 6 is estimated to come from the supercritical CO_2 β- carotene extract.

Upstream pond - harvesting production costs range between €3.0 - €3.7 million per annum for all scenarios apart from scenario 1, where they range between €8.6 - €9.5 million per annum: this latter cost is due to harvesting without a membrane pre-concentration step, which increases costs because culture medium is not as easily recycled and consequently higher volumes of brine, water and magnesium need to be purchased each year and culture medium needs to be treated before discharge. Downstream solvent extraction costs range between €16.3 - €25.3 million per annum for the “optimistic” scenarios 1 to 5. These costs arise predominantly due to the cost of ionic liquid in the Heptane/Ethanol separation and recycle step after solvent extraction of algal biomass and the power costs of running the HPLC carotene separation steps. No solvent extraction is performed in scenario 6 apart from the use of $scCO_2$.

None of the “conservative” scenarios generate a profit. The “optimistic” scenarios all show profits apart from scenario 6 (processing up to and including $scCO_2$ only). The profitability of the “optimistic” scenarios in comparison to the “conservative” scenarios reflects the fact that the growth productivity of the “optimistic” scenarios is estimated as 83% higher than that of the “conservative” scenarios. Both “optimistic” scenario 2 and 5 have the highest gross margin of 41% each, however, scenario 5 has the higher profit margin of 27%. This arises as under scenario 5 the level of capital expenditure is significantly lower due to the HPLC solvent separation steps being excluded.

An IRR is calculated for the profitable scenarios; however, all but one of these scenarios achieves an IRR of less than the benchmark return of 25%. In order to achieve this benchmark return there would need to be an improvement in the realisations made under these scenarios. Improved realisations could be obtained by achieving higher sales prices for the production sold. The price increases required to achieve the benchmark return of 25% are between 7% and 25%.

The IRR of the “optimistic” scenario 5 is significantly higher than the benchmark return and reflects the return that could be achieved if the plant production could be optimized and the HPLC carotene separation steps are not performed as, based upon current estimates, they do not add value to the process.

The conclusions reached from the economic assessment are as follows:

- The best estimate of the D-Factory partners anticipates that through optimisation the productivity of the D-Factory plant could be improved by 83%.
- The scenario assessment shows that the recycling of the cultivation medium and the use of pre-concentration membranes (scenario 2) can give rise to a 12% increase in profit margin in comparison to scenario 1 where this is not in place.
- The use of the Westfalia centrifuge (scenario 2) is more profitable than the use of the Evodos centrifuge (scenario 3) although higher levels of biomass material recovery are achieved by the Evodos cen-

trifuge coupled with lower cultivation medium treatment costs and therefore scope would appear to exist to improve the profitability of this scenario.

- The recovery of glycerol as a by-product (scenario 4) can give rise to a marginal 0.4% improvement in profit margin over scenario 3 when there is no recovery.
- Scenario 5 demonstrates that significant returns could be achieved with the separation of target carotenoids and the optimisation of the D-Factory production.
- The HPLC solvent processing step provides no added value to the production of *9-cis* and α-carotene based upon the price estimates anticipated. Further research is required to determine a commercially viable extraction process to isolate *9-cis* β-carotene and α-carotene.

5.4 Summary: social assessment and SWOT analysis

This section presents a short outline with the key features of the social risk assessment and SWOT analysis by the project partner Research Institutes of Sweden (RISE). For more detailed information about the work the reader is referred to the dedicated report on social assessment [Peñaloza & Stahl 2017].

5.4.1 Introduction and goal

Most approaches used to define what sustainability is follow the so-called “triple bottom line”. This concept establishes social sustainability as one of the three pillars of sustainability, meaning that social aspects are just as important as economic or environmental when assessing what is or is not sustainable. Social life cycle assessment (sLCA), a variation of the widely-used environmental assessment tool known as LCA, has been proposed as a tool to measure the social impacts of products and value chains. However, assessing social impacts comes with certain challenges. One of them is the still in development status of the sLCA tool, which results in data scarcity and lack of proper standardisation. Another challenge is the value-chain and location dependency of social impacts, which makes it difficult to assess the impacts of technologies and products in early stages of development where value chains, suppliers and process location are still not properly defined.

In order to overcome these challenges while screening the potential social impacts of the D-Factory concept, a social risk assessment was carried out. The goal is to measure the risks of social negative and positive impacts of the D-Factory technology under different scenarios and to identify early potential social hot-spots in these scenarios. The results are meant to be used as guidance for further development of the D-Factory concept from research to a full-scale business model. In this sense, the intended users for these results are the stakeholders that will take upon this further development, so they can make informed decisions where the social risks and hot-spots identified can be avoided.

5.4.2 Methodology

The scope of the assessment is cradle-to-grave, as it includes all the processes from raw material extraction until end-of-life of the product. The estimation of material flows in the system is made to represent the fully-developed and up-scaled D-Factory product system in the year 2025. The functional unit (FU) used for this assessment is kilograms of dry algae paste produced per year.

The activity variable used to measure the relative importance of each life cycle process is the amount of working hours, which are normalized in reference to the functional unit. Working hours were estimated using a combination of country-level statistics for different industrial sectors from the UNIDO databases MINSTAT and INDSTAT, the approximate price of goods and the average hourly wages in the respective country and sector. The social hotspot database has been used to determine the social impact per process. The database is a directory of social risks in 227 countries and 57 sectors, given in 23 social themes divided into 5 social categories.

The final result of the assessment is the sum of the social risks from all the processes in the system, in working hours-risk per functional unit. This unit results from multiplying the working hours required from each process in the system with the social risk factor of the process from the social hotspot database. The negative impacts of D-Factory correspond to the total social risks of the life cycle processes required to produce all the co-products of D-Factory per functional unit. In contrast, the positive impacts are the social risks avoided by the substitution of processes required to produce all the D-Factory co-products.

The baseline scenario of the assessment is scenario 3 ("whole cell harvesting"), located in Monzón (Spain) and with optimistic performance. Additional scenarios were then evaluated with conservative performance, other scenarios (see also Table 4-1), staffing of the D-Factory and alternative locations for the base case. The final result of each scenario shows then a comparison between the negative social risks (with positive values) and the avoided social risks (with negative value).

5.4.3 Key findings

The results for the base case and the contribution from different processes are presented in Figure 5-11. Meanwhile, Figure 5-12 presents a summary of the results obtained for all the remaining scenarios, including both negative risks and avoided risks of D-Factory.

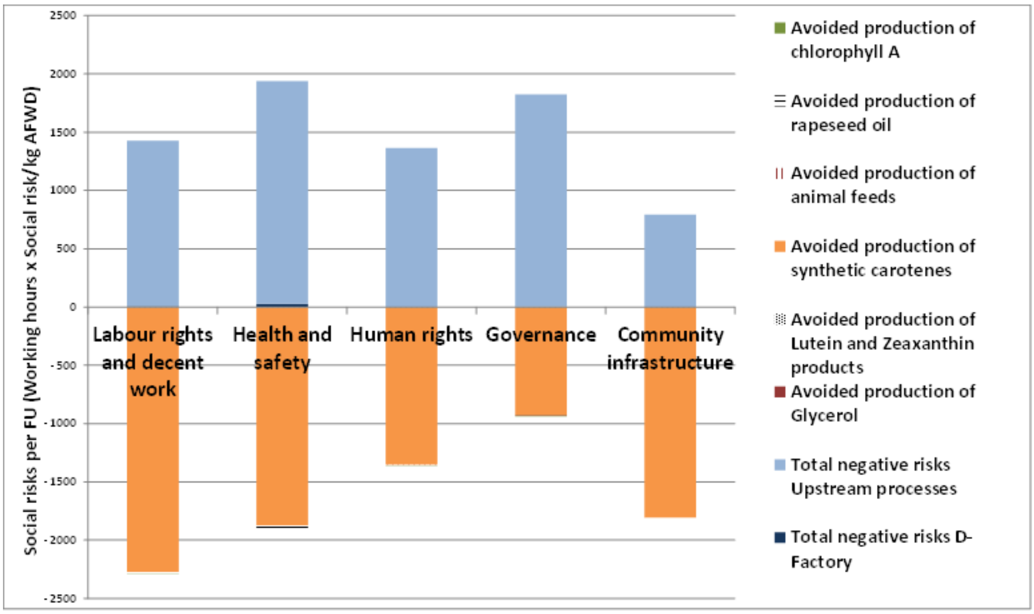
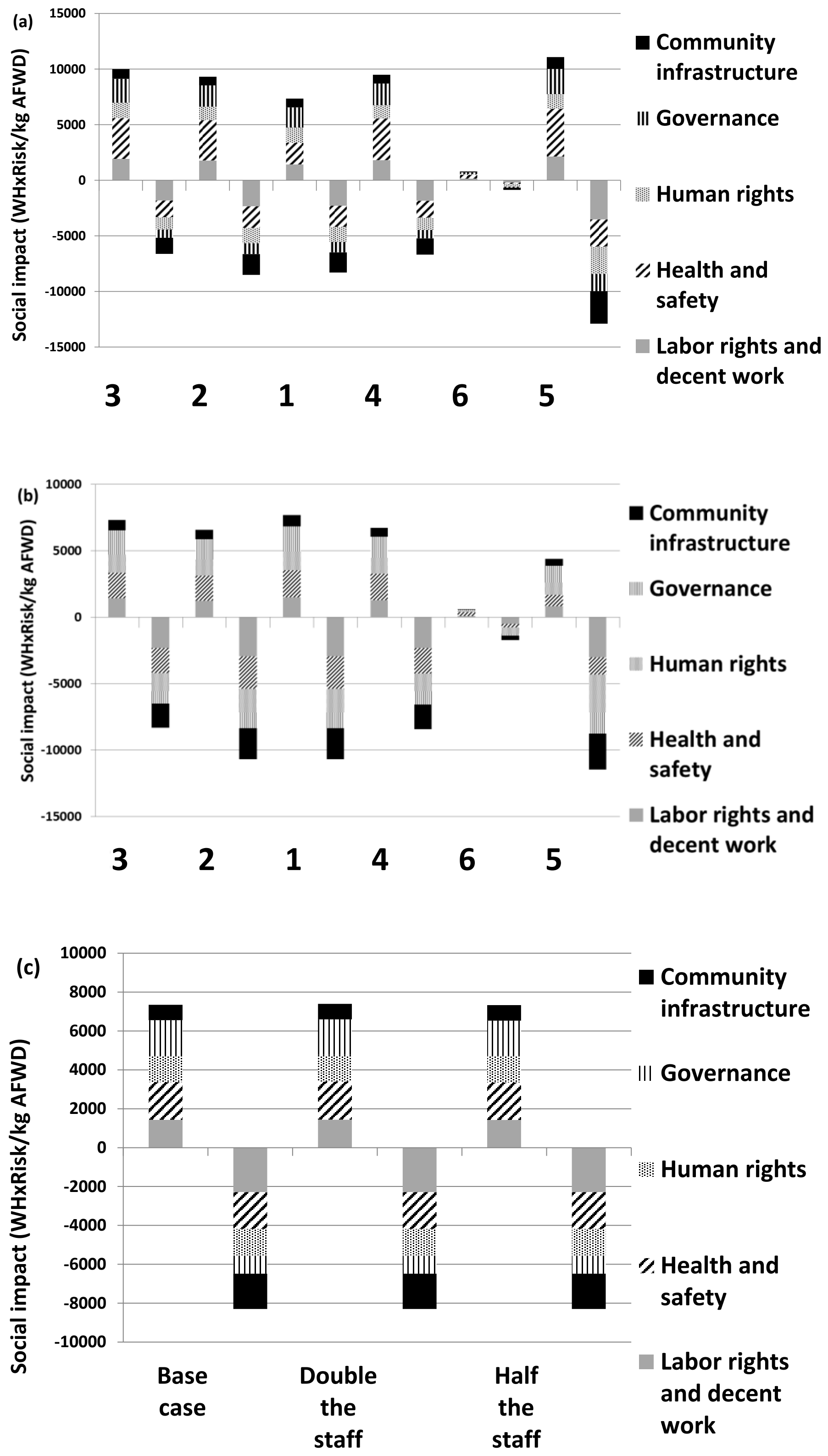


Figure 5-11: Social risk assessment for the base case scenario, located in Spain, under optimistic conditions.


(a)
Social impact (WHxRisk/kg AFWD)
15000
10000
5000
0
-5000
-10000
-15000
3
2
1
4
6
5
Community infrastructure
Governance
Human rights
Health and safety
Labor rights and decent work
(b)
Social impact (WHxRisk/kg AFWD)
10000
5000
0
-5000
-10000
-15000
3
2
1
4
6
5
Community infrastructure
Governance
Human rights
Health and safety
Labor rights and decent work
(c)
Social impact (WHxRisk/kg AFWD)
10000
8000
6000
4000
2000
0
-2000
-4000
-6000
-8000
-10000
Base case
Double the staff
Half the staff
Community infrastructure
Governance
Human rights
Health and safety
Labor rights and decent work

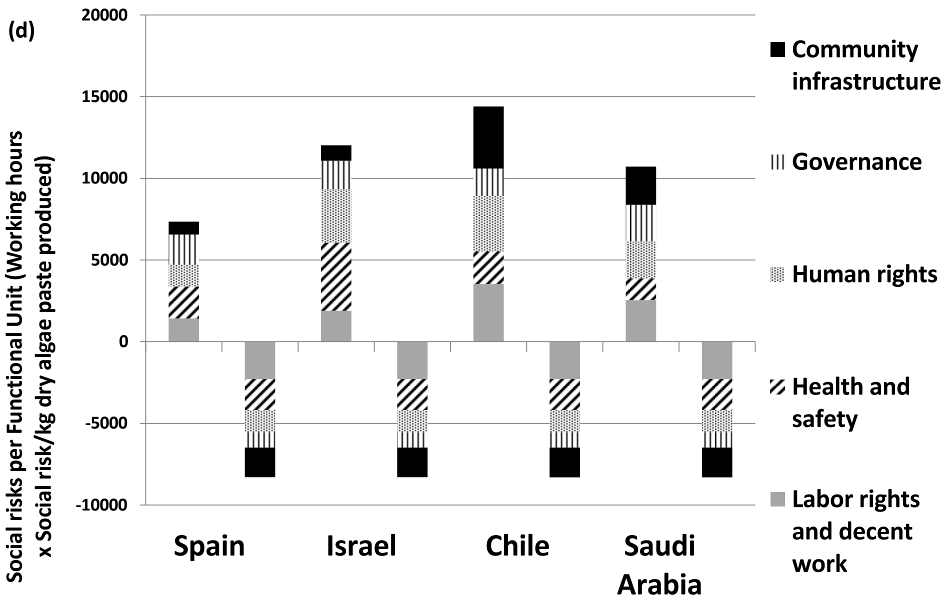


Figure 5-12: Social impact results for all the scenarios analyzed: (a) All scenarios with conservative performance, (b) All scenarios with optimistic performance, (c) sensitivity analysis for D-Factory staffing assumptions, (d) Sensitivity analysis for D-Factory location.

