# Integrated life cycle sustainability assessment – a practical approach applied to biorefineries

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**Highlights:**

- Integrated life cycle sustainability assessment provides ex-ante decision support.
- It extends LCSA by several features including a barrier analysis.
- A benchmarking procedure for result integration is presented.
- Practicability has been successfully demonstrated in five large EC-funded projects.

# Abstract

Politics and industry increasingly request comprehensive ex-ante decision support from a sustainability perspective in complex strategic decision situations. Several approaches have been introduced in the last years to increase the comprehensiveness of life cycle based assessments from covering only environmental aspects towards covering all sustainability aspects. This way, (environmental) life cycle assessment (LCA) has been extended towards life cycle sustainability assessment (LCSA). However, a practical application in ex-ante decision support requires additional features and flexibility that do not exist in the newly devised frameworks. Our methodology of integrated life cycle sustainability assessment (ILCSA) builds upon existing frameworks, extends them with features for ex-ante assessments that increase the value for decision makers and introduces a structured discussion of results to derive concrete conclusions and recommendations. At the same time, the 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. ILCSA has so far been successfully applied in five large EC-funded projects. We discuss our methodology based on a concrete application example from these projects.

# 1. Introduction

If a new technology or product is coming up, decision makers often do not know whether or under which conditions they should support its implementation or production, respectively. This is a classical decision situation that benefits from ex-ante decision support based on sustainability assessment. Main addressees are often politicians as they are appointed to serve long-term public well-being. Additionally, sustainability assessment becomes increasingly important for companies. They have to decide about high investments and thus need long-term business perspectives, which are more and more influenced by sustainability-related legislation and public perception. Therefore, the proactive interest of companies in their impacts on sustainability and in potential pitfalls is rising.

Several approaches for comprehensive sustainability assessments of products or processes along their whole life cycles have been suggested in the last years [1]–[3]. The term life cycle sustainability assessment (LCSA), which is used in this context, was introduced as a combination of (environmental) life cycle assessment (LCA), life cycle costing (LCC) and social life cycle assessment (sLCA) [1]. The suggested LCSA approaches extend existing methodologies and often also provide options how to integrate results into one or few scores [4]. Heijungs et al. discuss options of modelling and integrating the assessment procedure and Finkbeiner et al. highlight possibilities of integrating the results obtained for different sustainability aspects [2], [3]. The UNEP/SETAC Life Cycle Initiative summarised the current state of LCSA to provide a framework for its further development [5].

LCSA approaches share the intention to (1) assess *all* sustainability impacts of a given subject (mostly a product) mostly in order to (2) improve sustainability *in the future*. However, two kinds of conceptual limitations towards these goals are not sufficiently addressed so far.

Both arise from a lack of information and knowledge and become apparent during practical application but are of a more fundamental nature.

First, LCSA can in practise not be comprehensive if it is limited to being a combination of LCA, LCC and sLCA because parts of the impact assessment methodologies are still under development and are not yet robustly applicable [6], [7]. Nevertheless, specialised assessment methodologies can fill specific gaps (such as local environmental impacts) that are very relevant for some objectives and contexts of the assessment. Since the development of the generally applicable methodologies LCA, LCC and sLCA will always be an ongoing process and the availability of data required for their sound application will never be perfect, a conceptual extension of LCSA is necessary which allows the incorporation of further context-specific methodology.

Second, future-oriented recommendations (decision support) need to be based on analyses of potential future systems, which can be envisioned more or less well, but are inherently connected with uncertainty. Generally, most methodologies for sustainability assessment were developed for assessing existing systems but also applied to potential future systems with the tacit implication that the latter are not fundamentally different from existing ones. However, such an extrapolation from the past to the future is not necessarily valid, especially if non-gradual changes occur such as the implementation of a new technology. Instead, it is increasingly recognised that potential future systems (i.e. decision options) have to be compared to each other in the form of scenarios [8].

The more innovative such scenarios are, the more important become barriers, which are not routinely analysed in sustainability assessment yet: The intention to implement a very sustainable scenario according to the recommendations of the sustainability assessment may lead to a completely different outcome due to barriers and limitations such as lacking policy support or insufficient resource availability. For example, a newly built highly efficient combined heat and power plant may be forced by economic pressure to use unsustainable biomass if availability of sustainable biomass has not been assessed beforehand. Several LCA or sustainability assessment studies address some barriers informally [9]–[11] and methodological research highlights that they should be comprehensively studied [12]–[14]. A thorough assessment of these barriers in a systematic manner and with sufficient resources within LCSA would increase the value for decision makers substantially. Thus, LCSA should be extended by a module assessing barriers that can lead to failures in scenario realisation and their consequences.

A flexible, modular, scenario-based and practicable methodology can overcome those limitations and yield valuable comprehensive decision support with manageable effort. The methodology we present in this paper, termed integrated life cycle sustainability assessment (ILCSA), follows this approach. ILCSA has so far been successfully applied in five large EC-funded projects (GLYFINERY, BIOCORE, SUPRABIO, SWEETFUEL and BIOLYFE) [15]–[19].

# 2. Results

We developed the methodology of integrated life cycle sustainability assessment (ILCSA) to provide comprehensive ex-ante decision support from a sustainability point of view in the process of establishing new technologies, processes or products. This methodology extends LCA and LCSA in two ways: First, it is more comprehensive regarding the impacts that can be covered in practice and, second, it can better treat uncertainties connected with the assessment of potential future systems.

In principle, a common set of scenarios is subjected to an assessment of various aspects of sustainability including environmental, economic and social issues based on the same settings and definitions. Indicators and results from these separate assessments are subsequently combined to form an overall picture (Figure 1). This modular structure allows for using the most appropriate assessment methodologies in each context and the distribution of work among several experts or expert groups.

