Seventh framework programme
Food, Agriculture and Fisheries, and Biotechnology

Specific International Co-operation Actions
Small or medium scale focused research project

Sweet Fuel

Sweet Sorghum
an alternative energy Crop

SWEETFUEL / Grant Agreement n° 227422

WP 6

Deliverable 6.6:

Report on integrated sustainability assessment

Composition of the consortium

CIRAD
ICRISAT
EMBRAPA
KWS
IFEU
UNIBO
UCSC
ARC-GCI
UANL
WIP

Acknowledgements

The authors would like to thank all SWEETFUEL partners for the provision of the data and information, for their fruitful discussions, collaborations and cooperation, which form the basis of this report.

This work was supported by the European Commission's Seventh Framework Programme (FP7) under Grant agreement no. 227422 (Duration 01/01/2009 – 30/06/2014).

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Suggested citation

Reinhardt, G., Keller, H. et al. 2014: Report on integrated sustainability assessment of the SWEETFUEL project, www.sweetfuel-project.eu, Heidelberg, 2014

SWEETFUEL:

Sweet Sorghum: an alternative energy crop

Deliverable 6.6:
Report on integrated sustainability assessment

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Heidelberg, 30 June 2014

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Executive summary

Increasing world market prices for fossil fuels, driven by limited reserves, growing demand and instability in producing regions make renewable fuels such as bioethanol or biogas economically more attractive. Bioethanol is one of the most prevalent biofuels in the world and represents an actual alternative fuel for the transport sector. Worldwide, the main source of bioethanol is sugarcane. However, the cultivation of this crop cannot be realised in water-limited regions. On this **background**, sweet sorghum (*Sorghum bicolor* (L.) Moench) has several advantages due to its efficiency in both water use and nutrient uptake. Another variant of this plant, termed biomass sorghum, is adapted to high biomass yields especially in temperate regions. It is a promising alternative feedstock for biogas production. The SWEETFUEL project funded by the European Commission mainly aims at developing sweet sorghum cultivars for tropical and semi-arid regions and biomass sorghum cultivars for temperate environments. The production of these variants and the use of their products such as bioethanol or biogas may represent a sustainable alternative to meet future energy needs.

An **integrated sustainability assessment** is performed as part of the SWEETFUEL project. It primarily analyses whether a mature and large-scale cultivation and use of sweet and biomass sorghum in 2020 provides benefits from environmental, economic and social perspectives primarily compared to the use of fossil fuels. This sustainability assessment applies a generic and scenario-based comparison of whole life cycles from cradle to grave. It collects, joins and extends results of the preceding environmental and economic assessments as well as of the SWOT analysis, which covers further sustainability aspects especially in the social domain, and the ethical assessment. These results are integrated into an overall picture using multi-dimensional comparison metrics and a structured transparent discussion to be able to derive consistent recommendations and highlight potential conflicts.

Several **scenarios** regarding the production and use of sweet and biomass sorghum were defined as a common basis for all assessments of individual sustainability aspects (environmental, economic, social) and for the integrated assessment. Three different approaches of sweet sorghum cultivation and use are assessed in several scenarios each: Cultivation on fallows between cycles of sugarcane with a focus on fuel production also from grains ("Cane fallow"), substitution of grain sorghum cultivation with co-production of food and fuel ("Grain to food"), and non-mechanised cultivation with a focus on keeping a big part of the fuel value chain in the villages through concentrating sugar juice to syrup ("Syrup production"). In all scenarios, the main product is ethanol. The main biomass sorghum scenarios involve cultivation that aims at high biomass yields for biogas production. Alternatively, the combustion of the biomass and the production of second generation fuels is analysed (second generation ethanol via fermentation and synthetic Fischer Tropsch fuels via gasification).

Results of the integrated sustainability assessment show that the production and use of sweet and biomass sorghum can cause a wide spectrum of potential impacts ranging from significant benefits to distinctly detrimental impacts. Responsible for the individual outcome are factors such as the use of the by-products (for sweet sorghum scenarios), the choice and

configuration of the conversion process (for all scenarios) but also external factors like land availability, prices and the way energy is produced elsewhere. The observed variability of results leads to concrete recommendations under which conditions and, if so, how sweet and biomass sorghum cultivation and use should be implemented.

In general, **social** impacts are mostly neutral to positive as long as land rights are respected. The results of the economic assessment show that there are options to produce and use both sweet and biomass sorghum **profitably** via the approaches “Cane fallow” and “Grain to food” (sweet sorghum) or via biogas production (biomass sorghum). For “Syrup production” (sweet sorghum) and 2nd generation fuel production (biomass sorghum), profitability is not immediately achievable and requires more or less substantial process improvements or subsidies depending on the assessed scenario. The profitable scenarios mostly also come along with the highest **climate change mitigation and energy resource savings** potentials because energy efficiency is very important for all of these aspects. To realise these potentials for environmental benefits, further optimisations are needed like the prevention of methane leaks from biogas plants, which may result in some extra costs but should not prevent profitability as such. Therefore, an implementation of sorghum-based fuel and energy production does not require continuous financial support beyond existing programs but some regulatory guidelines to improve sustainability. However, all scenarios lead to **additional environmental burdens** mainly caused by intensive agriculture such as acidification, excess nutrient inputs into ecosystems or detrimental local effects on soils and biodiversity. This pattern of environmental advantages and disadvantages is common for most biofuels from annually cultivated biomass. A political process is needed in each concerned region to decide how far these disadvantages are acceptable in return for the advantages.

A further major limitation for sweet and biomass sorghum cultivation is the **availability of agricultural land**. In any case, direct or indirect clearing of valuable ecosystems for its cultivation and violation of land rights have to be avoided. In this respect, **specific advantages of sorghum** should be taken advantage of to mitigate competition about land: For sweet sorghum, the use of co-products such as grains and surplus bagasse, which is not required for powering the conversion process, as feed or food can reduce the demand of land for separate food / feed production elsewhere. This way, an integrated production of these products and fuels on the same land using sweet sorghum may in some cases even suffice with less total area than separate cultivation without fuel production. For biomass sorghum, drought tolerance and resistance against a certain pest may open up opportunities for cultivation, which are not available to competing energy crops such as maize. To take advantages of these particular properties, energy sorghum cultivation has to be integrated into overall strategies for land and biomass use on a regional and national level. This requires a full sustainability assessment for any concretely planned and publicly supported large scale energy sorghum cultivation project.