5.4.4 Conclusions and recommendations

The main conclusion of the social assessment is that the D-Factory concept shows potential for mitigation of negative social impacts. This outcome holds for every scenario analysed assuming an optimistic performance after up-scaling in Spain. However, the risk of negative social impacts out-weights the positive impacts of D-Factory if different assumptions are made concerning location, staffing and future performance after scale-up.

- A significant share of the positive impacts from D-Factory can be attributed to the substitution of high-value products, more specifically all-trans-ß-carotene, pure *9-cis* ß-carotene and α-carotene. This is due to the fact that these products are produced in significant amounts, have a high value and their benchmarks have significant social impacts. Their high value means that they require relatively higher amounts of working hours to produce small amounts of the end product. Meanwhile, their associated social impacts are higher because their manufacturers and raw materials are mostly located in countries with relatively high social impacts in their agricultural and chemical sector such as China, India and even USA. Given that the social risks of each process in our model is a product of the working hours per functional unit and the associated social impact of the unit process, the substitution of these high-value products have a significant influence in the result. Consequently, the social impact mitigation potential of D-Factory depends heavily on the assumption that these products can be substituted, and any change in that regard would affect significantly the outcome of this assessment.
- If D-Factory fails to substitute high-value products, the substitution of lesser value products such as glycerol, animal feed, chlorophyll or rapeseed oil would not be enough to offset the social impacts caused by the D-Factory system and its upstream processes. The outcome of the assessment would depend then on which products are successfully produced and which are not, as well as in each quan-

tity. Still, it is necessary that at least some of the high-value products aimed are obtain in the range of the quantities estimated.

- With regard to social hotspots, the main social impacts caused by the D-Factory production system are concentrated in the health and safety and governance impact categories. The high risk of negative impacts in health and safety are due to the fact that besides energy, most of the inputs required by the D-Factory are chemicals or related to this industrial sector, which is commonly associated with occupational hazards in Spain and Europe. On the other hand, the high score for governance are caused by the use of oil-based materials such as heptane, hexane, ethyl acetate, methanol and ethanol. The market of these products is dominated by high-risk countries such as Saudi Arabia, Iran and India. The processes that have the highest contribution to the negative social impacts of the D-Factory are the production of hexane and heptane, the production of ionic liquids and the production of bottled CO_2.
- The results are not particularly sensitive to the choice of scenario setting in relation to the main scenarios defined in chapter 4.2. The results for all scenarios are quite similar to the result of the base case, with the particular exception of scenarios 5 and 6. In the case of scenario 6, the positive and negative impacts of D-Factory are significantly reduced due to the reduction in inputs and outputs achieved by skipping purification processes. As for scenario 5, its significant reductions of material inputs are achieved while keeping high product yield.
- The amount of personnel for the plant does not have a significant influence on the outcome of the assessment. This because the avoided impacts are still significantly higher than the impacts from D-Factory, no matter the assumptions for staff requirements. However, even if the difference made by the D-Factory plant are relatively low, this difference is enough to tip the balance between positive and negative impacts if the staff of the D-Factory rises beyond double than in the baseline scenario.
- In contrast, the results are significantly sensitive to the level of development of the up-scaled D-Factory system. If conservative productivity values are assumed, the negative impacts caused by the D-Factory value chain become higher than the impacts avoided by product substitution in most of the analysed scenarios. This outcome is not surprising since lower productivity would mean higher material inputs while producing lower amounts of co-products, thus reducing the avoided impacts. Therefore, it can be said that the potential benefit of D-Factory depends significantly on a successful scale-up of the system.
- The results of the social assessment also depend heavily on the country where the D-Factory is located. This is caused by the assumption that most of the input materials (as well as some avoided products such as animal feed) for the D-Factory are easily sourced locally anywhere in the world, which is a base assumption for the assessment. Therefore, what is achieved with D-Factory is that mostly processes that occur in high-risk countries and sectors are avoided (manufacturing of the benchmarks) and substituted by processes in one single country, that where D-Factory is located. If such country is to be Spain, any other country in Europe or even Israel for some impact categories; the social impact mitigation potential of D-Factory remains. In contrast, if D-Factory is located in high-risk countries such as Saudi Arabia, there is no mitigation potential and the negative social impacts of D-Factory out-weight its benefits. What is more, if D-Factory is located in a high-risk country and the up-scaling productivity turns lower than expected, the implementation of D-Factory would generate negative social impacts much greater than its benefits.

- This dependency on location for the social impact mitigation potential of D-Factory does not mean that the plant should not be implemented in the above mentioned countries. It rather means that if that was the case, the implementation should be closely followed so negative social impacts are avoided, especially concerning the impact categories where the risks are higher for each country. In other words, social standards that comply with global social regulations should be followed in whatever location where D-Factory is implemented.
- The outcome of this assessment should not be interpreted as a red or green light for the D-Factory concept. Rather than that, it should be used as a roadmap for future developments of the technology. The main recommendation for the stakeholders that take up on advancing with the D-Factory is to keep in mind that its social sustainability depends substantially on three key variables; 1) the successful substitution of the aimed high-value products, 2) the productivity of the system after upscaling and 3) the location of the plant. Keeping this in mind, measures should be adopted when implementing the D-Factory and establishing its value chain towards preventing social impacts related to the hot-spots identified (health and safety in the case of Spain). And in case another country is chosen as location, additional measures may be required depending on the circumstances.
- In order to reduce the negative social impact of D-Factory and its upstream processes, it is recommended to account for social reporting among the selection criteria for suppliers of a scaled-up system. Examples of these criteria are the provision of manufacturer-specific indicators, suppliers that include social indicators in sustainability reports, or the possibility to carry out sustainability audits to the suppliers. These indicators, reports and audits should be focused on the hot-spots identified for each country concerning social impact category and process. For example, for the base case scenario with the D-Factory plant located in Spain, health and safety impacts from heptane and hexane, ionic liquids and bottled CO_2 should be prioritized.

5.4.5 SWOT analysis

A SWOT analysis has been performed to identify the key internal and external factors for the success of the D-Factory pathways. The methodology followed consisted of a screening analysis based on existing information and literature, which was complemented with interviews with different stakeholders in order to integrate external expertise. It consists of two parts on algae biomass cultivation and on bioprocessing. It supplements the detailed analyses of sustainability aspects in the other assessment parts by external views to ensure that no aspect was missed that may be relevant in the perception of external stakeholders.

SWOT Analysis of algae biomass cultivation

This section describes the final results of the SWOT analysis regarding the algae production (Figure 5-13).

	Helpful to achieving the objective	**Harmful** to achieving the objective
Internal origin (attributes of the system)	*Strengths* • Salt & performant/resistant algal strain control and reduce contamination • Raceway ponds with CO2 input are easier to build and with lower CAPEX • Industrial symbiosis with CO2, salt and heat recycling from nearby industry	*Weaknesses* • Land use associated costs can be high • Brine and power plant/industries are not available everywhere • Mostly SMEs and not yet access to large cash amount or larger order-book • Corrosive hypersaline environment
External origin (attributes of the environment)	*Opportunities* • Better understanding of Dunaliella • Become a flagship for the algae industry • Export tech to ideal countries with sun/salt water/land • Strong demand for natural/bio product • Large production scale could help solve societal issues (ex: sustainable food from the ocean)	*Threats* • Algae process using industrial flue-gases may need more control and cleaning to be food/drugs compliant • External factors threatening the scale-up from demo • Other use of land (ex: real estate or solar power) • Public perception of – marine – water usage for algae project • Competition from lower price/quality producers

Figure 5-13: SWOT analysis of algae biomass cultivation.

The main Strengths, Weaknesses, Opportunities and Threats of the D-Factory cultivation system are presented below. They are categorized in technical, financial, environmental and social categories.

STRENGTHS:

- **Technical Strengths of the D-Factory cultivation system**

  One of the main technical strengths of the D-Factory cultivation system is its potential for industrial symbiosis. Indeed, flue gas could be used directly to feed the algae. Pure CO_2 injection would actually be suboptimal since it will not all be absorbed or used by the algae. When using CO_2 originally from the combustion of natural gas, direct flue gas injection into the pond is possible without the need of any flue-gas treatment. In addition, depending on the amount of CO_2, additional inputs may be needed, and an industrial symbiosis could be relevant with local industrial sites in the neighborhood of the D-Factory. One such industrial site with potential symbiosis has already been identified in Spain. Historically, many of the initial microalgae cultivation projects were related to waste water treatment via algae cultivation and this symbiosis with waste water treatment plants is also possible. Another technical strength of the D-Factory cultivation system is its hypersalinity. The hypersalinity of the ponds and robust Dunaliella algae strains give an extra resistance argument against external contamination of the pond by bacteria and other contaminants and helps control and reduce contamination.

- **Financial Strengths of the D-Factory cultivation system**

  Another strength identified for the D-Factory cultivation system is that it uses raceway ponds. Raceway ponds with CO2 input are easy to build and with a relative low CAPEX.

WEAKNESSES:

- **Financial Weaknesses of the D-Factory cultivation system**

  Thought land-use per output for algae cultivation systems is usually smaller than conventional bio-pathways, the total land use necessary for significant output production may still be quite important, especially in sunny countries where locations close to infrastructures are highly valued. This will put weight on the CAPEX of the D-Factory cultivation system. Another weakness of the D-Factory cultivation system is that the salt water and corrosive environment may add cost and other requirements to the demo plant. In addition, brine is not available everywhere so in order to get to the right hyper-salinity, water and salt may have to be mixed locally. Finally, from a cash-flow perspective, the D-Factory consortium do not have any Fortune 500 "large" company as partner and may hence lack the global network and large order-book specific to big multinational corporations which is much needed for commercialization of new products.

OPPORTUNITIES:

- **Financial Opportunities of the D-Factory cultivation system**

  One opportunity for the D-Factory cultivation system is the high demand for bio-based and natural products from consumer brands. The D-Factory is ideally positioned to answer this demand. Another financial and social opportunity is the potential to export D-Factory technologies to ideal countries when it comes to sun, brine and land resources. This list of countries with ideal Dunaliella cultivation conditions availability is extensive, so the D-Factory demo plant could be replicated and technology exported to a number of suitable locations. There are production facilities in the world similar to Monzón. Following the drop in oil prices, the micro algae cultivation business is contracting and the D-Factory with focus on nutrition and pharmaceutical could boost the whole interest in this field by becoming a flagship for the algae industry. Indeed, higher margin products have been saving the algae industry for decades and could, one more time, present interesting financial opportunities. These more advanced products add to the virtuous cycle of helping develop new technologies for algae production. These technologies enable larger size algae production, which in turn helps to reduce the cost of algae production and help target commodities. Basically, the same lessons learnt from large scale agriculture production can be observed from algae production.

- **Social Opportunities of the D-Factory cultivation system**

  From a social/financial perspective, large scale production of algae could solve societal issues like sustainable food production. In addition, a better scientific understanding of Dunaliella could benefit the global society. A better dissemination of knowledge through publications and shared best practice would give a better understanding of Dunaliella to the stakeholder and constitutes a social opportunity for the D-Factory project.

THREATS:

- **Technical Threats of the D-Factory cultivation system**

  External factors influencing the late technology development for specific parts of the D-Factory biorefinery demo could threaten the scale up of the demonstration plant.

- **Financial Threats of the D-Factory cultivation system**

  The CO_2 requirement and flue gas sources are not a real technical threat since the flue gas source does not impact the FDA or regulatory approval. Therefore, "dirtier" flue gas sources than natural gas combustion would need more expensive cleaning systems to achieve such purity requirement. This will still add operational expenditures to the process and could be considered a financial threat. In addition, other biotechnologies than Dunaliella with lower price or quality products could reach the market and compete with the D-Factory demo.

- **Social Threats of the D-Factory cultivation system**

  In tourist areas, the access to land and the real estate boom may be a threat to the implementation of the D-Factory. In addition, since solar PV costs have been substantially reduced, electricity production may also be competing for land with algae production, especially in countries where electrification is still lacking.

- **Environmental Threats of the D-Factory cultivation system**

  Freshwater usage and other environmental issues need to be addressed and clarified in order to promote the D-Factory as a sustainable alternative. Indeed, the public perception of marine water usage and energy used to circulate, pump and filter this water for algae is usually negative and could be considered an environmental threat.

SWOT Analysis on algae bioprocessing system

	Helpful to achieving the objective	**Harmful** to achieving the objective
Internal origin (attributes of the system)	*Strengths* ● Unique combination of centrifuge+ScCO2+HPCCC + membrane extraction ● Potential high value product ● Waste stream minimization	*Weaknesses* ● Clinical trials put into place ● Most promising algae scenario, including current/future market volumes/prices with externalities not decided yet ● Some of the flagship products have not been quantitatively assessed yet production-wise ● Some techniques are still in R&D level
External origin (attributes of the environment)	*Opportunities* ● Extraction processes of the D-Factory applied to other carotenoid content biomass ● International development of the D-Factory biorefinery concept ● Mathematical modelling optimisation of the extraction process	*Threats* ● Market demand side (nutraceutical/pharmaceutical) is not structured ● It may be harder than thought to comply with products legislation ● Availability and contractibility of Dunaliella algae feedstock

Figure 5-14: SWOT analysis of algae bioprocessing system.