## 2.1. General procedure

The ILCSA procedure follows the principle of life cycle thinking and builds on the procedure defined for LCAs in ISO standards 14040 / 44. The procedural scheme of LCA can be extended as shown in Figure 1. The goal and scope definition in principle remains the same although care has to be taken to respect the requirements of all assessment methodologies when defining the system boundaries. Generally, the whole life cycle has to be taken into account for all aspects of sustainability. However, certain parts may fall under cut-off criteria regarding some sustainability aspects but not for others (e.g. certain infrastructure may in some cases be irrelevant for environmental impacts but very relevant for economic impacts). As a result, system boundaries may deviate to some degree for the individual assessment methodologies. For ex-ante assessments, it is especially important that the goal and scope definition contains a qualitative description of the assessed scenarios since these systems do not exist yet. The life cycle inventory analysis (LCI) step has to be split into two separate steps: The first is quantitative modelling of foreground processes, which is common for all assessments of individual sustainability aspects and therefore termed $LCI_C$ (including e.g. complete mass and energy balances for any unit process, see Figure 2). The second is the generation of impact-specific inventories from those models for each assessment and therefore termed $LCI_S$ (e.g. yielding primary energy demand for LCA, energy costs for LCC and social impacts of energy provision for sLCA). This is followed by specific life cycle impact assessment steps ($LCIA_S$). In LCC, impact assessment is limited to summing up all costs with optional provision of further indicators such as internal rate of return. Besides LCA, LCC and sLCA, several other methodologies can be chosen to assess further impacts on environment, economy and society, which are not yet robustly covered by these three methodologies but are relevant for the assessed system. This feature of ILCSA addresses the limitation of LCSA of being restricted to a combination of LCA, LCC and sLCA and therefore potentially overlooking important sustainability issues. Furthermore, ex-ante decision support benefits from an analysis of barriers that may prevent the realisation of the scenarios as they have been defined and assessed. Depending on the subject of the study, barriers may be related to feasibility (e.g. technical, political, regulatory), stability (e.g. durability, yield stability, hazard risks) and implementation potentials (e.g. feedstock availability, market potentials). The barrier analysis overcomes the limitation of LCSA, which does not systematically assess unintended effects that may arise from the implementation of recommended scenarios. In the result integration step, combined indicators such as greenhouse gas abatement costs can be added in an extension of the LCIA step termed $LCIA_c$ (common) in Figure 2. Furthermore, a formalised step of result comparison and presentation is necessary in ILCSA, which is usually an informal part of the interpretation in LCA. We suggest using a benchmarking procedure for this purpose.

## 2.2. Result integration

A central new feature in ILCSA is the result integration step that requires formalisation compared to e.g. LCA because many more aspects have to be considered when deriving conclusions and recommendations. Furthermore, the flexibility of ILCSA to incorporate non-standard assessment methodologies (in addition to LCA, LCC and sLCA) requires the evaluation of qualitative indicators (without available scoring and / or normalisation factors) besides quantitative indicators.

The integration step based on a benchmarking procedure consists of the following parts:

- Selection of relevant scenarios and indicators
- Addition of suitable cross-disciplinary indicators such as greenhouse gas abatement costs
- Compilation of overview tables
- Benchmarking
- Discussion

The selection of scenarios and indicators is necessary to avoid an overload with data, which is not relevant for the assessed decision options. This may e.g. exclude indicators, which show the same values for all assessed scenarios or are irrelevant for decisions between the assessed options (e.g. ionising radiation for an assessment of bio-based products). Scenarios may be excluded that only deviate from other included scenarios by parameters with a negligible influence on results. Such exclusions should be nevertheless documented because the irrelevance of certain parameters and impacts may be of interest to decision makers, too.

The addition of further indicators based on existing indicators from different assessments such as greenhouse gas abatement costs may provide additional valuable information. However, it is important to keep in mind that such combined indicators do not integrate the information of the original indicators (here: climate change and costs or profits of involved businesses, respectively) but provide additional information. They indicate the efficiency of reaching a certain target (e. g.: How expensive is it to avoid greenhouse gas emissions?) but not the efficacy of reaching it (e. g.: How much can emissions be reduced?). Therefore, the applicability of such combined indicators and their relevance for decision makers has to be analysed case by case to avoid misperceptions.

Displaying the results for all scenarios and indicators in one or more overview tables provides a basis for further analyses. These tables contain qualitative and quantitative data. A categorisation of quantitative data and an identical colour coding of both qualitative and categorised quantitative data was found to increase readability.

The benchmarking step compares all scenarios to one benchmark scenario. This serves the purpose to answer concrete questions such as "What are the trade-offs if the economically most favourable scenario would be implemented?". The categorisation reflects the robustness of advantages or disadvantages over the benchmark. Quantitative differences (calculated from indicators before categorisation) between a certain scenario and the benchmark are categorised into advantageous [+], neutral [0] or disadvantageous [-]. According to the purpose, the cut-off value for the category neutral is e.g. set as a percentage of the bandwidth of the results regarding a specific indicator. Additionally, bandwidths of the results are taken into account. If the scenario under consideration achieves better results under less favourable conditions than the benchmark does under standard conditions, it is rated very advantageous [++]. If not, but all direct comparisons under identical conditions show e.g. 10 % better results than the benchmark, it is rated advantageous [+]. An analogous procedure is applied for the ratings disadvantageous [-] and very disadvantageous [- -]. For all qualitative indicators, rating of differences is done analogously but without applying minimum differences.

The discussion follows the structure provided by the resulting overview and benchmarking tables.

## 2.3. Application example

ILCSA has so far been successfully applied in five large EC-funded projects (GLYFINERY, BIOCORE, SUPRABIO, SWEETFUEL and BIOLYFE) and is being applied in the EC-funded projects D-FACTORY and PUFAChain. As one practical example, shortened excerpts from the ILCSA study of the BIOCORE project are presented here that highlight the assessment procedure [19]. It shows how conclusions and recommendations can be deduced from the presented data. For simplicity, we chose largely self-explanatory examples instead of key messages of the project.

The BIOCORE project developed an advanced lignocellulosic biorefinery concept using an innovative, patented Organosolv technology. The Organosolv fractionation technology provides the three major biomass components (cellulose, lignin and hemicellulose) from various biomass feedstocks. Obtained in forms optimal for further processing, these fractions are used as major building blocks for the synthesis of viable product portfolios.