In summary, the production and use of sweet and biomass sorghum as studied in the SWEETFUEL project can be designed largely sustainably. However, several environmental disadvantages typical for many biofuels have to be accepted by society. Particular opportunities for sweet and biomass sorghum cultivation arise from the plants’ properties. Thus, sweet and biomass sorghum are a valuable addition to the portfolio of energy crops. Specific options for the realisation of this potential have been identified.

1 Introduction, goal and scope

Bioethanol contributes to the increasing use of biofuels. Worldwide, sugarcane is the main source of bioethanol. However, the cultivation of this crop cannot be realised in water-limited regions. On this background, sweet sorghum (*Sorghum bicolor* (L.) Moench) has several advantages due to its efficiency in both water use and nutrient uptake. Furthermore, the production of food, feed and fuel can be combined in one crop. This is an important asset on the background of the currently increasing discussion on fuel production and food security. Another variant of *Sorghum bicolor* (L.) Moench, termed biomass sorghum, is adapted to high biomass yields especially in temperate regions. Drought tolerance and resistance against specific pests make it a promising alternative feedstock for biogas production.

As the more widespread use of sweet and biomass sorghum for bioethanol and biogas production is primarily limited by the lack of variants specifically bred for this purpose, a project funded by the European Commission with the title “SWEETFUEL: Sweet Sorghum: an alternative energy crop” was launched (Grant agreement no. 227422). The SWEETFUEL project aims at developing sweet sorghum cultivars for tropical and semi-arid regions and biomass sorghum cultivars for temperate environments. The focus lies on tolerance to cold, drought and acidic soil as well as on a high production of stalk sugars, easily digestible biomass or grains – depending on the climatic region the crop shall be cultivated in and depending on the purpose it shall be used for. Properties and cultivation conditions of energy sorghum are described in the energy sorghum handbook /Khawaja et al. 2014/. This project was split in seven work packages (WPs). WPs 1-5 focussed on breeding aspects as well as cultivation and harvest practices. Based on the results of WPs 1-5, WP 6 performed a global assessment while WP 7 transferred project results to the stakeholders.

WP 6 “Integrated assessment” of the SWEETFUEL project provided a multi-criteria sustainability assessment of several sorghum production and use pathways taking into account technological, environmental, economic and social aspects.

This report is the outcome of Task 6.5 “Integrated assessment”. It was composed by IFEU with contributions from all SWEETFUEL partners, namely ARC, CIRAD, EMBRAPA, ICRISAT, KWS, UANL, UCSC, UNIBO and WIP. The report joins and integrates results from all other tasks of WP 6, which assessed individual sustainability aspects covering environmental, economic and social sustainability. While environmental and economic assessment results originate from the respective reports /Reinhardt et al. 2014/, /Basavaraj, Parthasarathy Rao et al. 2014/, social aspects were covered in the SWOT analysis /Rutz & Janssen 2012a/. Furthermore, the picture is complemented by technological aspects of feasibility and risks /Braconnier et al. 2013/. The report on technological aspects also includes common scenarios based on common definitions and settings, which are the basis for all assessments of individual sustainability aspects.

The report on integrated sustainability assessment provides answers to the following core question:

- Which are the most sustainable options to use **sweet and biomass sorghum as energy crops**?

To address the core question, the following issues were assessed:

- What are the advantages and disadvantages of the different sweet and biomass sorghum **cultivation systems** investigated in this project?
- What are the **main influencing life cycle steps** and where are **the main optimisation potentials**?
- How do different usage pathways of the **by-products** affect the overall results? Which usage should be preferred considering all sustainability aspects?

The following chapter of the report defines general specifications and settings chosen to address these questions as well as the methodology of the integrated sustainability assessment (chapter 2). In chapter 3, short descriptions of sweet and biomass sorghum scenarios are presented. Results of the environmental assessment, the economic assessment, the SWOT analysis and the ethical assessment are summarised in chapter 4 followed by further results of the integrated sustainability assessment. Conclusions based on these results as well as recommendations and an outlook are presented in chapter 5. Chapter 6 lists references and in the annex (chapter 7), supplementary material can be found. Chapter 8 contains the glossary and abbreviations.

2 Methodology

This chapter describes the general procedure and defines general specifications and settings (subchapter 2.1) as well as the methodology of the integrated sustainability assessment (subchapter 2.2). The methodologies of the environmental and economic assessments as well as of the SWOT analysis are summarised in subchapters 7.3 to 7.5 in the annex.

2.1 General procedure, specifications, definitions and settings

The sustainability assessment in the SWEETFUEL project is based on the so called integrated life cycle sustainability methodology (see /Keller et al. 2014/). For this project it was modified to the needs of all goal and scope questions: it follows a three stage approach (see Fig. 2-1). First, scenarios, general definitions and settings were described in the technological assessment /Braconnier et al. 2013/. These settings are summarised in the following paragraphs of this subchapter. In a second stage, individual sustainability aspects were assessed based on these settings in the environmental assessment, economic assessment and SWOT analysis with further input from an ethical assessment /Reinhardt et al. 2014/, /Basavaraj, Parthasarathy Rao et al. 2014/, /Rutz & Janssen 2012a/, Bursztyn 2014/. This way, consistency of the assessments of individual sustainability aspects can be ensured. In the third stage, all sustainability aspects are joined in the integrated sustainability assessment, which is subject of this report.