STRENGTHS:

- **Technical Strengths of the D-Factory extraction system**

  The four extraction processes of the Evodos centrifuge, the supercritical CO_2 extraction and the High Performance Countercurrent Chromatography with membrane separation all together is a new combination of separation processes for algae compound extraction. Indeed, since the Evodos centrifugation technique does not destroy the cell structures of the Dunaliella there are many possible extraction scenarios and much optimization potential. This is one of the technical strengths of the D-Factory. In addition the D-Factory has a strong knowledge network covering all the parts of the algae production and chemical extraction value chains, both timewise and geographically.

- **Financial Strengths of the D-Factory extraction system**

  The carotenoid market is a high value products market and in addition to this, the D-Factory intends to be able to produce these products directly from the demo plant. There is no competitor on the market for such carotenoids purity. Nobody has done pharmaceutical production from algae before. D-Factory has a first mover advantage on a high margin market here. This is one of the main advantage and differentiator of this algae based project.

- **Environmental Strengths of the D-Factory extraction system**

  One of the strengths of the D-Factory algae biorefinery concept is that it is minimizing waste and all streams are optimized for the production of the final products.

WEAKNESSES:

- **Technical Weaknesses of the D-Factory extraction system**

  Some techniques used in the D-Factory processes are still at R&D level and may need more funding or different approaches for upscaling the production. Indeed, HPCCC is still an expensive and custom-made process which may need to be cost optimized for the D-Factory biorefinery process. The HPCCC with liquid/liquid extraction technology is not yet ready for the D-Factory concept. For production sake, today solid substrate chromatography is used to extract carotenoids. In addition, HPCCC is for the moment using freeze-dried material since spray dried does not work because of particulate size. For the supercritical CO_2 extraction process, the cost of extraction usually favors large volumes. This is not the case today, leading to suboptimal separation. Finally, some of the flagship products have not been quantitatively assessed yet, production-wise. Hence it is harder to make plans for future scaling-up or address new potential markets.

- **Financial Weaknesses of the D-Factory extraction system**

  One of the weaknesses inherent to the biorefinery and extraction system configuration of the D-Factory today is the fact that the D-Factory could produce a wide variety of products which means that the most promising scenario, including current and future market volumes as well as prices are not defined yet. This will take time and it is included in this list of financial weaknesses. Another financial weakness of the D-Factory is the absence of clinical trials for some of the products it focuses on. These trials are essential to establish prices, volumes and to address new market. However, they are expensive and were not included in the scope of the D-Factory project. They may need to be implemented and will definitely add costs to the final product's commercialization.

OPPORTUNITIES:

- **Technical Opportunities of the D-Factory extraction system**

  The four separation processes with the Evodos centrifuge, the supercritical CO_2 extraction, the High Performance Countercurrent Chromatography and the membrane separation combination could be optimized for best investment returns. Potential new algae projects and further research could use and enhance the mathematical optimization modelling of such D-Factory biorefinery for the production of a specific range of compounds. Another technical opportunity of the D-Factory is that extraction processes could be applied to other carotenoid content biomass, helping decreasing the cost of extraction and enhancing the quality of the final products.

- **Financial Opportunities of the D-Factory extraction system**

  One of the main financial opportunities for the D-Factory bioprocessing system is that it may open new possibilities for international development of the D-Factory biorefinery or some specific extraction or purification technologies. This would help the international development and deployment of the D-Factory biorefinery concept.

THREATS:

- **Financial Threats of the D-Factory extraction system**

  One financial threat to the D-Factory extraction system is that product legislation may be harder to comply with than initially assessed. This may add extra costs related to enhancing the separation and purification technologies used in the D-Factory biorefinery. Another financial threat to the D-Factory extraction system is that the market demand side for the nutrition and pharmaceutical sectors is not structured. Because the carotenoids extracted are from a natural product, the composition will change depending on natural conditions. Being a first mover here is challenging. Buyers will indeed have to deal with one production source at the beginning and that could be perceived as a threat. These issues could be solved but need to be solved carefully in order for the D-factory biorefinery concept to thrive. Part of this issue is more related to being able to reproduce the D-Factory production lines somewhere else with the same quality output. From a buyer perspective this could translate into a lock-in agreement, which is not always possible. To be able to have a lock-in situation, there is a need to be able to replicate the production. In addition to these issues, one has to keep in mind that the D-Factory is dealing with a basket of natural products with a multi-market target ranging from pharmaceuticals to colorant or food products. This increases the complexity and makes it harder to predict how the D-Factory could adapt to the market demand.

- **Social Threats of the D-Factory extraction system**

  Today the D-Factory extraction system and the algae cultivation systems are not located in the same place. Production takes place in southern countries, whereas extraction and purification takes place in northern countries. From a social perspective, it is beneficial to a country or local community to create new jobs in the primary sector. However, most developing countries want to move to secondary or tertiary activities and having the algae cultivation separated from the carotenoid extraction process could be seen as hindering this shift.

5.5 Integrated assessment

The integrated sustainability assessment joins and connects results on individual sustainability aspects to give an integrated view on sustainability of *Dunaliella*-based algae biorefinery concepts.

In a first step (chapter 5.5.1), indicators and results for relevant scenarios were collected from the assessments of individual sustainability aspects (for summaries see chapters 5.1-5.4). These scenarios represent potential algae biorefineries according to the D-Factory concept and alternative systems that would be replaced. This results in an overview of all relevant sustainability impacts.

In a second step (chapter 5.5.2), scenarios are compared to each other to determine which advantages and disadvantages may result from the realisation of selected front-runner scenarios.

5.5.1 Overview of sustainability impacts

Selection of indicators

Various technological, environmental, economic and social aspects relevant for sustainability have been studied in individual assessments, which form the basis of this integrated sustainability assessment (for summaries see chapters 5.1-5.4). The performance of assessed D-Factory scenarios and conventional reference systems regarding all these aspects is quantified or qualitatively rated using various indicators.

They include sustainability indicators in the strict sense, which depict impacts on objects of protection such as climate or health and safety. Further indicators depict barriers that may prevent the realisation of the scenario. Such barriers may lead to substantially worse real sustainability impacts when trying to realise a scenario, for which low potential impacts were anticipated. Another type of indicators reflects risks that may lead to substantially worse sustainability impacts in case of accidents etc. This is needed because scenarios are only assessed under routine operation conditions thus excluding such rare incidents by definition. The suitability and scientific validity of the indicators has been verified in the individual assessments.

In the integrated sustainability assessment, those indicators were chosen from the set of available indicators, which give additional information that is relevant for decisions between the assessed options. This means, for example, that indicators that do not show differences between scenarios have been left out. Indicators on local environmental impacts have been combined into five summarising indicators (see Table 5-1 in chapter 5.2 for original indicators). For an overview and a short description of the indicators see Table 5-2.

Additional indicators

There are indicators like CO_2 avoidance costs, which connect aspects of more than one pillar of sustainability (here: environment and economy) so that they can only be added in the integrated assessment. They indicate the efficiency of reaching a certain target and can only be interpreted if it is sufficiently certain that the target (in this example avoidance of greenhouse gas emissions compared to the reference system) is reached [Fankhauser 1995; Nordhaus 1994; Pehnt et al. 2010]. Since this is not the case in any assessed scenario, such indicators were not added.

Table 5-2: Overview of sustainability indicators selected for the integrated assessment

Impact category	**Short description**
Technology	
Maturity	Technical maturity of involved processes on EC's technology readiness level (TRL) scale from 1: basic principles observed to 9: actual system proven in operational environment [European Commission 2014]. (potential barrier).
Legislative framework and bureaucratic hurdles	Existing regulation that are hard to fulfil in particular for SMEs developing new processes and products (potential barrier).
Availability of competent support systems	Risk of not reaching expected performance because e.g. maintenance services of non-routine technologies are suboptimal (spare parts, availability of instrument support, to extent of software dependency). Scale from 1: many alternatives exist to 9: highly dependent.
Vulnerability	Risk of not reaching expected performance because of downtimes etc. (Susceptibility to external factors e.g. IT failure, power failure, misuse of technology, growth of predators). Scale from 1: low vulnerability to 9: highly vulnerable.
Complexity	Risk of not reaching expected performance because process control is challenging (technical complexity e.g. degree of integration).
Biological risk	Risk of not reaching expected performance because of internal contaminations.
Technological risk: Hazardous substances	Risk of product contaminations by e.g. toxic substances (hazard risk).
Technological risk: Explosions and fires	Risk of explosions and fires within industrial facilities like biorefineries (hazard risk).
Environment: global/regional impacts	
Global warming	Global warming/climate change as a consequence of the anthropogenic release of greenhouse gases. Besides carbon dioxide (CO_2), a number of other gases like methane (CH_4) and nitrous oxide (N_2O) are included.
Energy resources	Depletion of non-renewable energy resources, i.e. fossil fuels such as mineral oil, natural gas, coal and uranium ore.
Acidification	Shift of the acid/base equilibrium in soils by acidifying gases like sulphur dioxide, nitrogen oxides and ammonia (keyword 'acid rain').
Eutrophication	Input of excess nutrients into sensitive ecosystems (e.g. nitrogen and phosphorous)
Photochemical smog	Formation of specific reactive substances, e.g. ozone, in presence of nitrogen oxides, volatile hydrocarbons and solar radiation in the lower atmosphere (keyword 'ozone alert' or 'summer smog').
Ozone depletion	Loss of the protective ozone layer in the stratosphere by certain gases such as CFCs or nitrous oxide (keyword 'ozone hole').
Human toxicity (respiratory inorganics)	Damage to human health due to air pollutants from routine operation such as fine, primary particles and secondary particles (mainly from NO_X, NH_3 and SO_2, keyword 'winter smog' or 'London smog'). This is not connected to toxicity risks from exceptional product contaminations (see indicator toxicity risks).
Freshwater use (global)	Consumption of freshwater e.g. for algae cultivation or irrigation from tap water, water from wells, rivers or lakes but not rainwater ("blue water").

Impact category	Short description
Environment: local impacts	
Water (local)	Local water availability for ecosystems and its quality.
Soil	Soil quality is affected e.g. by erosion, compaction or organic matter content.
Fauna	Local biodiversity among animals is affected e.g. by the presence of diverse habitats.
Flora	Biodiversity among plants on and around cultivated areas is affected e.g. by weed control measures.
Landscape	Characteristics and diversity of the landscape.
Economy	
Operating Expenditure	Ongoing cost for running the biorefinery.
Total Revenue	Return from product sales.
Gross Margin	Difference between total revenue and operating expenditures.
Capital Expenditure	Sum of invested capital for the biorefinery facility.
Economic Internal Rate of Return (10 years)	Measure for profitability.
Net Present Value (10 years, 5% discount)	Measure for attractiveness to investors.
Society	
Labour rights and decent work	Risk of unfair conditions of work or labour accords violations in the value chain; such as child labour, low wages, forced labour, excessive working time or suppression of workers association.
Health and safety	Risk along the value chain of high prevalence of occupational injuries and deaths, as well as high exposure to workplace hazards.
Human rights	Risk of human right violations along the value chain; such as infringements of indigenous rights, weakness of gender equality, potential for high conflicts and prevalence of diseases.
Governance	Risk of manufacturing processes located in countries or regions with weak legal systems, with high risk of corruption or poor law enforcement.
Community infrastructure	Risk of negative impacts along the value chain to the local community; such as school for children, drinking water, sanitation, hospital beds and land ownership of small land holdings.

Categorisation

For comparability to qualitative indicators, quantitative indicators are categorised and the tables are coloured accordingly (Table 5-3). Quantitative results are categorised according to their position in the range from worst to best result for each indicator: A result is categorised as neutral (yellow) if it does not deviate by more than 10% from the middle of this range. Better (light green) or worse (orange) than neutral are chosen according to the meaning of each indicator (e.g. lower expenditures are better but lower revenues are worse). The best or worst 10% of the range are highlighted dark green and red, respectively. This way of categorising results supports the identification of options that perform best among all studied options. It does not indicate if an outcome is acceptable or not because it could also be that all or none of the scenarios show acceptable performance regarding a certain indicator.

Acceptability of sustainability impacts

Whether sustainability impacts are acceptable or not depends on the benefits gained in return for accepting these impacts. Such decisions cannot be made on an entirely scientific basis because unrelated advantages and disadvantages have to be balanced. Nevertheless, a scientific analysis of advantages and disadvantages can support a public value-based debate whether the assessed *Dunaliella*-based algae biorefinery concepts should be supported or not. The assessed options to implement a *Dunaliella*-based algae biorefinery for the production of *9-cis* β-carotene share the following features:

- *9-cis* β-carotene is provided, which currently cannot be produced by other means. If clinical trials support the novel health benefits of *9-cis* β-carotene, this is a strong argument for realising a *Dunaliella*-based algae biorefinery.
- Considerable to very substantial amounts of energy and material resources are required for operations. This can only be partially compensated if co-products of *9-cis* β-carotene production substitute competing equivalent products. In that case, avoided production can save energy and material resources elsewhere – but only, if the total market volume is not affected and production of competing products really decreases. As a consequence, considerable to very substantial environmental impacts and social risks will be caused by *9-cis* β-carotene production in particular in the industries supplying the biorefinery.
- Used technology is not yet mature and operations may still create technological challenges.
- The ranges from conservative to optimistic performance are wide for many sustainability indicators and scenarios. It thus very much depends on boundary conditions and success of further process development whether more or less favourable sustainability impacts can be achieved.

Conclusions on the overall acceptability of sustainability impacts

Highly valued health benefits expected from *9-cis* β-carotene cannot be achieved without damages and risks to environment and society that can be very substantial. The extent of damages and risks depends very much on how *9-cis* β-carotene is production is realised. Therefore, the available options have to be compared carefully.