The ILCSA study was an integral part of the project. In a first step, goal and scope were defined for all subsequent assessment steps. An exemplary life cycle scheme for one scenario is shown in Figure 3. Based on these definitions and settings, quantitative system modelling was performed for all scenarios based on data and information provided by all partners involved in technology development and a study on energy integration of the potential biorefinery plants [20]. The system models for all scenarios were analysed in terms of their environmental, economic and social sustainability as well as regarding further aspects relevant for providing decision support on future implementation options of the

BIOCORE biorefinery concept [21]–[23]. This part of ILCSA was carried out by several institutions, with expertise in their respective fields of sustainability assessment.

Results were joined and processed in the final result integration step following the procedure outlined in chapter 2.2. An excerpt of the result overview table containing a selection of the assessed scenarios and most assessed indicators is shown in Figure 4. For details on scenarios, methodologies and non-standard indicators, please refer to [19]. This table was used to derive and illustrate several conclusions. For example, it can easily be understood from this chart that the sustainability impacts, especially regarding environment and economy, can be either positive or negative, which is heavily influenced by the product portfolio. This is an important message as biorefineries are often viewed as sustainable *per se*. Furthermore, it can be seen that in this case economically sustainable product portfolios also show environmental advantages. In contrast, social impacts do not depend very much on the product portfolio but on “soft” implementation conditions (which are not varied in the selected scenarios).

Further conclusions can be derived from and illustrated by benchmarking tables (see Figure 5 for one simple example). One exemplary question to be answered by a specific benchmarking table is whether it is sustainable produce low-value products as reflected in the scenario “Fallback options” from the obtained biomass fractions. Figure 5 supports the conclusion that it is essential to convert the biomass fractions into high-quality products that replace energy-intensive conventional products. Hence, using the high-quality biomass fractions for energy generation and production of low-value products is not sustainable, although implementation barriers such as technological maturity and required capital investment are lower. These conclusions resulted together with others in a many concrete recommendations that can be found in the assessment report [19].

Several further ILCSA studies have been successfully finished so far [15]–[18]. These studies are in the field of energy and / or material use of biomass and therefore use similar additional assessment methodologies beyond LCSA (with a slightly reduced set in [15]). LCA is complemented by life cycle environmental impact assessment (LC-EIA), which qualitatively assesses local environmental impacts on soil, water, biodiversity and landscape [26]. Some studies cover selected macroeconomic aspects as an extension of the economic assessment. Barriers regarding implementation potentials are analysed in market analyses and biomass competition analyses. Feasibility and stability related barriers are addressed in technological assessments and policy assessments. Depending on the project, some of these aspects and further individual sustainability implications have been analysed by using a SWOT (strengths, weaknesses, opportunities, threats) analysis instead of performing a dedicated assessment for each aspect.

# 3. Discussion

The methodology of integrated life cycle sustainability assessment (ILCSA) is a practical way of providing ex-ante decision support based on the concept of life cycle sustainability assessment (LCSA). The application of ILCSA in a number of biorefinery projects demonstrated the value of several aspects that extend the UNEP/SETAC framework for

LCSA. Importantly, these extensions do not require changes of LCA methodology when used within this framework so that compatibility to existing standards is given. One extension overcomes the limitation of the current LCSA approach regarding future-oriented recommendations: The barrier analysis studies aspects that could lead to failures when implementing certain scenarios. A second extension allows the integration of non-standard assessment methodologies to complement LCA, LCC and sLCA regarding aspects that these standard methodologies cannot assess robustly yet. Both extensions emphasise the need for a flexible result integration step that can fully utilise the information contained in both quantitative and qualitative indicator results. The presented approach using a benchmarking procedure, which has been developed for ILCSA, fulfils these criteria.

## 3.1. Barrier analysis

Ex-ante decision support requires the comparison of “possible futures” that result from the decisions. These “futures” are depicted in scenarios. The main reason is that processes to be implemented in the future most likely deviate from corresponding existing processes e.g. in efficiency. The assessment of scenarios is no exclusive feature of ILCSA but ILCSA has new features to analyse additional uncertainty that arises from the assessment of scenarios that are not yet realised.

The realisation of scenarios that were found to be sustainable in a sustainability assessment may still cause unexpected and sometimes undesirable consequences. There are two kinds of such consequences:

1) The scenario is implemented as intended but causes consequences in other sectors of the economy outside the original scope of the assessment. For example, mineral fertiliser production is affected if fertiliser is increasingly produced as a co-product in biorefineries. Consequential assessment using system expansion is designed and used to capture these kinds of effects.

2) The scenario is not realised as intended because external barriers prevent this. For example, a newly built highly efficient combined heat and power plant may be forced by economic pressure to use unsustainable biomass if sustainable biomass is not sufficiently available. The identification of such barriers, the analysis of their consequences and measures to avoid them is a new feature in ILCSA. Ideally, the consequences of implementation failures due to barriers are depicted in further “worst case” scenarios and assessed for their sustainability impacts. Often, however, such scenarios are very hard to quantify (such as known from indirect land use changes) or trivial (infrastructure is built but the facility never really becomes operational). In many of these cases, rough calculations can already reveal that the “worst case” scenario is surely undesirable. Then efforts can be concentrated on identifying measures to overcome the barriers instead of trying to determine the effects more exactly. The concrete subjects of such barrier analyses are dependent on the goal and scope of the assessment.

This way, the ILCSA adds aspects relevant for a sustainable development that go beyond classical sustainability assessment of environmental, economic and social aspects covered in current LCSA frameworks.