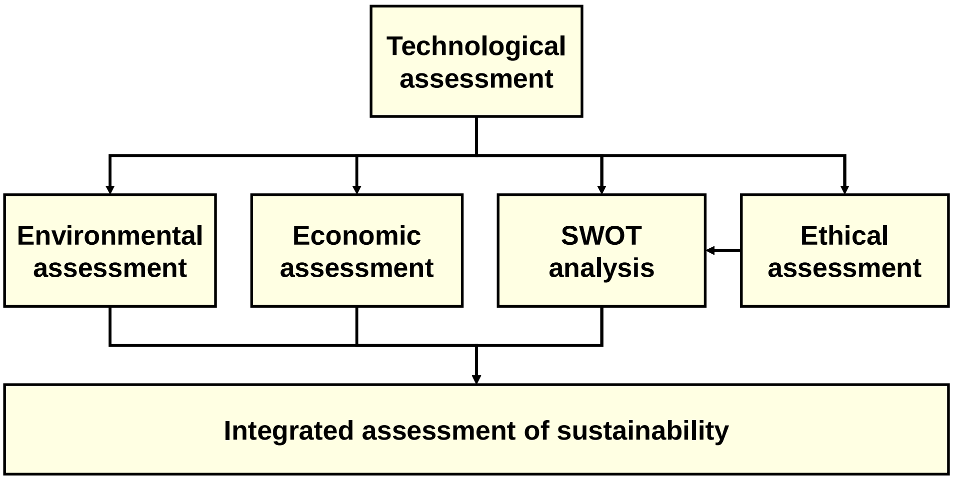

Fig. 2-1 Overview of the sustainability assessment approach in SWEETFUEL. SWOT: Strengths, Weaknesses, Opportunities, Threats.

Definition of sorghum variants

Sorghum is a crop which has quite a large diversity in phenotypic variability and composition. In the SWEETFUEL project the following terminologies are used:

Sweet sorghum: Sorghum cultivars with juicy stems and high juice sugar content in their stalks; potentially used as an energy and / or food crop.

Biomass sorghum: Sorghum cultivars with high lignocellulosic biomass yield, potentially used as energy crop.

Energy sorghum: Sweet and biomass sorghum cultivars used in this project.

Grain sorghum: Sorghum cultivars with high grain yield established as food and feed crop.

Fibre sorghum: Sorghum cultivars with a high content of fibre; potentially used as fibre or energy crop.

This project mainly focuses on sweet and biomass sorghum, whereas grain sorghum is treated as reference system. Fibre sorghum is not investigated in this project.

Time frame

In this project the use of sweet and biomass sorghum for both 1st generation and 2nd generation fuel technologies is assessed. The former, i.e. the production of bioethanol, is already well-established. In contrast, second generation technologies such as the production of ethanol from lignocellulose or the biomass gasification for so-called BtL (Biomass-to-Liquid) fuels are not yet commercially available, however, pilot and demonstration plants are operated in some countries (e.g. Europe, USA, Brazil, China, India). In this project prospective conditions given in the year 2020 are considered as main scenario since it is expected that the technology described will be mature then and thus comparable with other 1st generation ethanol production technologies. Additionally, the situation in 2015 is described for some scenarios since this reflects the state of the art at the end of the project, which is currently existent in Brazil for instance.

Geographical coverage

Sweet sorghum: In general, sweet sorghum is a manifold plant which can be cultivated in many parts of the world. Due to its high efficiency in water use and light exploitation it is particularly suitable for semi-arid and subtropical areas. Additionally, however, it is also thoroughly suitable for tropical regions. Thus, the following definitions are set for sweet sorghum cultivation:

- Subtropical / semi-arid climate with around 700 mm rainfall
- Tropical climate with around 1,200 mm rainfall per year.

Biomass sorghum: In future, biomass sorghum will be mainly cultivated to obtain high biomass yields for biogas production. This requires protruding growing conditions. Coming along with the recent discussion on fuel versus food as well as political regulations, biomass

sorghum has a high potential to be cultivated especially in temperate regions. Thus, for this investigation biomass sorghum scenarios are only settled in those areas.

Within the regions investigated in this project, there might be great variations due to differences in environmental conditions as well as due to varying production practices and conditions in different countries. These differences are captured by sub-scenarios and sensitivity analyses taking into account various yields, uses of products and by-products or production costs etc. It is outside the scope of the project to analyse every single country where sweet or biomass sorghum could be produced.

Functional unit

The functional unit has to be chosen depending on the questions to be answered. As the project aims at increasing the output of the crop by developing improved cultivars and since land usually is the limiting factor, the use of sorghum cultivars from 1 hectare of land in 1 year is assessed.

Alternative land use options

The alternative land use defines how the land would be used if energy sorghum was not cultivated. It also comprises any change in land cover induced by the cultivation of energy sorghum. As agricultural land is becoming increasingly scarce, more and more natural land (e.g. forests or grass land) is transformed into arable land. Such land use and land cover changes may have considerable influences on the outcomes of the environmental assessment since e.g. the area’s carbon stock or biodiversity are influenced. For example, a decline in above-ground and below-ground carbon stocks leads to greenhouse gas emissions, which have to be included in the greenhouse gas balance. Beside direct land use changes also indirect changes can occur. This is the case if for example the cultivation of sweet sorghum displaces the production of a food crop to other areas. Depending on use and / or land cover of that area, the displacement can cause different environmental effects.

In this project, the standard scenario refers to reference systems where the difference in carbon stock between initial vegetation and energy sorghum cultivation is close to zero. This includes reference systems such as degraded soils, degraded pastures or land that becomes free due to the intensification of existing land use. Furthermore, also idle land can be used to cultivate energy sorghum. In the further course of the report all these land use options are referred to as **“idle land”**.

In order to derive a bandwidth of different vegetation types for the alternative land use, two reference systems are identified, which are captured by sensitivity analyses:

- Dense thickets / sparse forests (carbon loss around 60 t carbon / hectare)
- Wooded grassland / planted pastures / (carbon loss around 15 t carbon / hectare)

This classification is mainly oriented at the carbon difference which occurs if reference vegetation is replaced by energy sorghum cultivation. The carbon loss given here serves the purpose to characterise the reference systems. It does not reflect real carbon contents but serves as an indicative differentiation between the different reference systems defined.

Since the alternative land use differs among scenarios, more detailed descriptions are specified within respective scenario descriptions (see subchapters 3.1 and 3.2).

Technical reference

The technical reference describes the technology to be assessed in terms of plant capacity and development status / maturity. As the investigated scenarios cover both “central” and “decentralised production at village level” two main technical references were defined:

- 25,000 – 120,000 t ethanol per year production capacity in the case of centralised production.
- 3 t syrup per day in the case of decentralised production.
- For all plant capacities, mature, full-scale industrial plants are assessed.