Identification of front-runner scenarios

Results for indicators and assessed standard scenarios are shown in Table 5-3. None of the scenarios scores best in all indicators. Therefore, no best solution can be identified on an entirely scientific basis without value-based choices. This is an almost unavoidable result if the sustainability assessment of a system with a certain degree of complex is truly comprehensive. Valuable decision support can still be provided to involved stakeholders such as businesses, policymakers or consumers if advantages and disadvantages of selected decision options are made transparent. The following front-runner scenarios, which perform best regarding certain groups of indicators, are selected for a detailed discussion in chapter 5.5.2:

- Scenario 1 (initial configuration): The realisation and operation of a *Dunaliella*-biorefinery according to this concept will face least technical barriers.
- Scenario 5 (shorter downstream processing), optimistic performance: If this scenario can be implemented as expected, it will be the most profitable option and will pose least potential social risks.
- Scenario 6 (no carotenoid separation), optimistic performance: If this scenario is realised and the performance expected under optimistic boundary conditions can be achieved, lowest environmental impacts can be reached.

Table 5-3: Overview of results for life cycle comparisons of D-Factory scenarios to its alternatives. N/D: no data, N/A: not applicable.

			Conservative performance						Optimistic performance					
			D-Factory scenarios						D-Factory scenarios					
	Indicator	Unit	Scenario 1 Initial configuration	Scenario 2 Membrane pre-concentration	Scenario 3 Whole cell harvesting	Scenario 4 Glycerol recovery	Scenario 5 (shorter down-stream pro-cessing)	Scenario 6 (no carotenoid separation)	Scenario 1 Initial configuration	Scenario 2 Membrane pre-concentration	Scenario 3 Whole cell harvesting	Scenario 4 Glycerol recovery	Scenario 5 (shorter down-stream pro-cessing)	Scenario 6 (no carotenoid separation)
Technology	Maturity	-	7.4	7.3	7.0	6.9	N/D	N/D	7.4	7.3	7.0	6.9	N/D	N/D
	Legislative framework and bureaucratic hurdles	-	6.7	6.7	7.1	7.4	N/D	N/D	6.7	6.7	7.1	7.4	N/D	N/D
	Availability of competent support systems	-	7.4	7.6	7.3	7.4	N/D	N/D	7.4	7.6	7.3	7.4	N/D	N/D
	Vulnerability	-	7.1	6.9	6.4	6.2	N/D	N/D	7.1	6.9	6.4	6.2	N/D	N/D
	Complexity	-	7.0	6.8	6.3	6.0	N/D	N/D	7.0	6.8	6.3	6.0	N/D	N/D
	Biological risk	-	7.5	6.7	5.3	5.3	N/D	N/D	7.5	6.7	5.3	5.3	N/D	N/D
	Technological risk: Hazardous substances	-	5.8	5.8	5.8	5.9	N/D	N/D	5.8	5.8	5.8	5.9	N/D	N/D
	Technological risk: Explosions and fires	-	7.4	7.4	7.4	7.5	N/D	N/D	7.4	7.4	7.4	7.5	N/D	N/D
Environment	Global warming	t CO2 eq. / kg 9-cis β-c.	26	22	26	26	4	1	14	12	15	15	2	0.2
	Energy resources	GJ / kg 9-cis β-c.	453	389	472	462	70	22	250	216	271	265	30	4
	Acidification	kg SO2 eq. / kg 9-cis β-c.	111	100	121	120	10	4	64	58	71	71	3	1
	Eutrophication	kg PO4 eq. / kg 9-cis β-c.	5.2	4.5	5.3	5.3	0.6	0.3	2.8	2.4	3.0	3.0	0.1	0.1
	Photochemical smog	kg ethene eq. / kg 9-cis β-c.	11	10	13	12	5	0.3	6	6	7	7	3	0.1
	Ozone depletion	g CFC-11 eq. / kg 9-cis β-c.	14	13	14	14	-0.4	1	7	6	7	7	-2	1
	Human toxicity (respiratory inorganics)	kg PM10 eq. / kg 9-cis β-c.	110	88	105	104	12	5	62	49	60	59	4	1
	Freshwater use (global)	m^3 / kg 9-cis β-c.	606	137	56	56	45	115	114	-104	-133	-133	-126	8
	Water (local)	-	- -	-	-	-	-	-	-	0	0	0	0	0
	Soil	-	-	0	0	0	0	-	0	+	+	+	+	+
	Fauna	-	-	0	0	0	0	-	0	+	+	+	+	+
	Flora	-	-	0	0	0	0	-	0	+	+	+	+	+
	Landscape	-	0	0	0	0	0	0	+	+	+	+	+	+
Economy	Operating Expenditure	Million €/year	16	11	15	15	11	4	27	20	29	29	20	4
	Total Revenue	Million €/year	11	11	14	14	12	2	33	33	41	41	34	4
	Gross Margin	%	-43%	5%	-9%	-8%	12%	-85%	21%	41%	29%	29%	41%	11%
	Capital Expenditure	Million €	51	52	53	53	4	4	51	52	53	53	4	4
	Economic Internal Rate of Return (10 years)	%	N/A	N/A	N/A	N/A	N/A	N/A	3%	20%	15%	15%	296%	N/A
	Net Present Value (10 years, 5% discount)	Million €	-119	-51	-77	-76	-3	-45	46	111	91	93	124	-15
Society	Labor rights and decent work	Risk of negative impact/ g 9-cis β-carotene	-97	-64	9	-3	-103	-3	-91	-107	-45	-53	-107	-16
	Health and safety		5	191	200	205	138	11	-24	-35	2	4	-23	0
	Human rights		0	-23	27	9	-86	-8	-22	-38	0	-11	-96	-17
	Governance		100	109	131	110	54	3	43	23	46	33	-16	-3
	Community infrastructure		-115	-122	-53	-62	-138	-6	-94	-106	-54	-60	-110	-13

5.5.2 Structured comparison of scenarios

This chapter discusses advantages and disadvantages that are expected to arise from the realisation of selected front-runner scenarios (see chapter 5.5.1 for selection criteria). To this end, all scenarios are compared to one front-runner scenario at a time, which serves as a benchmark. Alternatives are considered advantageous (+) and disadvantageous (-) regarding a certain aspect if they have qualitative rating differing from the benchmark value by more than 5% of the total range of values for that indicator, respectively. The rating very advantageous (++) and very disadvantageous (- -) are given for a deviation by more than 50%. For qualitative ratings, thresholds of one or two grades on the used 5 part scale are applied. For some scenarios, performance indicators such as economic internal rate of return cannot be calculated because, for this indicator, there is no return (designated as "N/A" in Table 5-3). Other scenarios are rated very advantageous when compared to a benchmark without score for such reasons ("N/A").

Benchmark scenario 1 (initial configuration)

This scenario was selected as front-runner scenario because the realisation and operation of a *Dunaliella*-biorefinery according to this concept will face least technical barriers. No scenario scores better than scenario 1 (initial configuration) regarding the technological indicators *maturity*, *vulnerability*, *complexity* and *biological risk* (Table 5-4). This reflects that the simplest technology is used, which can be planned, installed and operated facing least challenges.

Comparing all other analysed options of installing a *Dunaliella*-based algae biorefinery to this scenario, on can see that several other options have many advantages compared to this benchmark (green cells in Table 5-4). These advantages could not be realised if scenario 1 (initial configuration) would be implemented and thus represent drawbacks of the benchmark scenario.

The most important drawbacks of scenario 1 (initial configuration) are:

- Overcoming other technical barriers and risks is expected to require more efforts than for other scenarios. In particular, management of e.g. big amounts of wastewater creates regulatory challenges (see *Legislative framework and bureaucratic hurdles* in Table 5-4).
- Environmental impacts can be much lower for many other scenarios.
- Although this scenario can already be marginally profitable under optimistic conditions, the internal rate of return is very low even under these conditions. Much higher profitability can be expected when realising other versions of a *Dunaliella*-based algae biorefinery.
- Social risks would be lower for other scenarios.

Conclusions on the technically easiest solution scenario 1 (initial configuration)

This version of a *Dunaliella*-based algae biorefinery is easiest to realise if a legal solution for wastewater discharge can be found. It is already profitable if a performance like in the scenarios under optimistic conditions can be achieved. However, this option should not be aimed for mainly because of severe environmental impacts and questionable profitability. These can be much better when implementing other scenarios.

Table 5-4: Comparison of all other scenarios to the benchmark scenario 1 (initial configuration) under optimistic conditions. N/D: no data, N/A: not applicable.

			Conservative performance						Optimistic performance					
			D-Factory scenarios						D-Factory scenarios					
	Indicator	Unit	Scenario 1 Initial configuration	Scenario 2 Membrane pre-concentration	Scenario 3 Whole cell harvesting	Scenario 4 Glycerol recovery	Scenario 5 (shorter down-stream pro-cessing)	Scenario 6 (no carotenoid separation)	Scenario 1 Initial configuration	Scenario 2 Membrane pre-concentration	Scenario 3 Whole cell harvesting	Scenario 4 Glycerol recovery	Scenario 5 (shorter down-stream pro-cessing)	Scenario 6 (no carotenoid separation)
Technology	Maturity	-	0	-	-	-	N/D	N/D		-	-	-	N/D	N/D
Technology	Legislative framework and bureaucratic hurdles	-	0	0	+	+	N/D	N/D		0	+	+	N/D	N/D
Technology	Availability of competent support systems	-	0	+	-	0	N/D	N/D		+	-	0	N/D	N/D
Technology	Vulnerability	-	0	-	-	-	N/D	N/D		-	-	-	N/D	N/D
Technology	Complexity	-	0	-	-	-	N/D	N/D		-	-	-	N/D	N/D
Technology	Biological risk	-	0	-	- -	- -	N/D	N/D		-	- -	- -	N/D	N/D
Technology	Technological risk: Hazardous substances	-	0	0	0	0	N/D	N/D		0	0	0	N/D	N/D
Technology	Technological risk: Explosions and fires	-	0	0	0	0	N/D	N/D		0	0	0	N/D	N/D
Environment	Global warming	t CO_2 eq. / kg 9-cis β-c.	-	-	-	-	+	+		+	0	0	+	++
Environment	Energy resources	GJ / kg 9-cis β-c.	-	-	-	-	+	+		+	0	0	+	++
Environment	Acidification	kg SO_2 eq. / kg 9-cis β-c.	-	-	-	-	+	+		+	-	-	++	++
Environment	Eutrophication	kg PO_4 eq. / kg 9-cis β-c.	-	-	-	-	+	+	BENCHMARK	+	0	0	++	++
Environment	Photochemical smog	kg ethene eq. / kg 9-cis β-c.	-	-	-	-	+	+		+	-	0	+	++
Environment	Ozone depletion	g CFC-11 eq. / kg 9-cis β-c.	-	-	-	-	+	+		+	0	0	++	+
Environment	Human toxicity (respiratory inorganics)	kg PM10 eq. / kg 9-cis β-c.	-	-	-	-	+	++		+	0	0	++	++
Environment	Freshwater use (global)	m^3 / kg 9-cis β-c.	- -	0	+	+	+	0		+	+	+	+	+
Environment	Water (local)	-	-	0	0	0	0	0		+	+	+	+	+
Environment	Soil	-	-	0	0	0	0	-		+	+	+	+	+
Environment	Fauna	-	-	0	0	0	0	-		+	+	+	+	+
Environment	Flora	-	-	0	0	0	0	-		+	+	+	+	+
Environment	Landscape	-	-	-	-	-	-	-		0	0	0	0	0
Economy	Operating Expenditure	Million €/year	+	++	+	+	++	++		+	-	-	+	++
Economy	Total Revenue	Million €/year	- -	- -	- -	- -	- -	- -		0	+	+	0	- -
Economy	Gross Margin	%	- -	-	-	-	-	- -		+	+	+	+	-
Economy	Capital Expenditure	Million €	0	0	0	0	++	++		0	0	0	++	++
Economy	Economic Internal Rate of Return (10 years)	%	- -	- -	- -	- -	- -	- -		+	0	0	++	- -
Economy	Net Present Value (10 years, 5% discount)	Million €	- -	-	- -	-	-	-		+	+	+	+	-
Society	Labor rights and decent work	Risk of negative impact/ g 9-cis β-carotene	+	-	- -	- -	+	- -		+	-	-	+	- -
Society	Health and safety	Risk of negative impact/ g 9-cis β-carotene	-	- -	- -	- -	- -	-		0	-	-	0	-
Society	Human rights	Risk of negative impact/ g 9-cis β-carotene	-	0	-	-	++	-		+	-	-	++	0
Society	Governance	Risk of negative impact/ g 9-cis β-carotene	-	-	- -	-	-	+		+	0	+	+	+
Society	Community infrastructure	Risk of negative impact/ g 9-cis β-carotene	+	+	-	-	+	- -		+	-	-	+	- -

Benchmark scenarios 5 (shorter downstream processing)

Scenario 5 was selected as front-runner scenario because it is most profitable and it causes mostly lower social risks than all other scenarios (*labour rights and decent work, health and safety, human rights* and *governance*).

Compared to scenarios 1-4, scenario 5 lacks the last step of downstream processing, which separates carotenes into α-carotene and *9-cis* β-carotene via preparative HPLC (high performance liquid chromatography). This process consumes about 85-90% of all electric energy in the whole algae biorefinery including algae cultivation in scenarios 1-4. If it is omitted, α-carotene cannot be sold as product but remains as a harmless impurity with *9-cis* β-carotene.

The advantages of scenario 5 over the others (Table 5-5):

- No scenario shows decisively lower environmental burdens regarding *acidification, eutrophication, photochemical smog, ozone depletion, human toxicity via respiratory inorganics*, *freshwater use* and all local environmental impacts)
- Lower social risks with the exceptions of impacts on *community infrastructure*.
- Highest profitability at much lower capital expenditures compared to scenarios 1-4 (by a factor of about 10). In this case, the slightly lower *total revenue* than in some other scenarios is compensated by similarly decreased *operating expenditures*.

Its main drawback is:

- Impacts on *global warming, energy resources* and *photochemical smog* are still about 10 times higher than for scenario 6.

Technological indicators cannot be evaluated due to lacking data. Nevertheless, leaving away a high-tech process such as preparative HPLC should make the technical implementation easier.