### 3.1.1. Feasibility

For scenarios depicting future systems, there are several barriers on the way towards implementation. These may be e.g. of technical, political or social nature depending on the context. Complementary non-formal assessments of these aspects in previous studies yielded additional qualitative indicators [15], [16], [19]. Examples are “maturity level” of a production technology that reflects the risk of not being technically realisable or “acceptance by (stakeholder group)” that reflects impacts expected by a certain group (which may be completely unrealistic) and thus possible resistance against implementation. The results of life cycle costing (LCC) may also be viewed as a feasibility indicator from a business perspective rather than a genuine sustainability indicator [27], [28]. Yet, the aim of analysing feasibility aspects in the context of ILCSA is not to deliver prognoses or predictions of how likely a scenario can be implemented. Instead, it should highlight barriers that may need further attention if a decision maker considers realising a certain scenario.

### 3.1.2. Stability

The assessment of existing systems is usually based on average performances of several facilities over several years. Because this information is not available for possible future systems, care has to be taken to take stability into account in an assessment for ex-ante decision support. First and foremost, the scenario definition during in the goal and scope definition step needs to address this topic. Scenarios need to reflect the expected average performance of the processes to be implemented. This includes unavoidable downtimes, losses, site-specific restrictions etc. but also expected improvements compared to demonstration plants instead of the best achievable performance under optimally controlled experimental conditions. In practise, expert judgement and close contact to developers as well as independent experts is necessary to define realistic scenarios. Second, further indicators may prove useful in certain cases to highlight risks of unexpected deviations from standard operation such as accidents (e.g. “risk of explosions”), bad harvests (e.g. “susceptibility to drought”), etc. This cannot replace a real risk assessment, for which dedicated methodologies exist, but call the attention of decision makers to such aspects.

### 3.1.3. Implementation potentials and competition

Further unintended but avoidable deviations from scenarios can be cause by exceeding implementation potentials. Limits can either be on the product side by competition with other products or limited demand / market size or on the resource side by competition e.g. about land. One result from low potentials can be an unsuccessful attempt to implement a scenario with resulting damages (e.g. economic losses and negative environmental impacts due to created and abandoned infrastructure). Another consequence, which is not foreseen in the original scenario definition, can be clearing of natural ecosystems if sufficient sustainably available resources are lacking after implementation. Furthermore, demand for a product may be created so that the precondition of life cycle comparisons, the replacement of a reference product, is not valid anymore. Some of these aspects are already widely discussed in certain contexts such as indirect land use changes in the context of limited biomass and / or land availability. Building on these discussions, sustainability analyses for ex-ante decision support benefit from systematic accompanying analyses on implementation potentials. Results can be incorporated in the result integration step in the form of additional indicators such as “iLUC risk” or “market potential”. This way, decision makers can judge better, when and under which conditions associated “worst case” scenarios may become reality instead of the intended original scenarios.

### 3.1.4. Practical application of barrier analyses

It is most appropriate and practicable to choose the methodologies to assess feasibility, stability and implementation potentials depending on the respective goal and scope of the study. In previous applications of ILCSA, some of these aspects were usually covered by a technological assessment and displayed as technological indicators besides environmental, economic and social indicators. So far, we additionally included complementary political assessments (feasibility, potentials), extended social assessments including the perception of scenarios or stakeholder workshops (feasibility, stability), biomass potential analyses (implementation potentials) and market analyses (implementation potentials). Furthermore, SWOT (strengths, weaknesses, opportunities, threats) analyses are an option to collect and cover further relevant aspects out of this spectrum that do not justify dedicated assessments.

## 3.2. Flexibility in methodologies and indicators

ILCSA is open for the incorporation of results from formal, general-purpose, established and quantitative assessment methodologies such as LCA as well as from informal, subject-specific and / or qualitative assessment methodologies, which may be under development. Like LCSA, ILCSA incorporates results from environmental, economic and social sustainability assessments. In contrast to LCSA, ILCSA is not limited to the methodologies of LCA, LCC and sLCA. These methodologies, whose current status of development is summarised e.g. in [5], are not yet suitable to comprehensively and robustly cover all environmental, economic and social sustainability aspects. For example, environmental assessment in many cases benefits from complementary approaches next to the established LCA methodology. In the context of biomass-related processes, we contributed to developing a new methodology termed life cycle environmental impact assessment (LC-EIA), which qualitatively assesses local and site-specific environmental impacts on soil, water, biodiversity and landscape [26]. Respective quantitative indicators are still under development in LCA and additionally lack available and robust location-specific background data. Thus, these LCA indicators do not yet provide robust results suitable as a basis for decision support. Generally, quantitative indicators are preferable over qualitative ones: Quantitative results allow for an aggregation of many small contributions over many life cycle stages. In contrast, qualitative results on several life cycle stages or unit processes cannot be summed up but are only useful if big impacts of hot spots dominate life cycle impacts. Nevertheless, a hot spot analysis is preferable over not taking the respective aspects into account at all. Similarly, economic sustainability assessment could be extended beyond LCC to incorporate further indicators besides life cycle costs such as value added or dependency on imports [27]. Furthermore, ILCSA can also incorporate cross-disciplinary indicators such as greenhouse gas abatement costs. Such indicators do not integrate all information of the original indicators (here: climate change and costs) but provide additional information on the efficiency of reaching a certain target (here: climate change mitigation).

Flexibility of ILCSA regarding used methodologies and indicators does not only apply to the genuine sustainability assessment on environmental, economic and social aspects but also to additional barrier analyses as discussed in chapter 3.1.4. In all these cases, ILCSA benefits from not being limited to a combination of the three methodologies LCA, LCC and sLCA as it is the case for LCSA.

## 3.3. Result integration

There are two general ways of integrating information on several sustainability aspects into an overall picture to derive recommendations to decision makers:

**Aggregation by weighting**

All indicators can be mathematically combined into one or few scores using weighting factors or ranked otherwise according to a weighting algorithm. These approaches cannot be entirely based on scientific facts but depend on normative judgement (value-based choices). Several methods such as expert panels or surveys are available to provide weighting factors based on normative judgement, which are needed as input for the aggregation step. However, none of these factors are truly politically legitimated, which would be necessary if resulting recommendations are addressed at politicians. Furthermore, trade-off situations do not become apparent and decisions in such situations, which depend on weighting factors, are hard to understand for decision makers not involved in the study. Furthermore, most decision situations do not require absolute judgements, which can be best supported by one score (e.g.: Is 2$^{nd}$ generation ethanol generally better than 1$^{st}$ generation biodiesel?) but rather a differentiated assessment (e.g.: Under which conditions / in which niche is it better to implement 2$^{nd}$ generation ethanol or 1$^{st}$ generation biodiesel production?). For the latter situation, disaggregated results often make it easier to identify niches (in which specific disadvantages are not as important) or parameters that need optimisation (to overcome a certain disadvantage). Therefore, weighting is not applied in ILCSA.