2.2 Integrated sustainability assessment

This subchapter describes the methodology of the integrated sustainability assessment, which builds on results from previous assessments of individual sustainability aspects in environmental and economic assessment as well as SWOT analysis /Reinhardt et al. 2014/, /Basavaraj, Parthasarathy Rao et al. 2014/, /Rutz & Janssen 2012a/. The methodologies of the assessments of individual sustainability aspects are summarised in subchapters 7.3 to 7.5 in the annex.

2.2.1 General approach

Energy sorghum can be cultivated and used in several ways. These options are represented in this assessment in the form of scenarios. On each scenario, various indicators on economic aspects, environmental aspects (assessed via screening LCA and LC-EIA), social aspects (assessed via SWOT analysis) and additionally technological aspects are made available in this study. All these aspects are integrated into an overall picture to facilitate comparisons between the options.

There are two general options to integrate this information:

Weighting and mathematical integration

All indicators could be mathematically combined into one score using weighting factors or ranked otherwise according to a weighting algorithm. These approaches cannot be entirely based on scientific facts but depend on personal value-based choices defined beforehand. Furthermore, conflict situations do not become apparent and decisions regarding these conflicts depend on weighting factors, which are hard to understand for decision makers not involved in the study. Therefore, this approach is not applied.

Structured discussion

All strengths, weaknesses and conflicts of the options can be discussed verbally argumentatively. This can make conflicts transparent and enable their active management. Considering the amount of options and indicators, this requires a structured approach. This approach is followed in this study. This section describes the methodology used for the structured comparison and presentation of decision options based on a multi criteria analysis.

2.2.2 Collection of indicators and results

Indicators and results for all scenarios are provided by the individual assessments /Braconnier et al. 2013/, /Reinhardt et al. 2014/, /Basavaraj, Parthasarathy Rao et al. 2014/, /Rutz & Janssen 2012a/. They are collected in overview tables. In some cases, indicators are selected or aggregated by the authors of the respective individual assessment to focus on the most relevant aspects for decision support. No further adjustments are made except for rescaling quantitative data to a common basis if necessary. Thus, all specific settings, methodological choices including underlying estimates, and data sources apply unchanged as documented in the respective reports.

For comparability to qualitative indicators, quantitative indicators are categorised and the table is coloured accordingly. Results are rated advantageous (green) if the assessed scenario is better than the respective conventional reference scenario and the difference is bigger than 10 % of the bandwidth of all results for this indicator under standard conditions. Disadvantageous results are rated analogously and the rest is rated neutral. Net land use is categorised as disadvantageous if it is as high as the direct land use, advantageous if it is below zero and neutral for values in between. The investment sum is not categorised because there is no reference value.

2.2.3 Additional indicators

Climate protection under the condition of limited financial resources has to use the available financial resources as efficiently as possible. Efficiency means here to achieve the highest possible greenhouse gas (GHG) emission savings with the lowest monetary expenditures necessary for that. CO_2 avoidance costs are frequently used as indicator for this purpose. CO_2 avoidance costs are defined as quotient of the differential costs for a CO_2 reduction measure and the avoided CO_2 emissions by this measure.

In analogy to CO_2 avoidance costs, similar additional efficiency indicators can be defined for other quantitative sustainability indicators. In this case, such indicators are available from the screening LCA like for example acidification (basis for SO_2 avoidance costs) or resource depletion (basis for non-renewable energy savings costs). The same methods apply for those indicators as discussed in the following for the example of CO_2 avoidance costs.

CO_2 avoidance costs are used for microeconomic decisions as well as for the decisions in energy policy. Microeconomic decisions are always based on business analyses. If political decisions like the implementation of support programmes are concerned, the valuation is often more difficult, as the macroeconomic dimension, possible external effects as well as

second- and third-round effects have to be considered. For the determination of CO_2 avoidance costs, different methodological characteristics have to be considered concerning:

- The determination of a reference, which is e.g. for biofuels the use of fossil fuels.
- The inclusion of different cost items (e.g. full costs vs. additional costs).
- The inclusion of temporal dynamics of systems under consideration (e.g. developments of investment costs of systems, of prices for energy carriers, etc.).
- The different perspectives – especially microeconomic and macroeconomic approaches.

However, the sole consideration of CO_2 avoidance costs is often not sufficient to come to sustainable decisions. On the one hand, they do not contain any information about the amount of emissions that can be avoided and on the other hand, they do not take other environmental impacts into account. Therefore, CO_2 avoidance costs do not represent a single combined indicator resulting from the sustainability assessment but only one additional criterion.

CO_2 avoidance costs from a microeconomic perspective are calculated as follows:

$$\mathbf{CO_2\ avoidance\ costs} = \frac{\mathbf{costs - costs\ (reference)}}{\mathbf{GHG\ emissions - GHG\ emissions\ (reference)}}$$

CO_2 avoidance costs are expressed in euro per tonne of CO_2 equivalents. Costs refer to the support in € maximally required to make an investment attractive (i.e. to reach an expected rate of return of 25 % without green premium product prices unless specified otherwise) and greenhouse gas emissions (GHG emissions) expressed in CO_2 equivalents.

One methodological option is to discount the avoided CO_2 emissions for the calculation of the avoidance costs as well, in order to create a preference for temporally preceding measures. Otherwise a later realisation of the measure could be reasonable for decision makers. Moreover, a discounting reflects an assumed uncertainty about the degree and the time point of the environmental impact.

$$\mathbf{GHG\,em - GHG\,em(benchmark)} = \sum_{t=0}^{n} \frac{\mathbf{\Delta GHG\,em(t)}}{\mathbf{(1+i)^t}}$$

Generally, a discounting of the environmental costs results in higher CO_2 avoidance costs as without discounting. However, for further calculations in this study it is assumed that the discounting is neutralised by the fact that the environmental impact increases parallel to the so called social preference rate. The social preference rate consists of the time discounting and the growth accounting /Nordhaus 1994/, /IPCC 1996/, /Fankhauser 1995/. Therefore, the method without discounting is used.