Conclusions on the option with highest profitability and lowest social burdens and risks

If downstream processing is shortened (α-carotene and *9-cis* β-carotene are not separated via preparative HPLC) this saves a lot of energy, chemicals and investment but also lacks part of revenues and credits since α-carotene cannot be sold separately. Despite this trade-off, results improve dramatically for most indicators. The only drawback is that a further shortening of downstream processing could be even better for the environment. It seems promising that this drawback can be overcome by introducing a new modular and integrated version of the high-performance counter-current chromatography (HPCCC) technology used in this scenario [DeAmicis et al. 2017; Sutherland et al. 2013]. It was newly devised and developed within this project but could not be evaluated quantitatively yet because reliable modelling would have required more operational experience.

Table 5-5: Comparison of all other scenarios to the benchmark scenario 5 (shorter downstream processing), under optimistic conditions. N/D: no data, N/A: not applicable.

			Conservative performance – D-Factory scenarios						Optimistic performance – D-Factory scenarios					
	Indicator	Unit	Scenario 1 Initial configuration	Scenario 2 Membrane pre-concentration	Scenario 3 Whole cell harvesting	Scenario 4 Glycerol recovery	Scenario 5 (shorter down-stream pro-cessing)	Scenario 6 (no carotenoid separation)	Scenario 1 Initial configuration	Scenario 2 Membrane pre-concentration	Scenario 3 Whole cell harvesting	Scenario 4 Glycerol recovery	Scenario 5 (shorter down-stream pro-cessing)	Scenario 6 (no carotenoid separation)
Technology														
	Maturity	-	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D		N/D
	Legislative framework and bureaucratic hurdles	-	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D		N/D
	Availability of competent support systems	-	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D		N/D
	Vulnerability	-	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D		N/D
	Complexity	-	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D		N/D
	Biological risk	-	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D		N/D
	Technological risk: Hazardous substances	-	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D		N/D
	Technological risk: Explosions and fires	-	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D		N/D
Environment														
	Global warming	t CO2 eq. / kg 9-cis β-c.	- -	- -	- -	- -	-	0	-	-	- -	-		+
	Energy resources	GJ / kg 9-cis β-c.	- -	- -	- -	- -	-	0	-	-	- -	- -		+
	Acidification	kg SO2 eq. / kg 9-cis β-c.	- -	- -	- -	- -	-	0	- -	-	- -	- -		0
	Eutrophication	kg PO4 eq. / kg 9-cis β-c.	- -	- -	- -	- -	-	0	- -	-	- -	- -	BENCHMARK	0
	Photochemical smog	kg ethene eq. / kg 9-cis β-c.	- -	- -	- -	- -	-	+	-	-	-	-		+
	Ozone depletion	g CFC-11 eq. / kg 9-cis β-c.	- -	- -	- -	- -	-	-	- -	- -	- -	- -		-
	Human toxicity (respiratory inorganics)	kg PM10 eq. / kg 9-cis β-c.	- -	- -	- -	- -	-	0	- -	-	- -	- -		0
	Freshwater use (global)	m³ / kg 9-cis β-c.	- -	-	-	-	-	-	-	0	0	0		-
	Water (local)	-	- -	-	-	-	-	-	-	0	0	0		0
	Soil	-	- -	-	-	-	-	- -	-	0	0	0		0
	Fauna	-	- -	-	-	-	-	- -	-	0	0	0		0
	Flora	-	- -	-	-	-	-	- -	-	0	0	0		0
	Landscape	-	-	-	-	-	-	-	0	0	0	0		0
Economy														
	Operating Expenditure	Million €/year	+	+	+	+	+	++	-	0	-	-		++
	Total Revenue	Million €/year	- -	- -	- -	- -	- -	- -	0	0	+	+		- -
	Gross Margin	%	- -	-	-	-	-	- -	-	0	-	-		-
	Capital Expenditure	Million €	- -	- -	- -	- -	0	0	- -	- -	- -	- -		0
	Economic Internal Rate of Return (10 years)	%	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -		- -
	Net Present Value (10 years, 5% discount)	Million €	- -	- -	- -	- -	- -	- -	-	-	-	-		- -
Society														
	Labor rights and decent work	Risk of negative impact/ g 9-cis β-carotene	-	-	- -	- -	0	- -	-	0	- -	-		- -
	Health and safety		-	- -	- -	- -	- -	-	0	0	-	-		-
	Human rights		- -	- -	- -	- -	-	- -	- -	-	- -	- -		- -
	Governance		- -	- -	- -	- -	-	-	-	-	-	-		-
	Community infrastructure		0	+	-	-	+	- -	-	0	-	-		- -

Benchmark scenario 6 (no separation of carotenoid extract)

Scenario 6 performs best regarding most environmental impacts, in particular on a global and regional scale (*global warming, energy resources, acidification, eutrophication, photochemical smog* and *human toxicity via respiratory inorganics*).

Scenario 6 ends after the extraction of carotenoids from algae powder and does not separate the extract into several products. This saves about 95% of power compared to full downstream processing but produces 6 products less (α-carotene, *all-trans* beta-carotene, zeaxanthin, lutein, chlorophyll and polar lipids).

The advantages of scenario 6 over the others (Table 5-6):

- Much lower global/regional environmental burdens regarding *global warming, energy resources, acidification, eutrophication, photochemical smog* and *human toxicity via respiratory inorganics*) than most other scenarios at similar performance compared to the remaining scenarios.
- Lower or similar local environmental impacts.

Its main drawback is:

- Compared to scenarios 5, profitability is much lower and social risks are higher.

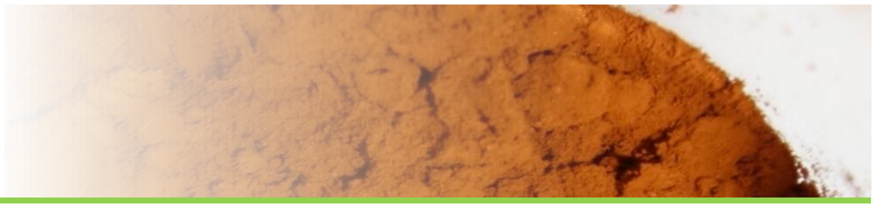
Technological indicators cannot be evaluated due to lacking data. Nevertheless, leaving away the HPCCC process, which is under active development, should make the technical implementation easier.

Conclusions on the option with lowest overall environmental burdens

If downstream processing is shortened further (splitting up the extract into 6 products via HPCCC), this saves energy, chemicals and some investment but also lacks part of revenues and credits since 5 products cannot be sold separately. This trade-off only leads to substantial improvements of the nevertheless important environmental impacts *global warming, energy resources* and *photochemical smog* (by a factor of about 10) while results are worse in most other aspects. Therefore, energy and material efficiency of this separation step should be improved with high priority to reduce this trade-off for a profitable, socially beneficial *and* environmentally friendly solution. The implementation of a new modular HPCCC method for this downstream processing step seems promising to overcome this limitation.

Table 5-6: Comparison of all other scenarios to the benchmark scenario 6 (no carotenoid separation), under optimistic conditions. N/D: no data, N/A: not applicable.

			Conservative performance						Optimistic performance					
			D-Factory scenarios						D-Factory scenarios					
	Indicator	Unit	Scenario 1 Initial configuration	Scenario 2 Membrane pre-concentration	Scenario 3 Whole cell harvesting	Scenario 4 Glycerol recovery	Scenario 5 (shorter down-stream pro-cessing)	Scenario 6 (no carotenoid separation)	Scenario 1 Initial configuration	Scenario 2 Membrane pre-concentration	Scenario 3 Whole cell harvesting	Scenario 4 Glycerol recovery	Scenario 5 (shorter down-stream pro-cessing)	Scenario 6 (no carotenoid separation)
Technology	Maturity	-	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	
Technology	Legislative framework and bureaucratic hurdles	-	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	
Technology	Availability of competent support systems	-	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	
Technology	Vulnerability	-	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	
Technology	Complexity	-	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	
Technology	Biological risk	-	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	
Technology	Technological risk: Hazardous substances	-	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	
Technology	Technological risk: Explosions and fires	-	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	
Environment	Global warming	t CO2 eq. / kg 9-cis β-c.	- -	- -	- -	- -	-	0	- -	-	- -	- -	-	
Environment	Energy resources	GJ / kg 9-cis β-c.	- -	- -	- -	- -	-	0	- -	-	- -	- -	-	
Environment	Acidification	kg SO2 eq. / kg 9-cis β-c.	- -	- -	- -	- -	-	0	- -	-	- -	- -	0	
Environment	Eutrophication	kg PO4 eq. / kg 9-cis β-c.	- -	- -	- -	- -	-	0	- -	-	- -	- -	0	BENCHMARK
Environment	Photochemical smog	kg ethene eq. / kg 9-cis β-c.	- -	- -	- -	- -	-	0	- -	-	- -	- -	-	
Environment	Ozone depletion	g CFC-11 eq. / kg 9-cis β-c.	- -	- -	- -	- -	+	0	-	-	-	-	+	
Environment	Human toxicity (respiratory inorganics)	kg PM10 eq. / kg 9-cis β-c.	- -	- -	- -	- -	-	0	- -	-	- -	- -	0	
Environment	Freshwater use (global)	m³ / kg 9-cis β-c.	- -	-	-	-	0	-	-	+	+	+	+	
Environment	Water (local)	-	- -	-	-	-	-	-	-	0	0	0	0	
Environment	Soil	-	- -	-	-	-	-	- -	-	0	0	0	0	
Environment	Fauna	-	- -	-	-	-	-	- -	-	0	0	0	0	
Environment	Flora	-	- -	-	-	-	-	- -	-	0	0	0	0	
Environment	Landscape	-	-	-	-	-	-	-	0	0	0	0	0	
Economy	Operating Expenditure	Million €/year	-	-	-	-	-	0	- -	- -	- -	- -	- -	
Economy	Total Revenue	Million €/year	+	+	+	+	+	-	++	++	++	++	++	
Economy	Gross Margin	%	-	0	-	-	0	- -	+	+	+	+	+	
Economy	Capital Expenditure	Million €	- -	- -	- -	- -	0	0	- -	- -	- -	- -	0	
Economy	Economic Internal Rate of Return (10 years)	%	0	0	0	0	0	0	++	++	++	++	++	
Economy	Net Present Value (10 years, 5% discount)	Million €	-	-	-	-	0	-	+	++	+	+	++	
Society	Labor rights and decent work	Risk of negative impact/ g 9-cis β-carotene	++	+	-	-	++	-	++	++	+	+	++	
Society	Health and safety		0	- -	- -	- -	- -	0	+	+	0	0	+	
Society	Human rights		-	0	-	-	++	-	0	+	-	0	++	
Society	Governance		- -	- -	- -	- -	-	0	-	-	-	-	+	
Society	Community infrastructure		++	++	+	+	++	-	++	++	+	+	++	



6 Recommendations

Based on the conclusions drawn in chapters 5 and detailed background information available in the reports on technological, environmental, economic and social assessment [Harvey 2017a; Keller et al. 2017; Mitchell & Goacher 2017; Peñaloza & Stahl 2017], the following recommendations can be made to businesses, science, policymakers and consumers from an overall sustainability perspective.

6.1 To businesses

From a technical point of view, *Dunaliella salina*-based algae biorefineries following the concept developed in this project can be set up in the near future – even if some analysed variants still need a few years development time. Depending on how much is invested in further optimisation and whether algae extracts are separated into several products or sold as such, the processes and products can be more or less sustainable. From a sustainability perspective, the following recommendations should be considered to reduce burdens and risks to adequate levels. Here, product use must be differentiated: if clinical studies demonstrate that *9-cis* β-carotene has novel medical value, i.e. it is a new medicine with no alternative, different sustainability demands must be placed on the product than if 'only' nutraceuticals were produced. In the former case, it would be sufficient to increase sustainability as far as possible, in the second case more stringent requirements apply in order actually generate sustainability benefits:

- **If a *Dunaliella* biorefinery is built, because clinical studies demonstrate a novel benefit of *9-cis* β-carotene,** include the following points in your **biorefinery concept design** to limit in particular the environmental burdens and social risks to an acceptable level:
  - **Only split up the carotenoid extract into its components instead of selling *9-cis* β-carotene as part of this mixture, if required for medical reasons or if new purification methods are confirmed to be sufficiently efficient.**
    If initial indications are confirmed that *9-cis* ß-carotene in extracts or mixtures displays similar efficacy to the pure substance, at least the last step to separate *9-cis* β-carotene from α-carotene by preparative high performance liquid chromatography (HPLC) should be omitted. The benefits of α-carotene as an additional co-product do not justify additional expenditures for HPLC from economic, environmental and social perspectives. The efficiency of fractionating the extract into 6 co-products should be improved to increase sustainability. Using the modular high performance countercurrent chromatography (HPCCC) system newly devised within this project, possibly integrated with membrane technology in a compact system, is expected to be the most promising approach for this.
  - Select a **site that facilitates the integration with existing facilities** for producing salt products or seawater desalination facilities and a CO_2 source such as a power plant. In particular, this is necessary to minimise the environmental burdens and costs of energy and material use, impacts on local freshwater availability and of the disposal of saltwater as well as efforts for regulatory compliance. The following measures can contribute to this:

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  - Use **flue gas CO_2 and where possible waste heat.** All scenarios are based on the use of CO_2 obtained as a waste product of power plants, steelworks, cement works or chemicals industry facilities. The impacts and cost of this input and the whole biorefinery would be significantly higher if instead liquefied CO_2 would be used. It may further be possible to capture unused waste heat generated by the same industrial facility to maintain pond temperatures during winter or unseasonal cold weather if necessary.

  - Develop **concepts for internal recycling of the medium and/or a cascading use of brine** in the participating facilities. Select the concept that leads to the lowest overall sustainability impacts considering the availability of the medium, medium reconditioning, wastewater treatment and downtime due to contamination. A screening LCA of relevant aspects may support this selection process.
- Guarantee sufficient **availability of freshwater**, in particular at inland sites in semi-arid and arid regions, but also in the Mediterranean region. Existing water uses in the respective catchment area must be taken into consideration. The use of fossil groundwater is not sustainable.
- Devise a concept for disposing of the remaining **wastewater with a high salt load** without causing ecological harm. It is expected that this will be easier in coastal locations.
- Contact authorities at an early stage, so that missing **permits** do not delay or prevent the construction of the plant. Regardless of where a facility is eventually built, amongst others, a specific environmental impact assessment must be performed compliant with Directive 2014/52/EU.
- Wherever possible, **select a site that cannot be used agriculturally** (brownfield site) and was previously sealed. If this is not feasible, sealing agricultural land can be acceptable under two conditions: (1) Lower value biomass streams are converted into co-products such as feed or fatty acids for oleochemistry in substantial quantities and high quality. In this way, other agricultural products can be substituted to reduce the overall demand for agricultural land. (2) Ecological compensation areas must be created according to the results of a site-specific environmental impact assessment. Whatever the case, avoid particularly ecologically valuable areas.