**Structured discussion**

All advantages, disadvantages and trade-offs of the options can be discussed verbally argumentatively. The results of such a process are more complex than single scores but only this is adequate in complex decision situations. This makes trade-offs transparent and supports their active management instead of just hiding existing complexity and trade-offs. This approach is followed in ILCSA.

Considering the amount of options and indicators, a verbal-argumentative discussion requires a structured approach such as the one presented in this article. One key element are colour-coded overview tables to illustrate the respective advantages and disadvantages of individual scenarios in all assessed sustainability aspects (Figure 4). The original results are hard to understand at a glance because some are quantitative and others are qualitative. Furthermore, indicators are sometimes advantageous if they show negative values (e.g. emission savings compared to the provision and use of reference products) and sometimes if they are positive (e.g. profits of involved businesses). Similar approaches have been followed before for fewer indicators and / or scenarios, which leaves room for graphical forms of displaying results or ranks such as radar charts or colour panels (e.g. [2], [9]). If more results have to be displayed, overview tables are suitable to illustrate general patterns and deduce concrete conclusions and recommendations.

Another key element is a benchmarking process of decision alternatives. For each specific decision to be taken, all relevant alternatives are compared to a benchmark (e.g. a promising option) using a suitable comparison metric. The qualitative result of this benchmarking process indicates advantages or disadvantages compared to the benchmark and how robust the difference is. The comparison metric builds on the original quantitative information instead of on the categorised values including their bandwidths. Benchmarking focusses the attention on one decision option and delivers additional information on the robustness of differences. Benchmarking tables can be used to deduce further concrete recommendations.

The deduction of recommendations from overview and benchmarking tables requires further in-depth analyses of the contributions e.g. of life cycle stages or unit processes that lead to these results. Of course, all available information on individual contributions to all results cannot be displayed in one table. This step, however, is not performed by the reader but is provided as background information in the discussion (e.g.: Differences A, B and C, which become apparent in benchmarking table, are caused by the input of substance X in process Y; therefore input X should be reduced as far as possible.). This way, overview and benchmarking tables support the discussion, help not to miss any relevant aspect and make recommendations comprehensible.

The result integration based on a benchmarking procedure, which is described here, has the following advantages compared to other approaches (e.g. [29], [30]): First, it does not require value-based weighting for result aggregation while providing the same or an even higher level of science-based decision support. Second, it can exploit the information content of quantitative indicators while being open for qualitative ones, too. With these two properties, it supports the integration of non-standard assessment methodologies into ILCSA.

As shown in several ILCSA applications and the example highlighted in this article, the structured discussion based on overview and benchmarking tables represents a practical and comprehensible way to deduce and present conclusions and concrete recommendations to decision makers.

## 3.4. Limitations

Any comprehensive life cycle based sustainability assessment methodology, be it LCSA or our suggested extension ILCSA, can only be as good as the methodologies used to assess each individual sustainability aspect within this overarching frame. Therefore, further effort has to be devoted to the development of these methodologies. Many impact assessment methods used in LCA have reached an impressive maturity, which can serve as a positive example for LCC and sLCA but also for other impact assessment methods used in LCA for example regarding water use or biodiversity [31]–[34]. Another issue is the availability of necessary background data. The more each method is applied, the more data from previous studies on existing processes will be available in databases. As methodologies and data availability will always be improving, overarching methodologies such as ILCSA need to remain flexible to always incorporate the best available knowledge.

Furthermore, comprehensive sustainability assessments are often criticised for not delivering simple answers. This is understandable because especially in business management there is often no time to ponder over lengthy discussions. However, truly complex problems such as whether to implement a new technology or produce a new product mostly do not have simple answers. If the problem is not very complex, such as decisions between very similar processes, a full sustainability assessment is not needed but in some cases even performance indicators such as efficiencies may be sufficient as decision support. If instead simple information is used to decide in a complex context, there is the risk that important parts of the problem are ignored. These will most likely materialise at a later point in time, when solving may be much more costly – if possible at all. Therefore, a comprehensive sustainability assessment is required in such cases. Nevertheless, the information it provides can only be useful in an adequately complex strategic decision process, which requires resources but helps to avoid much higher losses or damages. In a globalised world, increasing parts of such decision process are shifted to companies although they are in a big part of originally political nature. This emphasises the importance of support programmes for technological developments that are backed by political institutions such as the Framework Programmes or Horizon 2020 by the European Commission. Comprehensive sustainability assessment methodologies such as ILCSA can help business managers as well as politicians to cope with challenging decision in a complex world.

# 4. Conclusion

Integrated life cycle sustainability assessment (ILCSA) represents a practical approach that extends existing life cycle sustainability assessment (LCSA) methodologies. It adds important aspects especially for ex-ante assessments of new products or production technologies. Furthermore, it contains a structured discussion to derive concrete conclusions and recommendations from a multitude of individual assessment results. At the same time, it is flexible to incorporate results from interim assessment methodologies for individual sustainability aspects that cannot be robustly assessed by LCA, LCC or sLCA yet. Thus, ILCSA represents a valuable tool for sustainability-focussed decision support on complex systems.

# 5. Abbreviations and glossary

**1st generation biofuels**

Biofuels e. g. produced from sugar, starch, vegetable oil or animal fats using conventional technologies.

**2nd generation biofuels**

Biofuels e. g. produced from non-food biomass such as lignocellulose and waste biomass (e. g. wheat straw or corn stover) using innovative technologies.