As CO_2 avoidance costs represent an efficiency indicator, they are only defined in the case that the primary goal is met, this is, that there are greenhouse gas emission savings by the process under investigation compared to the benchmark. If the goal is not met, one obviously cannot define an indicator on how efficiently the goal is reached. This means, the CO_2 avoidance costs can be interpreted or not depending on the results of the numerator and the denominator.

Fig. 2-2 shows that out of nine possible result options only two allow an interpretation of the avoidance costs. If negative avoidance costs occur it has to be reconsidered if this results from the lower total costs or from the possibly higher emissions. Differences approaching zero make a calculation of avoidance costs impossible. If two differences are compared to each other, it can lead to disproportional influences of uncertainties. This is especially the case if either the emissions or the costs of the compared pathways are very similar. If for example the CO_2 emissions of the two pathways differ by 10 % then a 5 % error of estimating these emissions can lead to a deviation in CO_2 avoidance costs of 100 %. Furthermore, small emission savings mathematically lead to very high and at the same time very uncertain avoidance costs. Therefore, avoidance costs are only then a reliable indicator if the uncertainties of emissions and the costs are small compared to the respective differences between the pathways.

Δ profit / Δ emissions	**> 0**	**≈ 0**	**< 0**
< 0	calculation possible (less costs than for reference)	no calculation possible	calculation possible
≈ 0	no calculation possible	no calculation possible (similar systems)	no calculation possible
> 0	no CO_2 avoidance (not defined)	no CO_2 avoidance (not defined)	no CO_2 avoidance (not defined)

Fig. 2-2 Different result options for the calculation of CO_2 avoidance costs (modified from /Pehnt et al. 2010/).

The second limitation is that avoidance costs are very prone to changes in the course of time because they can generally be very sensitive to changes as discussed above and they depend on the technological developments as well as market changes for two different systems. Therefore, it is especially important only to compare avoidance costs if they are determined for the same timeframe and under the same conditions. This makes it difficult to find comparable avoidance costs outside of this study although there is plenty of data on avoidance costs in literature. This especially applies to analyses of technologies not yet implemented for a timeframe more than a decade ahead as it is the case in this study.

Taken together, avoidance costs for environmental burdens such as greenhouse gas emissions can help to decide how mitigations of environmental burdens can be reached for the lowest price or even with profits. However, avoidance costs have to be interpreted carefully because in many situations their robustness and comparability are poor.

For further details and a critical review of the method see /Pehnt et al. 2010/.

2.2.4 Benchmarking

For the comparison of many different processes, a common benchmark has to be defined. This benchmark has to be chosen according to the questions to be answered and the respective perspectives of various stakeholders. In this case, the benchmark could for example be the economically or environmentally most favourable pathway, or the currently most used option.

For all quantitative indicators, the benchmarking process involves calculating the differences between the respective scenario and the benchmark. These comparisons should serve as a decision support to answer the question whether a scenario performs better than the benchmark regarding a certain indicator. Therefore, these quantitative differences are categorised into very advantageous [++], advantageous [+], neutral [0], disadvantageous [-], or very disadvantageous [--]. A certain minimum difference was chosen as a cut off value for the category neutral. According to the purpose, this threshold is set as a percentage of the bandwidth from the best results to the worst result among all scenarios regarding a specific indicator. The certainty of this rating is evaluated by additionally taking the bandwidth of the data 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 [+]. If there is no bandwidth available for the scenario under consideration, it is rated very advantageous [++] if it is e.g. 10 % better than the benchmark under favourable conditions. For all qualitative indicators, rating of differences is done analogously but without applying minimum differences.

2.2.5 Overall comparison

For an overall comparison, a verbal argumentative discussion of decision options is supported by structured overview tables containing the integrated assessment results.

The integrated sustainability assessment of this project is based on six qualitative technological indicators originating from SWOT analysis, ten quantitative and five qualitative environmental indicators from environmental assessment, four quantitative economic indicators from economic assessment supplemented by two additional quantitative efficiency indicators within the integrated assessment, and seven qualitative social indicators from SWOT analysis and ethical assessment. These are a subset of all possible indicators, which were assessed in previous steps of the sustainability assessment and found to be relevant for the decision process. Depending on the question to be answered, overview tables may contain all or a part of these selected indicators and scenarios. Furthermore, the unit of reference is chosen according to the question.

3 Description of scenarios

This project investigates several sweet and biomass sorghum cultivations and use pathways to determine optimised and sustainable sweet and biomass sorghum production and use systems. The systems under investigation are described in subchapters 3.1 and 3.2. Further details can be found in the report on technological assessment /Braconnier et al. 2013/.

3.1 Sweet sorghum scenarios

Generally, sweet sorghum cultivation and use is described in three different scenarios: cane fallow, grain to food and syrup production. In all scenarios the main product is ethanol. However, the scenarios differ with respect to the processing of the sugar juice and the use of the by-products. In the cane fallow and syrup scenarios (see subchapters 3.1.1 and 3.1.3) grains are either used as fertiliser, for ethanol production or as feed. In the syrup production scenario the sugar juice is boiled down in a first processing step to syrup, which is used to produce ethanol in a further conversion process. The focus of the grain to food scenario (see subchapter 3.1.2) lies on the use of sweet sorghum as a multi-purpose crop to limit food / fuel trade-offs. This means that the grains are used as food whereas juice is used for energy production. In the following subchapters all scenarios are described in detail.

3.1.1 Cane fallow scenarios

In this project prospective conditions imaginable for the year 2020 are considered as main cane fallow scenario. Additionally, the situation in 2015 is described since this reflects the state of the art at the end of the project. Both scenarios are almost identical except the use of grains. In 2020, it is expected that the grains of sweet sorghum are used for ethanol production; however, in 2015 grains of sweet sorghum remain on the field, thus reducing the demand of mineral fertiliser.

Cane fallow

An overview of the cane fallow scenario is given in Fig. 3-1. After harvest, the sweet sorghum stalks and grains are transported from the villages to centralised ethanol facilities. The leaves either remain on the field (1 a) replacing mineral fertiliser or are used for energy production (1 b).

In the central ethanol production units, the sweet sorghum stalks are crushed and the juice is pressed out, leaving bagasse. The juice is fermented into ethanol which is used as transport fuel, replacing conventional gasoline.