- If you plan to construct an algae **biorefinery in countries with low social standards** outside of the EU, this can cause high social risks. This does not mean that the system should not be implemented there. It rather means that if that was the case, the implementation should be closely followed so that negative social impacts are avoided.
- It is recommended to account for **social reporting among the selection criteria for suppliers** in order to reduce the negative social impact of an algae biorefinery and its upstream processes. Examples of these criteria are the provision of manufacturer-specific indicators, suppliers that include social indicators in sustainability reports e.g. following guidelines of the Global Reporting Initiative (GRI), or the possibility to carry out sustainability audits to the suppliers. These indicators, reports and audits should be focused on the hot-spots identified for each country concerning social impact category and process. For example, if a Dunaliella-based biorefinery according to the scenarios studied in this report was located in Spain, health and safety impacts from heptane and hexane, ionic liquids and bottled CO_2 for supercritical CO_2 extraction should be prioritized. Similar selection criteria for suppliers should also be in-

Images from top to bottom: © Andreas Hermsdorf/pixelio.de; own image; Rainer Sturm/pixelio.de cluded for environmental aspects. This could for example be environmental product declarations or sustainability reports of suppliers following GRI criteria.

- **Install photovoltaic systems** to produce as much of the required electricity on site as possible. One option is to install only limited capacity at the outset and to set aside land for an extension once more data from actual operations allow for analysing and adjusting load and demand profiles. Additional modules could be financed from the first revenues. A second option would be to install sufficient solar power capacity from the outset and to feed excess power into the grid.

- If you are planning to build a Dunaliella algae biorefinery to supply **natural and sustainable nutraceuticals independent of the medicinal value of *9-cis* β-carotene**, you should ensure that the biorefinery truly contributes to mitigating environmental burdens and social risks. This is not possible with exactly those processes that are described in the analysed scenarios. Therefore, the following improvements have to be implemented before extending the recommendations given above:
  - **Confirm that new downstream processing technologies** meet expectations to sufficiently decrease energy and material consumption.

  Once this is achieved, the following measures have to be adopted in addition:
  - **Strictly limit the land used to unused infertile land** without ecologically particularly valuable areas.
  - **Optimise the whole process** so that efficiencies close to what is depicted in the scenarios under optimistic conditions are achieved.

  - Ensure that lower value **biomass streams are converted into co-products** such as feed or fatty acids for oleochemistry in substantial quantities and high quality.
  - Conduct a **comprehensive life cycle sustainability assessment**, e.g. based on the ILCSA methodology used in this study, once concrete concepts or plans are available, to verify the intended sustainability benefits. In addition, a specific environmental impact assessment must be performed for the planned site compliant with Directive 2014/52/EU.
- Once commercial quantities of the target products can be produced and the medical value of these products is verified, a **market demand study** should be undertaken to assess the size of the potential market. From this it will be possible to determine the market value of these products and their product contributions. This in turn will enable the product mix required to maximise the economic return of the plant to be established.

6.2 To science

The most important contribution of science to a sustainable *Dunaliella* biorefinery is to **gather knowledge for process optimisation**. This should aim at reducing the current high uncertainty with regard to the performance of the whole process chain. In this way, concrete optimisation measures can be identified to improve sustainability as far as possible.

- **Verify the novel medicinal value of *9-cis* β-carotene** as a pure substance and in mixtures in an adequate clinical trial.

- Continue the **development of an efficient process chain in downstream processing of carotenoid extracts** based on a new concept. Using the modular high-performance countercurrent chromatography (HPCCC) system newly devised within this project, possibly integrated with membrane technology in a compact system, is expected to be the most promising approach for this.
- Study the **conversion of lower value biomass streams into co-products** such as feed or fatty acids for oleochemistry in more detail once substantial amounts of these biomass fractions are available.

- Further develop **ideas for high-value products** such as anti-diabetic pharmaceuticals, specialty food ingredients, etc., which came up during this project, into **concrete process designs**. Based on a sustainability assessment, it can then be assessed whether they should be integrated in the biorefinery concept.
- **Collect and publish existing biotechnological knowledge on efficient *Dunaliella salina* cultivation** and possible disturbances that can cause the collapse of cultures and production downtimes.

6.3 To consumers

- **Carotenoids should only be taken as dietary supplements if there are health indications for this**. The consumption of dietary supplements is a lifestyle trend often encouraged by the media and the advertising industry based on somewhat dubious science. In many cases, however, dietary supplements do promote the health of certain groups, e.g. people with pre-existing conditions. Production of high-quality natural carotenoids, in particular zeaxanthin and lutein, is not currently feasible without substantial environmental burdens. Carotenoids should therefore only be consumed as dietary supplements by people who need them for health reasons [MedlinePlus n.d.]. In addition, a nature-identical synthetic alternative, which causes much lower environmental impacts, is available for (*all-trans*) β-carotene. Although many studies on animal establish that natural *9-cis* β-carotene from algae is better for health than *all-trans* β-carotene from other sources (e.g. [Ben-Amotz et al. 1989]), there is no accepted proof that the natural algae alternative is more effective in humans [European Commission & European Food Safety Authority (EFSA) n.d.]. Therefore, the nature-identical alternative should be preferred as long as no further evidence arises.

- **Be prepared to spend more money for healthy, sustainable nutrition.**
  Sustainable production of foodstuffs and dietary supplements is generally associated with higher costs than production based on resource exploitation. This applies to all foodstuffs, including algae-based products, in particular. If nature-identical synthetic products like (*all-trans*) β-carotene are available, they can however be significantly cheaper and better for the environment as to be seen in this case.

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6.4 To policymakers

Algae cultivation has raised high hopes for sustainable production of various bio-based products. Using the example of a *Dunaliella* biorefinery, this study has shown that algae-based products are not necessarily sustainable. **Certain boundary conditions need to be in place and efficiency still needs to increase to reach this goal.** Politics can support both by the following measures:

- Algae cultivation and use needs experience in large demonstration or small industrial scale facilities over several seasons in continuous operation to advance. The current limit of knowledge is reflected in the large uncertainty with regard to the anticipated sustainability impacts. *Dunaliella salina*-based algae biorefineries following the D-Factory concept could provide an additional module to fill this gap. If such projects are publicly supported, the following should be taken into account:
  - **Sufficient time should be allowed** for all necessary components to reach maturity. As also documented in this study, great improvements have been made, but the further optimisation potential still appears large.

  - After the improvement of central components mainly targeted in current approaches, **whole life cycles must be integrated and optimised** to achieve low environmental impacts and social risks. In this algae utilisation concept the focus is to be placed on substantially evolving or even redesigning downstream processing. Additionally, the following aspects should now be elaborated in more detail after the main processes of algae cultivation are set:
    - medium recycling concepts
    - the use of lower value biomass streams
    - the integration of heat and cooling (where applicable)
    - Comprehensive life cycle sustainability assessments should accompany such processes to guide optimisation.
- Intensify work towards consumers not being tempted to buy dietary supplements that are unnecessary for them. The EU regulation on nutrition and health claims made on foods is an important element of this, and at least prevents misleading advertising. However, this is insufficient. Additionally, easily understandable information materials should be produced explaining, for example, for which groups of people which dietary supplements make sense. This can help prevent unnecessary environmental impacts and social risks by the, in part, highly resource-intensive production of high value dietary supplements.
- Concepts for future algae cultivation and use perspectives need to be integrated into **overall European land use and decarbonisation concepts**. In particular, the following aspects should be taken into account:
  - Establish **land use plans for land that is not suitable for agriculture**, but which may be suited to photovoltaics and/or algae cultivation, to both avoid conflicts among these land use options and remove particularly ecologically valuable land from use.
  - Note **that the use of CO_2 by algae**, which is a variant of what is known as carbon capture and use (CCU), **does not intrinsically lead to any environmental benefits**. From a methodological perspective, CO_2 uptake and emission accounting for algae is no different to that for energy or industrial crops, which also initially take up a

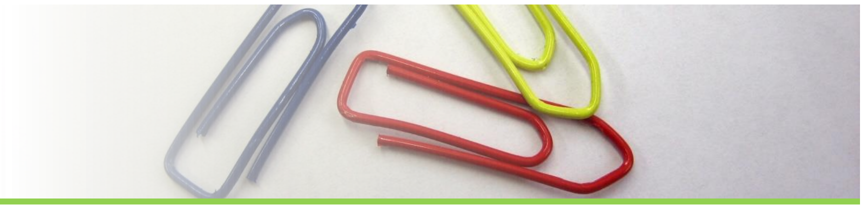
Images from top to bottom: © luise/pixelio.de; Marco Barnebeck/pixelio.de certain amount of CO_2. However, this is then emitted again, generally with a short delay, either during use or on disposal of the bio-based products. In contrast to the land-based crops, which take up CO_2 from the surrounding atmosphere, in algae cultivation CO_2 is generally used that is separated with energy input, and if necessary concentrated, from the exhaust gas streams of large emitters such as power plants, steelworks, cement works or chemicals industry facilities. Some of this CO_2 is emitted during algae production and some is incorporated as carbon in algae-based products. However, this 'interim storage' is only short-term and at the end of the life cycle of the algae-based products exactly the same quantity of CO_2, which would otherwise have been directly emitted by the industrial facility, is emitted again with minor delay. This is similar to most crops, which however capture CO_2 from air instead of flue gas. Shifting of CO_2 emissions using algae does not help the environment. If any kind of bonus or incentive would be available for such shifting, it may even be counter-productive if it leads to a longer service life for the industrial facility. Additionally, care must be taken in CO_2 accounting that this fossil CO_2 either appears in the accounts of the large emitter or is passed on to the algae cultivation operator in the form of a CO_2 backpack. From the life cycle assessment perspective, only the first approach makes sense given the questions that currently have to be answered. For this reason, we have used it in our accounting and thus only attributed the additional expenditure for CO_2 separation (carbon capture) to algae cultivation.

Against the backdrop of these deliberations, care must therefore be taken when developing accounting rules in directives, laws and regulations that the fossil CO_2 emissions do not remain disregarded twice. That is, the forwarded CO_2 may not be subtracted while at the same time the CO_2 emissions from use or disposal of the CCU products are set to zero.

- **Plans are required for synchronising the decarbonising processes and technologies based on CO_2 as an input substance, which will continue to grow in the future**, such as algae cultivation, power-to-X or carbon capture and storage (CCS). If the decarbonisation policy direction initiated today is successfully implemented in the coming decades, increasingly few CO_2 sources such as coal fired power stations will be available for CO_2 utilisation from exhaust gases in the future. Establish plans to synchronise the decarbonisation process and upcoming CO_2-based technologies, including algae cultivation, power-to-X and carbon capture and storage (CCS) to avoid misallocation of money and resources or unjustified delays in decarbonisation.

- **Focus development support for the algae industry on producing high-value, low-volume main products**. In this way, industrial production can be tested on a relatively small scale. This can then deliver insights into technological, practical and environmental aspects to adjust future plans.

Top image: © Frank-Andreas Jütte/pixelio.de



7 Annex

The annex provides the following additional information:

- Glossary and abbreviations (chapter 7.1)
- References (chapter 7.2)
- Detailed scenario schemes (chapter 7.3)
- Summary of quantitative input data (chapter 7.4)

7.1 Glossary and abbreviations

Agricultural land	Agricultural land is defined as land area that is either arable, under permanent crops, or under permanent pastures. Arable land includes land under temporary crops such as cereals, temporary meadows for mowing or for pasture, land under market or kitchen gardens, and land temporarily fallow.
Brownfield site	Land that was previously used for industrial, commercial or military purposes (often with known or suspected contamination) and is not currently used. Most of the area is expected to be already sealed and traffic infrastructure might (at least partly) be available.
CAPEX	Capital expenditures are funds used by a company to acquire physical assets such as property, industrial buildings or equipment
CCS	Carbon capture and storage is the process of capturing waste carbon dioxide (CO_2) from large point sources, such as fossil fuel power plants, and depositing it in e. g. underground geological formations.
CCU	Carbon capture and use summarises various process of capturing waste carbon dioxide (CO_2) from large point sources, such as fossil fuel power plants, to use it for producing products (see also “algae cultivation” and “PtX”).
CFC	Chlorofluorocarbon, substance contributing to ozone depletion.
CH_4	Methane
CO_2	Carbon dioxide
Disc-stack centrifuge	Conventional centrifuge using series of conical discs typically to remove small amounts of particles from large volumes of liquids in continuous operation. Also known as disc bowl centrifuge or conical plate centrifuge.
D-Factory	Project acronym, “*The Micro Algae Biorefinery*”
EIA	Environmental impact assessment
(e)LCA	(environmental) life cycle assessment
GMO	Genetically modified organism

HPCCC	High performance countercurrent chromatography
HPLC	High performance liquid chromatography
IE	Inhabitant equivalent, A comparison of the magnitude – of different environmental impacts can be done on the basis of inhabitant equivalents. In this case, the impacts caused by a certain scenario are compared (normalised) to the average annual impact that is caused by an inhabitant of the reference region, in this case the EU 28. Thus one inhabitant equivalent corresponds to the annual emissions in that impact category for one average EU inhabitant.
ILCD	International Reference Life Cycle Data System
ILCSA	Integrated life cycle sustainability assessment
iLUC	Indirect land use change
LC-EIA	Life cycle environmental assessment is a methodology for the assessment of local environmental impacts that cannot (yet) be adequately covered by LCA.
LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventory, its creation is part of an LCA study
LCIA	Life cycle impact assessment, part of an LCA study
N_2O	Nitrous oxide
NH_3	Ammonia
NOx	Nitrogen oxides
PBR	Photobioreactor, a closed system of transparent tubes or other containers for algae cultivation using sunlight.
Power-to-X	Power-to-X is used to summarise processes that use excess electric power, which is supposed to come from renewable sources in the future, to synthesise chemicals from substances such as water and CO_2.
PV	Photovoltaic
$scCO_2$	Supercritical carbon dioxide, can be used as solvent for extraction processes.
SEA	Strategic environmental assessment
sLCA	Social life cycle assessment
SO_2	Sulphur dioxide
SWOT	Acronym for strengths, weaknesses, opportunities, and threats
Spiral-plate centrifuge	Innovative centrifuge using spiral plates. In this project a model from project partner Evodos replaces conventional disc-stack centrifuges.