**C5**

Biomass fraction that primarily contains pentoses (sugars with **5 c**arbon atoms)

**C6**

Biomass fraction that primarily contains hexoses (sugars with **6 c**arbon atoms)

**CED**

**C**umulative **e**nergy **d**emand

**EC**

**E**uropean **c**ommission

**GMO**

**G**enetically **m**odified **o**rganism

**GP**

**G**reen **P**remium

**IA**

**I**taconic **a**cid

**ILCSA**

**I**ntegrated **l**ife **c**ycle **s**ustainability **a**ssessment

**ILO**

**I**nternational **l**abour **o**rganisation

**IRR**

**I**nternal **r**ate of **r**eturn

**LCA**

(environmental) **L**ife **c**ycle **a**ssessment

**LCC**

**L**ife **c**ycle **c**osting

**LC-EIA**

**L**ife **c**ycle **e**nvironmental **i**mpact **a**ssessment

**LCIA**

**L**ife **c**ycle **i**mpact **a**ssessment

**LCSA**

**L**ife **c**ycle **s**ustainability **a**ssessment

**sLCA**

**S**ocial **l**ife **c**ycle **a**ssessment

**N/A**

**N**ot applicable

**N/D**

**N**o data

**NMVOC**

**N**on **m**ethane **v**olatile **o**rganic **c**ompounds

**NPV**

**N**et **p**resent **v**alue

**PM10**

**P**articulate **m**atter with diameter of 10 micrometres or less

**R11**

Refrigerant (trichlorofluoromethane), also termed CFC-11

**ReCiPe**

LCIA methodology [25], acronym stands for the contributing institutes RIVM and Radboud University, CML, and PRé

**SETAC**

**S**ociety of **e**nvironmental **t**oxicology **a**nd **c**hemistry

**SWOT**

**S**trengths, **w**eaknesses, **o**pportunities, **t**hreats

**UNEP**

**U**nited **N**ations **e**nvironment **p**rogramme

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# 8. Figures and Captions

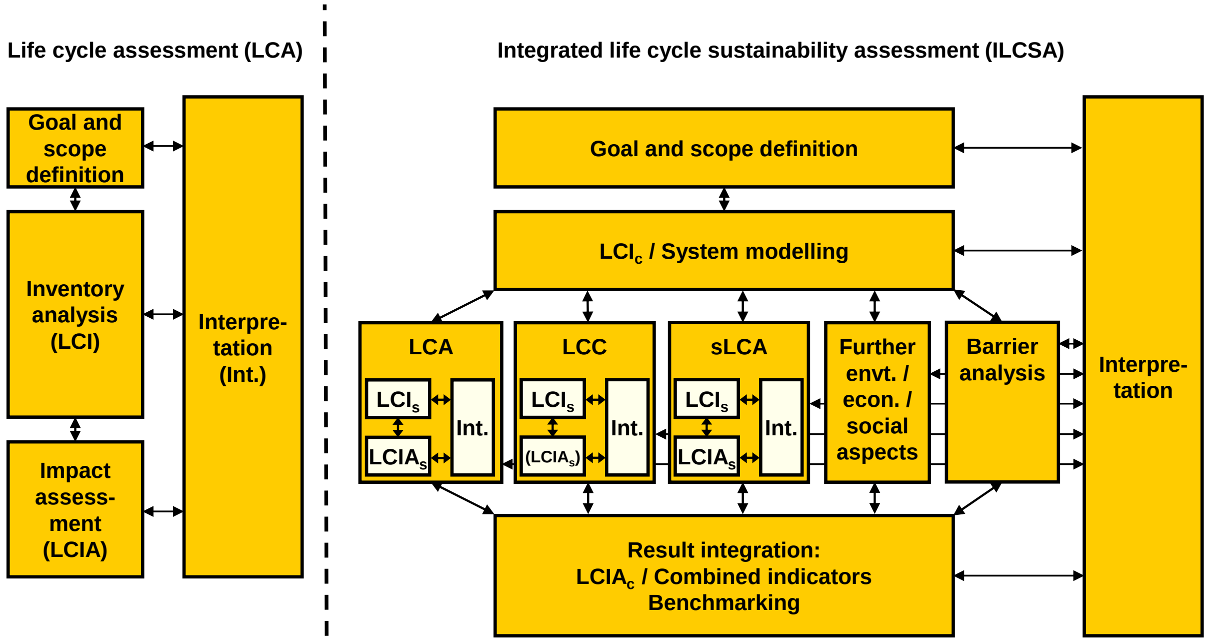


**Figure 1: Comparison of the structures of life cycle assessment (LCA) and integrated life cycle sustainability assessment (ILCSA). $LCI_c$, $LCI_s$, $LCIA_c$ and $LCIA_s$ are parts of the life cycle inventory analysis and life cycle impact assessment that are common (c) for all sustainability aspects and specific (s), respectively.**

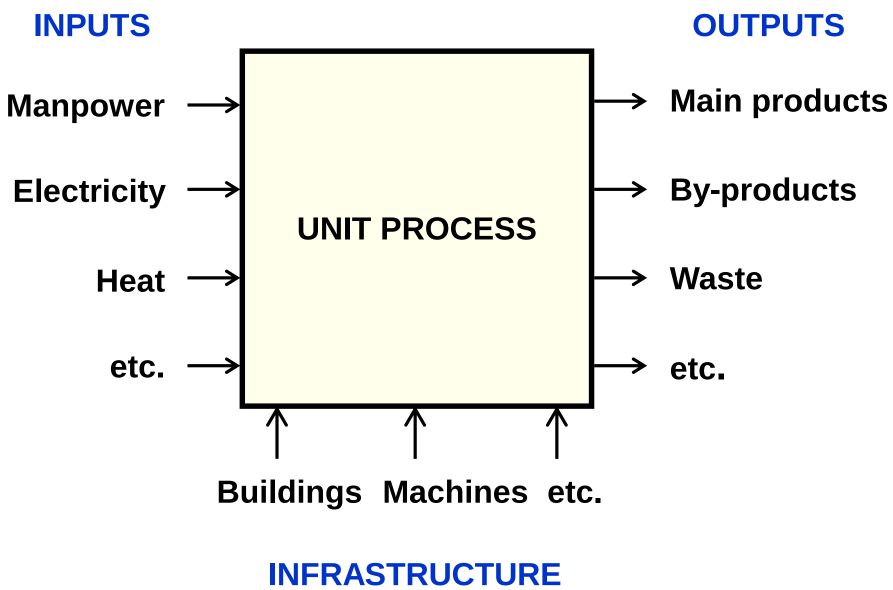


**Figure 2: System modelling, the common part of the life cycle inventory analysis, includes the definition and quantification of all inputs, outputs and required infrastructure for each unit process of the respective scenario.**