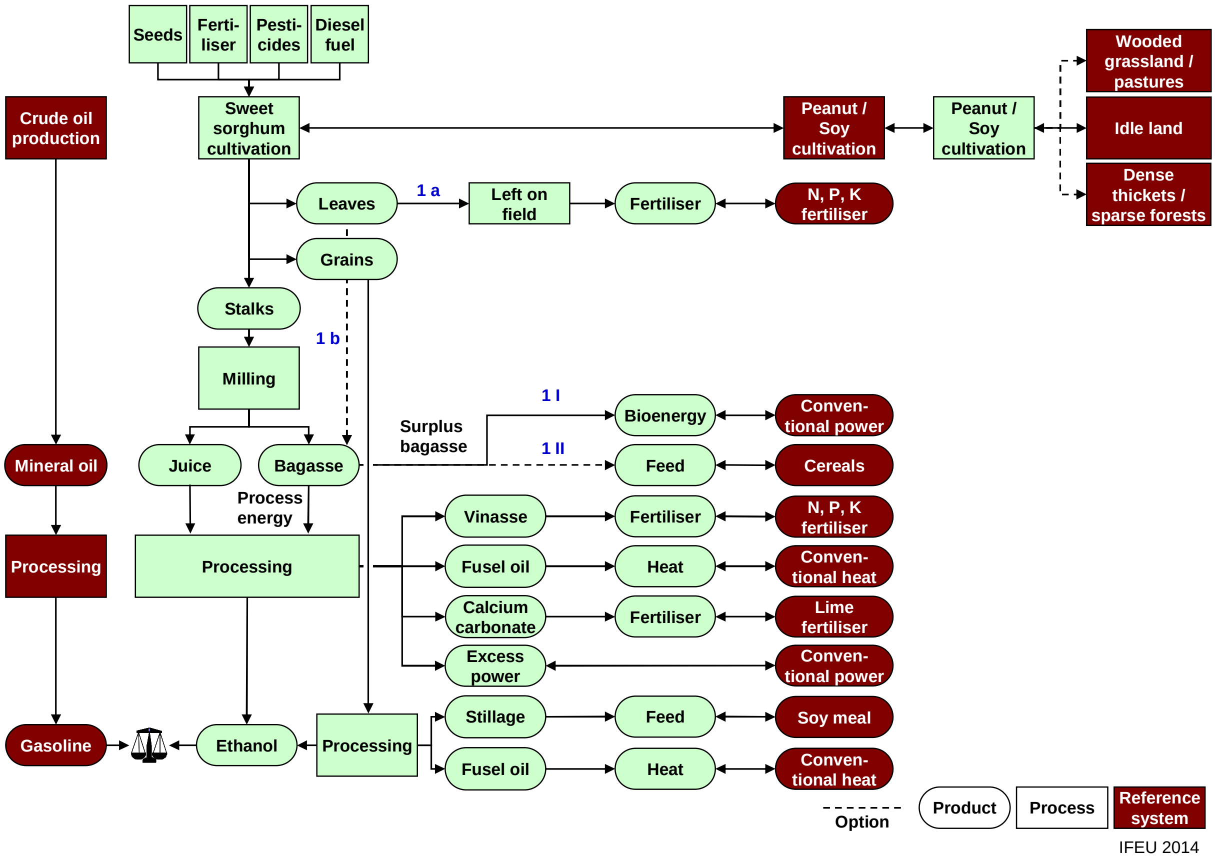

Fig. 3-1 Schematic overview of the cane fallow scenario; numbers indicate scenario numbers (for a summary of assessed scenarios see Table 3-1).

From the bagasse process energy is generated which is used internally in the ethanol production process. Surplus bagasse is either used for generating green power that is fed into the power grid, replacing conventionally produced electricity (1 I) or as animal feed, replacing cereals (1 II). In certain regions, bagasse is a very popular animal feed.

Other by-products derived during ethanol production are vinasse, stillage, excess power, fusel oils and carbonation lime. Vinasse is obtained as a by-product if sugar juice is processed and can be used as fertiliser, replacing mineral fertiliser. Stillage is a by-product, which occurs if grains are processed to ethanol and can be used as feed, replacing soy meal. Excess power can occur while process energy is generated from the bagasse, replacing conventional power. For energy generation, bagasse is combusted in a combined heat and power unit. If the heat demand is covered but less power is needed for the conversion process, excess power occurs which can be sold. Fusel oils are converted into heat, replacing conventional heat. In case of ethanol production from juice, carbonation lime is also derived as a by-product. Carbonation lime is used as fertiliser, replacing lime fertiliser.

Cane fallow 2015

An overview of the cane fallow scenario 2015 is given in Fig. 3-2. Cane fallow 2015 is almost identical to the cane fallow scenario (see subchapter "cane fallow"), except that nowadays sugarcane or forage harvesters are used for harvesting sweet sorghum. This technology works fine for stalks but grains and leaves are cut and left on field, thus a usage of both is not pursued. Consequently, by-products derived from ethanol production out of grains were not considered in the cane fallow 2015 scenario. By-products derived from ethanol production out of juice are identical to those of the cane fallow scenario. Surplus bagasse can either be used for generating green power, replacing conventional power (2 I) or as animal feed, replacing cereals (2 II).