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7.3 Detailed scenario schemes

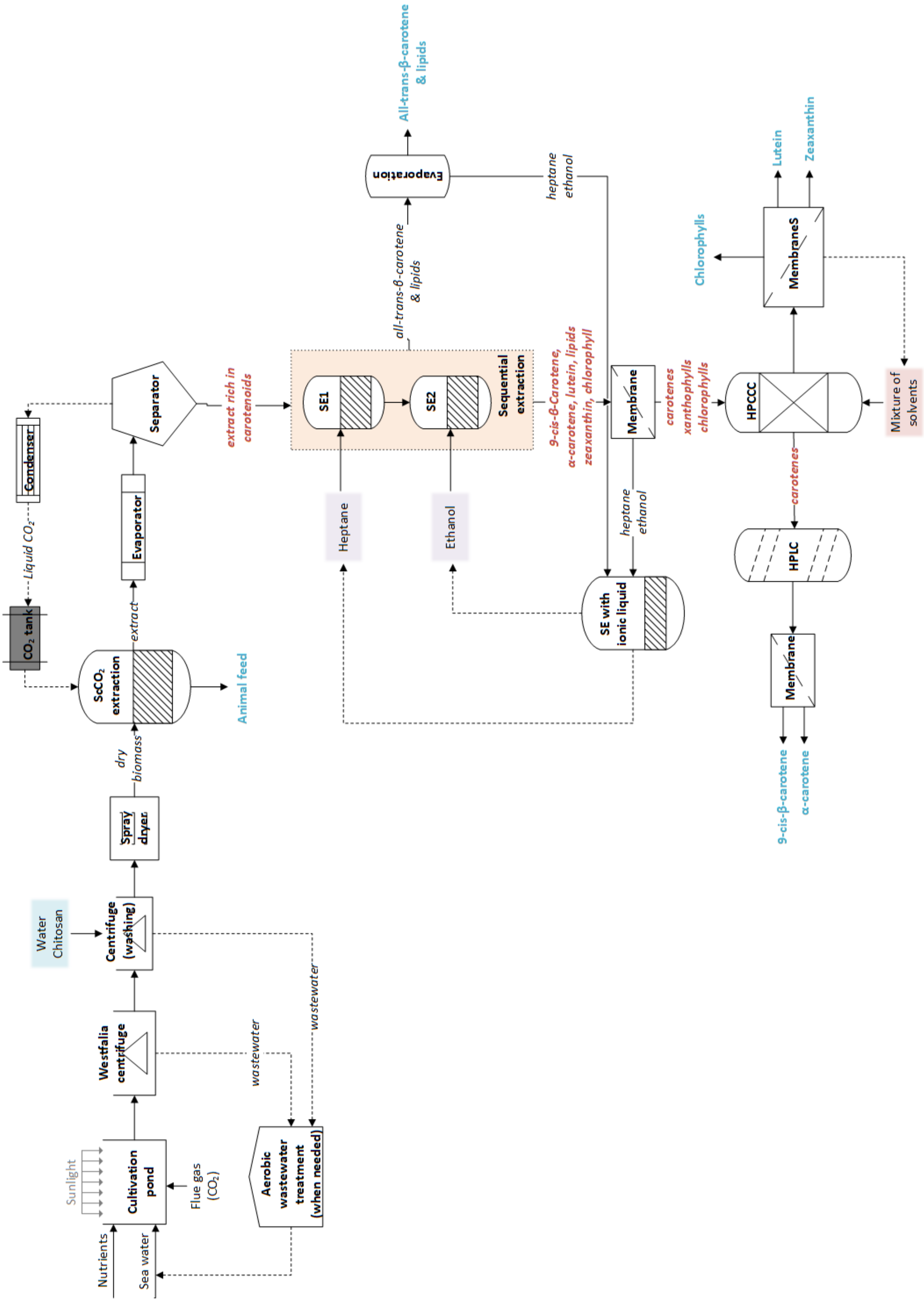

Figure 7-1: Detailed scheme of scenario 1, see chapter 4.2 for a description

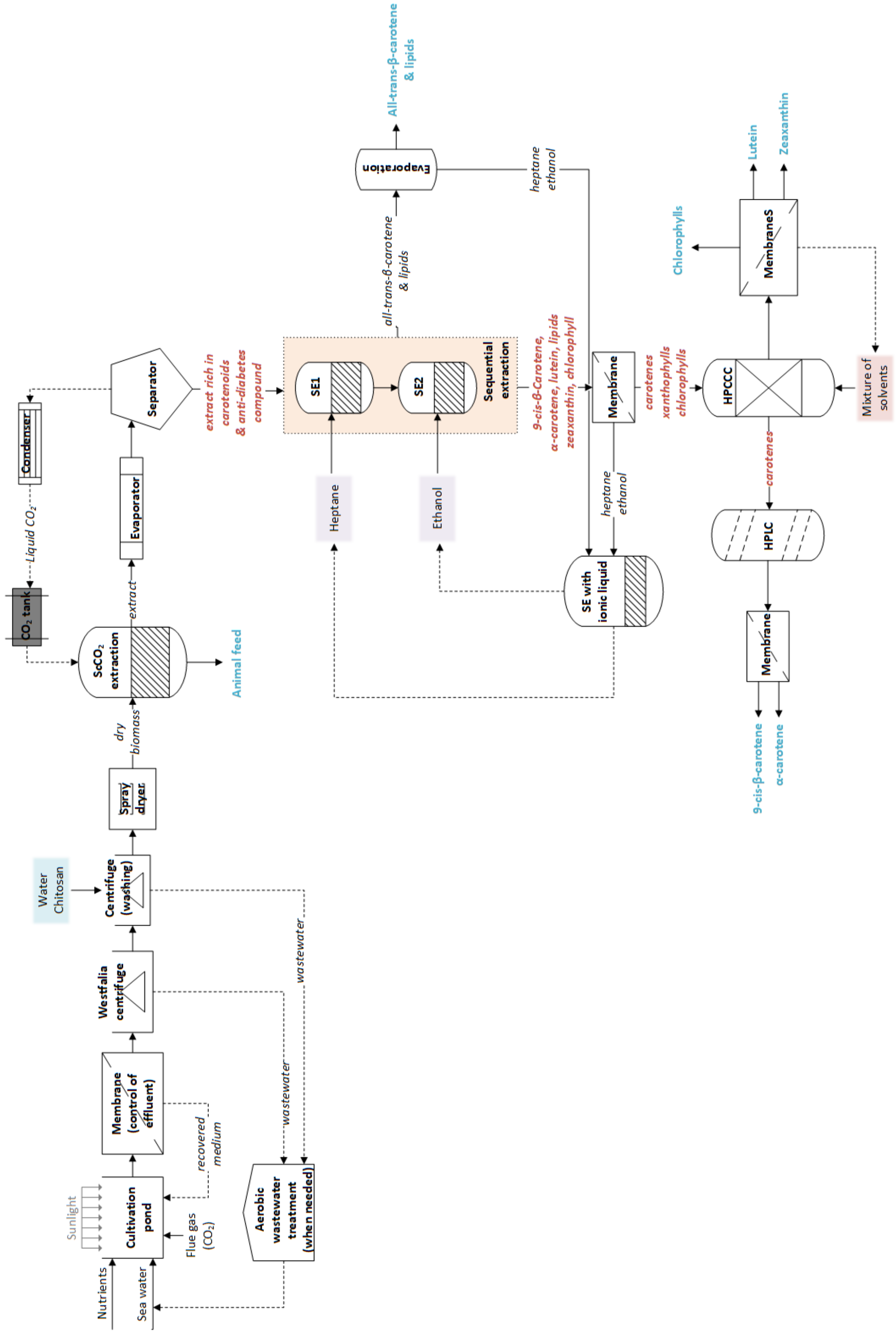

Figure 7-2: Detailed scheme of scenario 2, see chapter 4.2 for a description

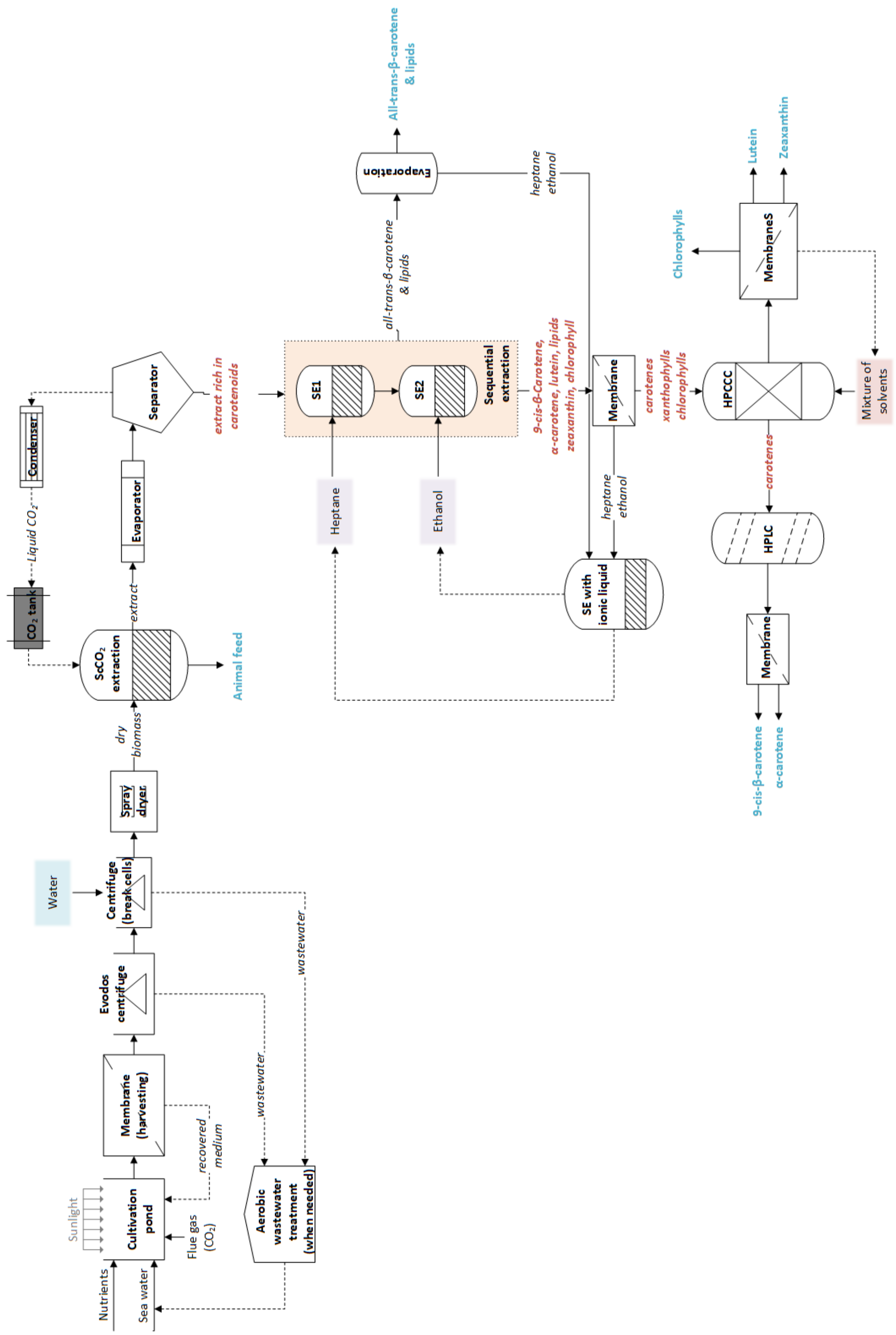

Figure 7-3: Detailed scheme of scenario 3 (whole cell harvest), see chapter 4.2 for a description. Scenario 5 and 6 are truncated versions of scenario 3 ending with the intermediates ‘carotenes’ and ‘extract rich in carotenoids’, respectively.