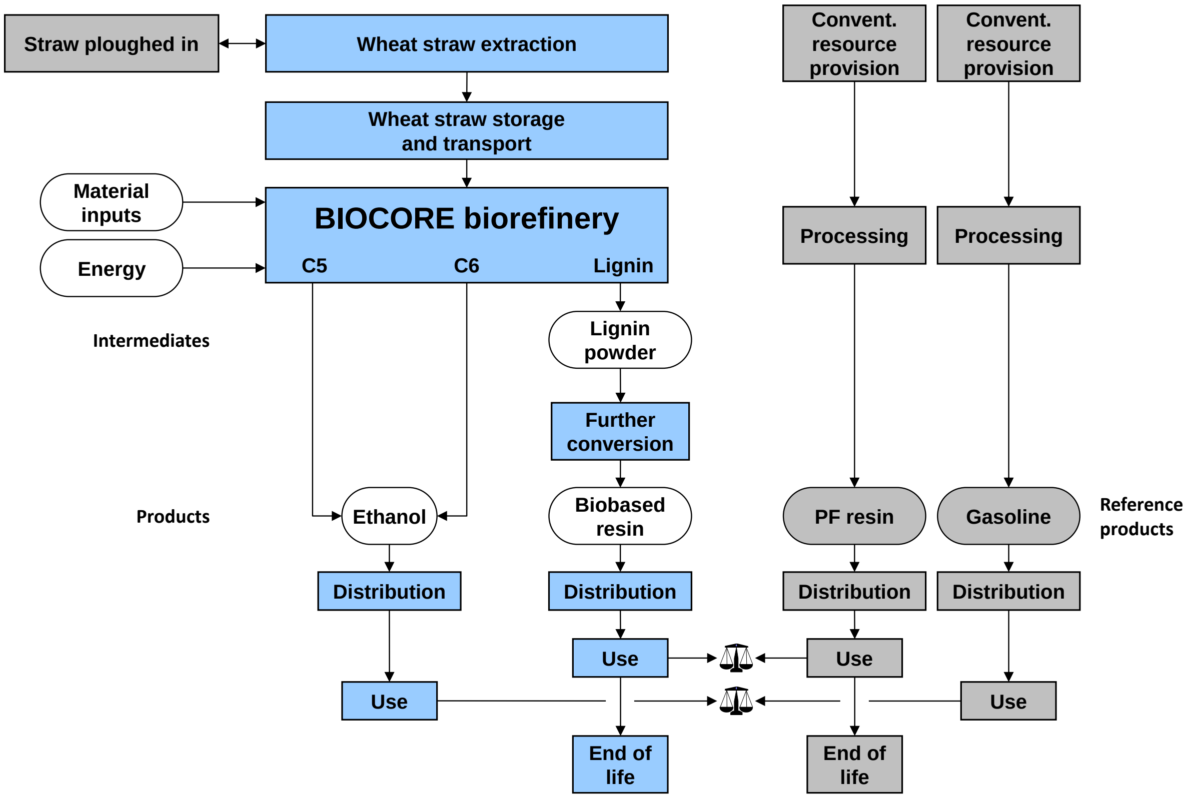


**Figure 3: Scheme of a life cycle comparison. This scheme exemplarily shows the products and reference products of the main scenario "Wheat straw (SHF ethanol / resin)" (ethanol via the separate hydrolysis and fermentation pathway). C5: pentose fraction, C6: hexose fraction.**