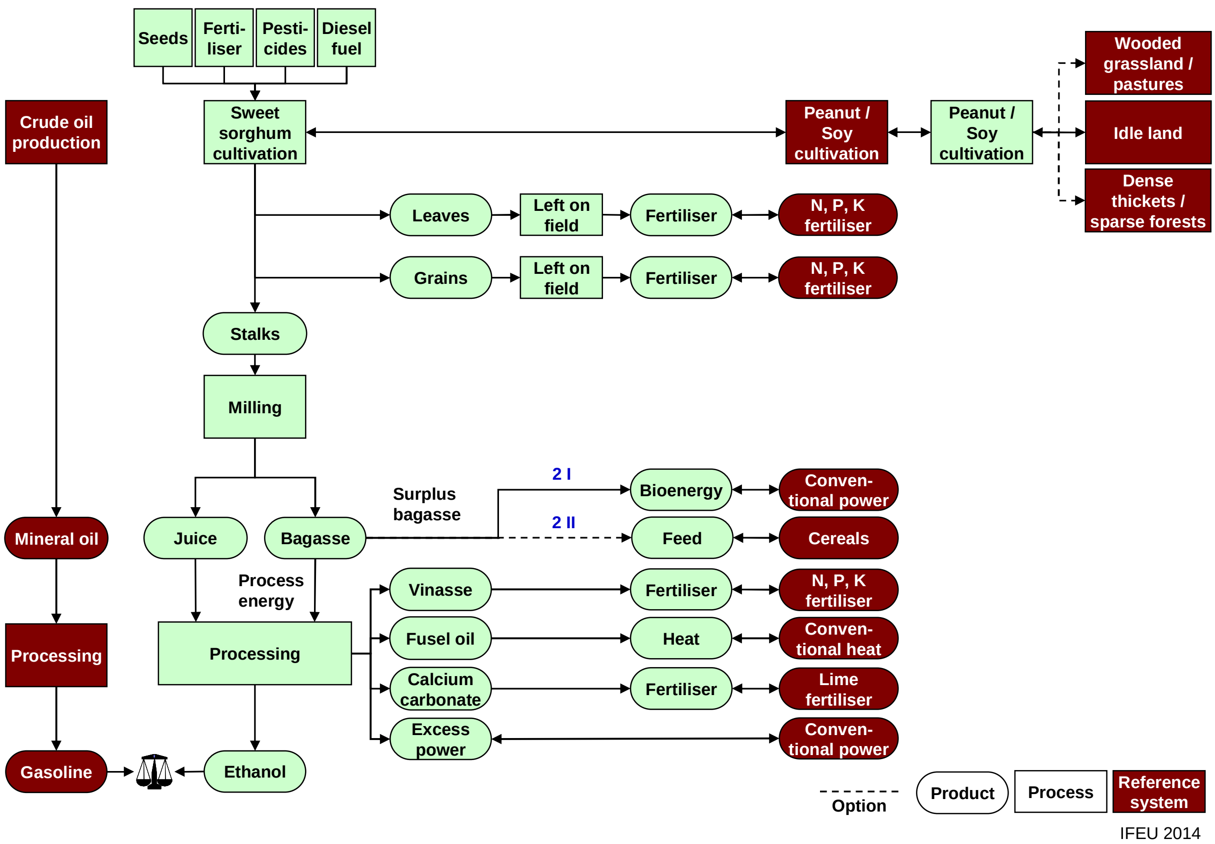

Fig. 3-2 Schematic overview of the cane fallow scenario 2015; numbers indicate scenario numbers (for a summary of assessed scenarios see Table 3-1).

3.1.2 Grain to food scenarios

In some regions sweet sorghum might not be grown as intermediate crop but replace grain sorghum cultivation. This has not been current practice so far but is conceivable in the future e.g. in semi-arid regions such as Southern Africa or North-eastern Mexico. We assume that sweet sorghum cultivars grown in those areas produce less grain than grain sorghum. Since the grains of grain sorghum are used in some countries for food and in others for feed, replacing grain sorghum with sweet sorghum might jeopardise food / feed security in those

areas (Fig. 3-3, “Initial situation”). To further guarantee food / feed security, differences in grain yield need to be balanced by cultivating additional grain sorghum. This requires an additional area which is e.g. in Southern Africa, transformed out of idle land that becomes free due to the intensification of existing land use or that is not used at present (see Fig. 3-3, “Grain to food”). For example: if the grain yield of sweet sorghum is 2.5 t / ha / year and of grain sorghum 3 t / ha / year, an additional area of 0.17 ha is needed to balance the difference of 0.5 t of grain yield (see Fig. 3-3). Some people argue that there are sweet sorghum hybrids which produce more grains than grain sorghum if cultivated on the same ground and under similar cultivation and climate conditions. However, this is far of today’s reality and there is still a lot of research and breeding work necessary to be able to use such hybrids commercially. Thus, as it cannot be foreseen whether those breeding efforts can be successful, especially since grain sorghum can also be further developed, this scenario is not considered in this report.

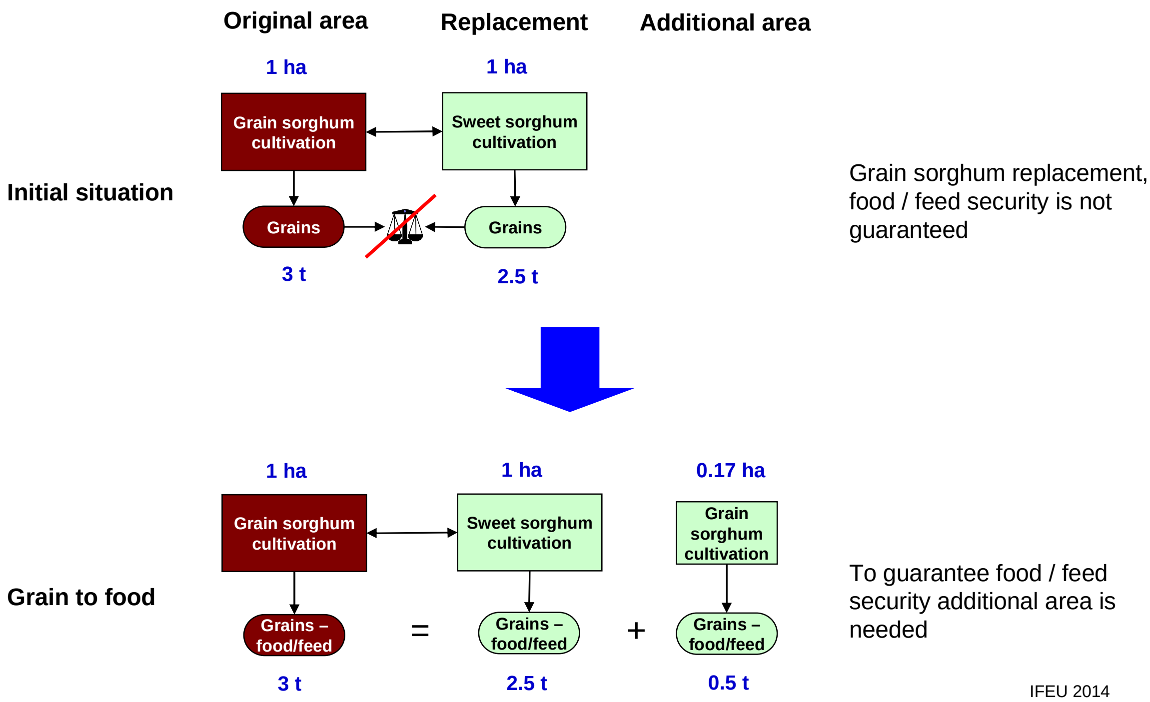

Fig. 3-3 Schematic overview of the grain to food scenario. Numbers are examples for illustration, see text.