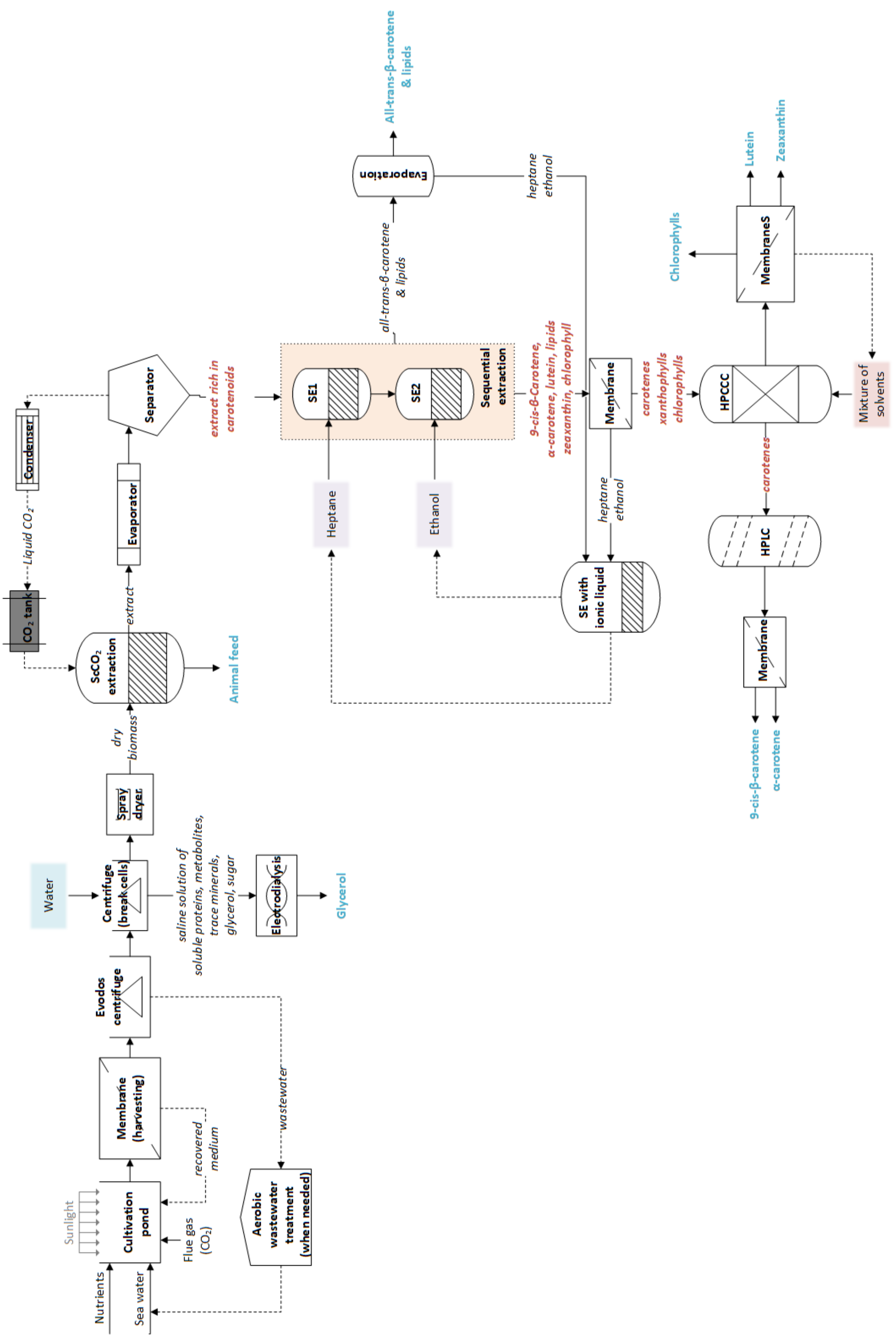

Figure 7-4: Detailed scheme of scenario 4, see chapter 4.2 for a description

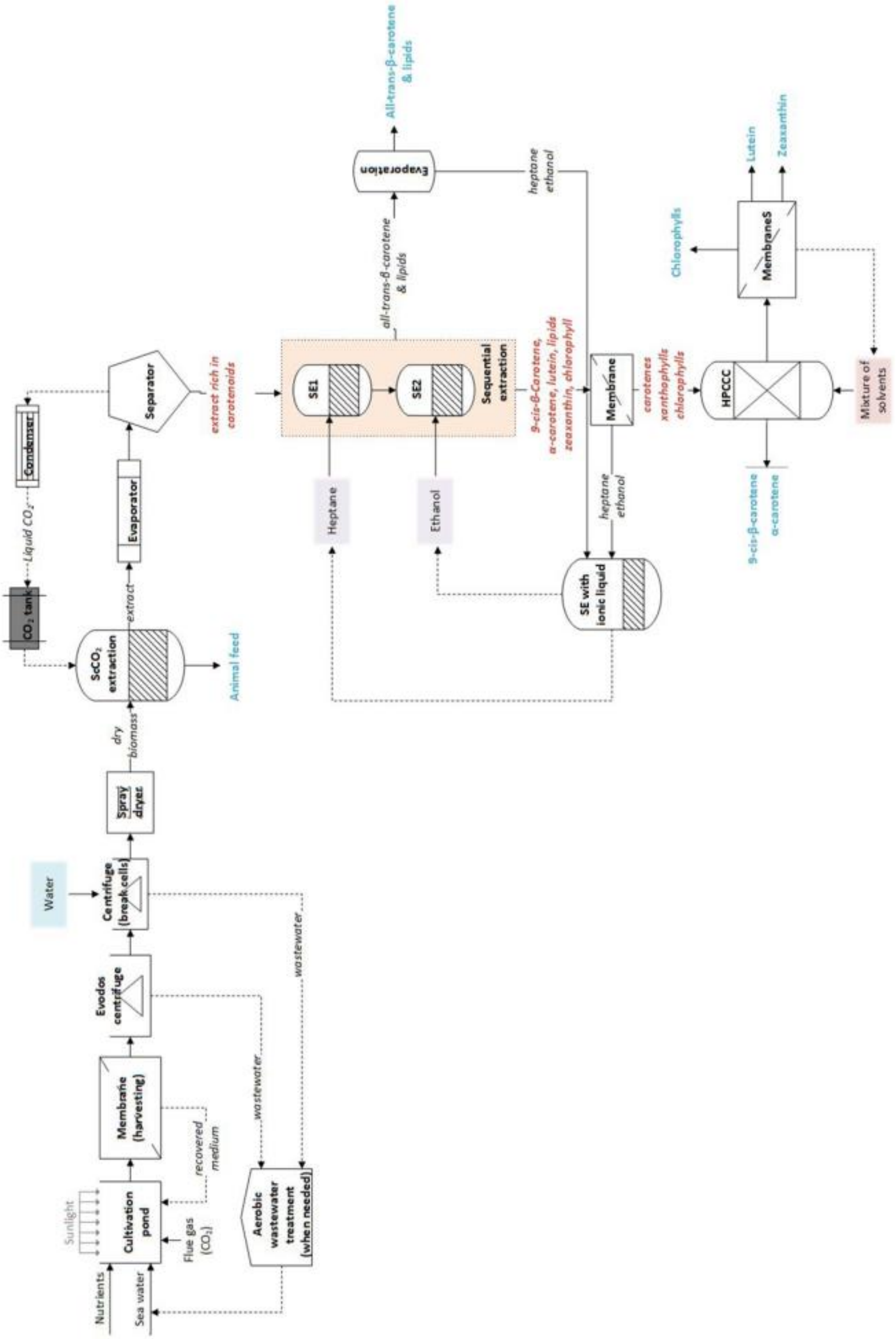

Figure 7-5: Detailed scheme of scenario 5, see chapter 4.2 for a description

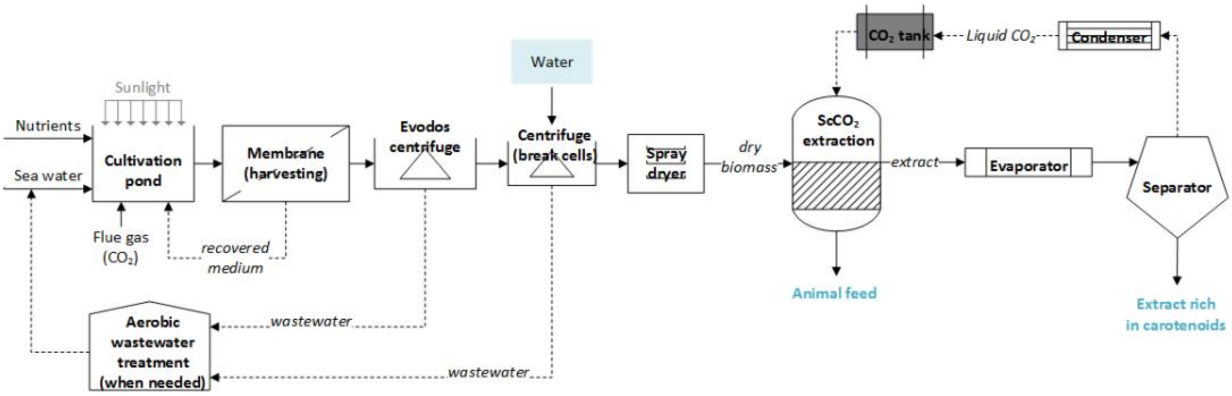

Figure 7-6: Detailed scheme of scenario 6, see chapter 4.2 for a description

7.4 Summary of quantitative input data

Common input data for the whole sustainability assessment, in particular LCA, LC-EIA, LCC and sLCA, are summarised in Table 7-1 and Table 7-2. For further specific input data please refer to the respective reports [Harvey 2017a; Keller et al. 2017; Mitchell & Goacher 2017; Peñaloza & Stahl 2017].

Table 7-1: Summary of most important energy and material inputs and outputs, part 1: scenarios 1 – 3. All data refers to 1 year of facility operation.

		1 Initial Configuration		**2 Membrane pre-concentration**		**3 Whole cell harvesting**	
		Optimistic	**Conservative**	**Optimistic**	**Conservative**	**Optimistic**	**Conservative**
CULTIVATION, HARVESTING AND WASHING							
Inputs							
Brine	m³	729 000	662 000	36 000	132 000	36 000	132 000
Fresh water	m³	364 000	331 000	18 000	66 000	18 000	66 000
KNO_3	kg N content	7 600	3 800	7 600	3 800	7 600	3 800
H_3PO_4	kg	7 600	3 800	7 600	3 800	7 600	3 800
$MgSO_4$	kg	12 200 000	6 000 000	600 000	1 200 000	600 000	1 200 000
CO_2	t	430	210	430	210	640	320
Further information							
Total Land area	ha	20	20	16	17	16	17
Production pond surface area	ha	14	14	14	14	14	14
Days of operation per year	d	330	300	330	300	330	300
GLYCEROL RECOVERY							
(Inputs contained in overall energy demand)							
Outputs							
Product: glycerol	t	0	0	0	0	0	0
DRYING							
Input							
Natural gas	t	20	25	20	25	20	25
$scCO_2$ EXTRACTION							
Input							
CO_2 (from bottles)	t	110	230	110	230	170	340
Output							
Product: Feed	t AFDW	120	60	120	60	170	90

		1 Initial Configuration		2 Membrane pre-concentration		3 Whole cell harvesting	
		Optimistic	Conservative	Optimistic	Conservative	Optimistic	Conservative
HEPTANE/ETHANOL EXTRACTION							
Input							
Heptane	kg	460 000	210 000	460 000	210 000	690 000	310 000
Ethanol	kg	640 000	290 000	640000	290000	950 000	430 000
Ionic liquid	kg	270 000	120 000	270000	120000	400 000	180 000
Output							
Pure all-trans beta carotene	t BC	5.5	2.2	5.5	2.2	6.4	2.5
Pure lipids	t	12	5	12	5	37	15
HPCCC							
Input							
Confidential							
Output							
Product: Pure chlorophylls	t	0.7	0.2	0.7	0.2	1.0	0.3
Product: Pure lutein	t	0.3	0.1	0.3	0.1	0.4	0.1
Product: Pure zeaxanthin	t	0.1	0.0	0.1	0.0	0.2	0.1
HPLC							
Input							
Solvents - methanol	kg	380 000	170 000	380 000	170 000	570 000	260 000
Output							
Product: *9-cis* beta carotene (pure or in mixtures)	t	4.0	1.1	4.0	1.1	4.8	1.4
Product: Pure alpha carotene	t	0.9	0.2	0.9	0.2	1.3	0.4
OVERALL ENERGY DEMAND							
Power	kWh	55 000 000	26 000 000	54 000 000	26 000 000	80 000 000	38 000 000
Heat	MJ	3 300 000	1 800 000	3 300 000	1 800 000	4 900 000	2 700 000

Table 7-2: Summary of most important energy and material inputs and outputs, part 2: scenarios 4 – 6. All data refers to 1 year of facility operation.

		4 Glycerol recovery		5 Shorter downstream processing		6 No carotenoid separation	
		Optimistic	Conservative	Optimistic	Conservative	Optimistic	Conservative
CULTIVATION, HARVESTING AND WASHING							
Inputs							
Brine	m³	36 000	132 000	36 000	132 000	36 000	132 000
Fresh water	m³	18 000	66 000	18 000	66 000	18 000	66 000
KNO_3	kg N content	7 600	3 800	7 600	3 800	7 600	3 800
H_3PO_4	kg	7 600	3 800	7 600	3 800	7 600	3 800
$MgSO_4$	kg	600 000	1 200 000	600 000	1 200 000	600 000	1 200 000
CO_2	t	640	320	640	320	640	320
Further information							
Total Land area	ha	16	17	16	17	16	17
Production pond surface area	ha	14	14	14	14	14	14
Days of operation per year	d	330	300	330	300	330	300
GLYCEROL RECOVERY							
(Inputs contained in overall energy demand)							
Outputs							
Product: glycerol	t	14	6	0	0	0	0
DRYING							
Input							
Natural gas	t	20	25	20	25	20	25
scCO_2 EXTRACTION							
Input							
CO_2 (from bottles)	t	170	340	170	340	170	340
Output							
Product: Feed	t AFDW	170	90	170	90	170	90
HEPTANE/ETHANOL EXTRACTION							
Input							
Heptane	kg	690 000	310 000	690 000	310 000	0	0
Ethanol	kg	950 000	430 000	950 000	430 000	0	0
Ionic liquid	kg	400 000	180 000	0	0	0	0
Output							
Pure all-trans beta carotene	t BC	6.4	2.5	6.4	2.5	0.0	0.0
Pure lipids	t	37	15	21	8	0	0

		4 Glycerol recovery		5 Shorter downstream processing		6 No carotenoid separation	
		Optimistic	Conservative	Optimistic	Conservative	Optimistic	Conservative
HPCCC							
Input							
			Confidential				
Output							
Product: Pure chlorophylls	t	1.0	0.3	1.0	0.3	0.0	0.0
Product: Pure lutein	t	0.4	0.1	0.4	0.1	0.0	0.0
Product: Pure zeaxanthin	t	0.2	0.1	0.2	0.1	0.0	0.0
HPLC							
Input							
Solvents - meth-anol	kg	570 000	260 000	0	0	0	0
Output							
Product: *9-cis* beta carotene (pure or in mix-tures)	t	4.8	1.4	5.1	1.7	5.6	2.7
Product: Pure alpha carotene	t	1.3	0.4	0.0	0.0	0.0	0.0
OVERALL ENERGY DEMAND							
Power	kWh	80 000 000	38 000 000	6 300 000	4 300 000	2 200 000	2 400 000
Heat	MJ	4 900 000	2 700 000	4 900 000	2 700 000	1 600 000	1 200 000

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