| | Indicator | Unit or subcateg. | Wheat straw (Xylitol / IA / resin) | Wheat straw (Xylitol / ethanol / resin) | Wheat straw (Ethanol / IA / resin) | Wheat straw (SHF ethanol / resin) | Wheat straw (PVC / resin) | Wheat straw (Fallback options) | Wheat straw (IA material recycling) | Wheat straw (Straw powered) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Standard | | | | | | | |
| | | | BIOCORE scenarios | | | | | | | |
| **Technology** | Maturity | - | - - | - - | - - | - - | - - | - | - - | - - |
| | Availability of infrastructure for logistics and storage | - | - | - | - | - | - | - | - | - |
| | Use of GMOs | - | - - | - - | - | - | - | 0 | - - | - - |
| | Risk of explosions and fires | - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Development of legislative framework and bureaucratic hurdles | - | - | - | - | - | - | - | - | - |
| | Feedstock flexibility of conversion technologies | - | + | + | + | + | + | + | + | + |
| **Environment** | Resource depletion: energy (CED) | GJ / t biomass (dry) | -14 | -4 | 17 | 16 | 14 | 12 | -11 | -15 |
| | Climate change (ReCiPe) | t $CO_2$ eq. / t biomass (dry) | -0.9 | -0.5 | 0.3 | 0.2 | 0.2 | 0.5 | -0.8 | -0.7 |
| | Terrestrial acidification (ReCiPe) | kg $SO_2$ eq. / t biomass (dry) | -0.3 | 0.7 | 5.2 | 4.9 | 4.9 | 1.5 | -0.1 | 1.0 |
| | Marine eutrophication (ReCiPe) | kg N eq. / t biomass (dry) | -4.3 | -4.3 | 1.4 | 1.7 | 1.6 | N/D | -4.4 | -1.8 |
| | Freshwater eutrophication (ReCiPe) | kg P eq. / t biomass (dry) | -0.4 | -0.4 | 0.1 | 0.1 | 0.1 | N/D | -0.4 | -0.1 |
| | Photochemical ozone formation (ReCiPe) | kg NMVOC eq. / t biomass (dry) | -1.9 | -1.4 | 0.7 | 0.3 | 0.2 | -0.5 | -1.7 | -0.6 |
| | Respiratory inorganics (ReCiPe) | kg PM10 eq. / t biomass (dry) | -0.7 | -0.4 | 1.0 | 0.8 | 0.7 | -0.1 | -0.6 | -0.1 |
| | Ozone depletion (ReCiPe + [24]) | g R11 eq. / t biomass (dry) | 2.4 | 1.9 | 2.9 | 2.8 | 2.9 | -0.2 | 2.4 | 4.4 |
| | Water | - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Soil | - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Fauna | - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Flora | - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Landscape | - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Economy** | Total capital investment | Million € | 150 | 144 | 156 | 149 | 161 | 123 | 157 | 138 |
| | NPV (5%, no GP) | Million € | -159 | -311 | -629 | -686 | -852 | -641 | -209 | -114 |
| | NPV (5%, incl. GP) | Million € | 6 | -311 | -464 | -686 | -787 | -641 | -38 | 51 |
| | Profit / loss (no GP) | € / t biomass (dry) | -11 | -114 | -324 | -370 | -459 | -353 | -40 | 12 |
| | Profit / loss (incl. GP) | € / t biomass (dry) | 123 | -114 | -114 | -370 | -328 | -353 | 103 | 139 |
| | IRR (no GP) | % | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| | IRR (incl. GP) | % | 6% | N/A | N/A | N/A | N/A | N/A | 1% | 10% |
| | Price support (no GP, 25% IRR) | % | 37% | 56% | 127% | 159% | 219% | 238% | 42% | 31% |
| | Price support (no GP, 15% IRR) | % | 25% | 43% | 108% | 137% | 191% | 208% | 29% | 20% |
| | Price support (incl. GP, 25% IRR) | % | 19% | 56% | 83% | 159% | 182% | 238% | 23% | 14% |
| | Access to markets | - | 0 | + | 0 | + | + | + | 0 | 0 |
| | $CO_2$ avoidance costs | € / t $CO_2$ eq. | 294 | 793 | N/A | N/A | N/A | N/A | 397 | 305 |
| | Energy resource savings costs | € / GJ | 19 | 97 | N/A | N/A | N/A | N/A | 29 | 15 |
| **Society** | Production of feedstock | Incentives | + | + | + | + | + | 0 | + | + |
| | | Barriers | - | - | - | - | - | 0 | - | - |
| | Identification of stakeholders | Producers (farmers) | + | + | + | + | + | + | + | + |
| | | Business | + | + | + | + | + | + | + | + |
| | | Traders | + | + | + | + | + | + | + | + |
| | Rural development and infrastructure | Road | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | Water (availability and quality) for the local population | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Labour conditions (enforcement) | ILO conventions | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Competition with other sectors | Competition for residues | - | - | - | - | - | - - | - | - |

**Figure 4: Overview of indicators and results for selected BIOCORE scenarios with varying product portfolios in comparison to conventional systems under standard conditions. IA: Itaconic acid, CED: cumulative energy demand, ReCiPe: specific life cycle impact assessment methodology [25], NPV: net present value, IRR: internal rate of return, GP: green premium, N/A: not applicable, N/D: no data, for further abbreviations see section abbreviations and glossary.**

| Benchmark: Wheat straw (Xylitol / IA / resin), feedstock basis | | BIOCORE scenarios: Wheat straw (Xylitol / IA / resin) | BIOCORE scenarios: Wheat straw (Fallback options: Feed, pulp, energy) |
|---|---|---|---|
| **Technology** | | | |
| | Maturity | | ++ |
| | Availability of infrastructure for logistics and storage | | 0 |
| | Use of GMOs | | ++ |
| | Risk of explosions and fires | | 0 |
| | Development of legislative framework and bureaucratic hurdles | | 0 |
| | Feedstock flexibility of conversion technologies | | 0 |
| **Environment** | | | |
| | Resource depletion: energy | | - |
| | Climate change | | - |
| | Terrestrial acidification | | - |
| | Marine eutrophication | | N/D |
| | Freshwater eutrophication | | N/D |
| | Photochemical ozone formation | | - |
| | Respiratory inorganics | | 0 |
| | Ozone depletion | | + |
| | Water | | 0 |
| | Soil | | 0 |
| | Fauna | | 0 |
| | Flora | | 0 |
| | Landscape | | 0 |
| **Economy** | | | |
| | Total capital investment | | ++ |
| | NPV (5%, no GP) | | - |
| | NPV (5%, incl. GP) | | - |
| | Profit / loss (no GP) | | - |
| | Profit / loss (incl. GP) | | - |
| | IRR (no GP) | | N/A |
| | IRR (incl. GP) | | N/A |
| | Price support (no GP, 25% IRR) | | - - |
| | Price support (no GP, 15% IRR) | | - - |
| | Price support (incl. GP, 25% IRR) | | - - |
| | Access to markets | | ++ |
| **Society** | | | |
| | Feedstock prod.: Incentives | | - - |
| | Feedstock prod.: Barriers | | ++ |
| | Identification: Producers | | 0 |
| | Identification: Business | | 0 |
| | Identification: Traders | | 0 |
| | Rural development: Road | | 0 |
| | Rural development: Water | | 0 |
| | Labour conditions (ILO) | | 0 |
| | Competition for residues | | - - |

**Figure 5: Comparison of one exemplary scenario with a deviating biorefinery configuration but same product portfolio vs. the main scenario "Wheat straw to xylitol / itaconic acid / resins" based on the input of identical amounts of the feedstock wheat straw. For abbreviations see Figure 4 and section abbreviations and glossary.**