An overview of the grain to food scenario is given in Fig. 3-4. As described above, in this scenario grains of sweet sorghum are used as food / feed to guarantee food / feed security. Leaves are separated during harvest and remain on the field, replacing mineral fertiliser (3 a). Since also the use of leaves as animal feed is promoted and might be an option in some regions, also this use was assessed. In this case, cereals are replaced as feed (3 b). Stalks are processed in a central ethanol production unit which correspond to the processing (including all by-products) described in the cane fallow scenario (see Fig. 3-1 and corresponding descriptions).

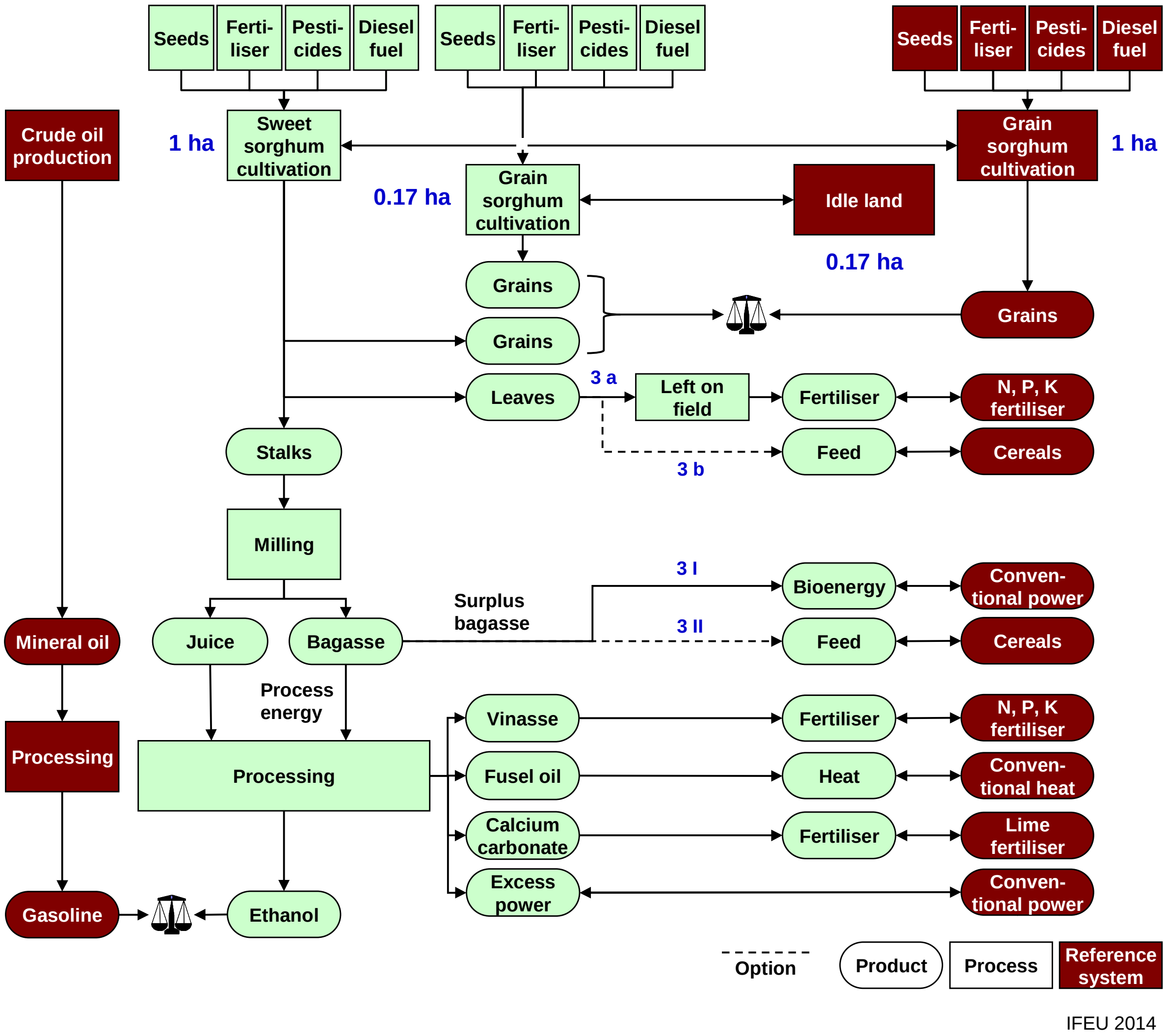

Fig. 3-4 Schematic overview of the grain to food scenario; numbers indicate scenario numbers (for a summary of assessed scenarios see Table 3-1). Large numbers are examples for illustration, see text.

Extra high yield scenarios

Besides semi-arid regions grain sorghum is also cultivated in regions such as Central-western Mexico with conditions preferable for an extra high yield. Three land use options are conceivable in those regions as described in the following paragraphs (Fig. 3-5).

Option I

This option is identical to the grain to food scenario described before (see Fig. 3-3 and Fig. 3-4 and corresponding explanations); however regions such as Central-western Mexico are characterised by preferable environmental conditions (e.g. high annual precipitation) which allow high grain yields of about 10 t per hectare per year. Since in those regions sweet sorghum yield might also be higher than in semi-arid regions grain sorghum is here replaced by high-yield sweet sorghum.

However, since there is no idle land in Central-western Mexico anymore, the additional area needs to be recruited in other regions where yields are expected to be lower. For example: if the grain yield of sweet sorghum is 7 t / ha / year and of grain sorghum 5 t / ha / year an additional area of 0.6 ha is needed to balance the difference of 3 t of grain yield if grain sorghum is cultivated (Fig. 3-5).

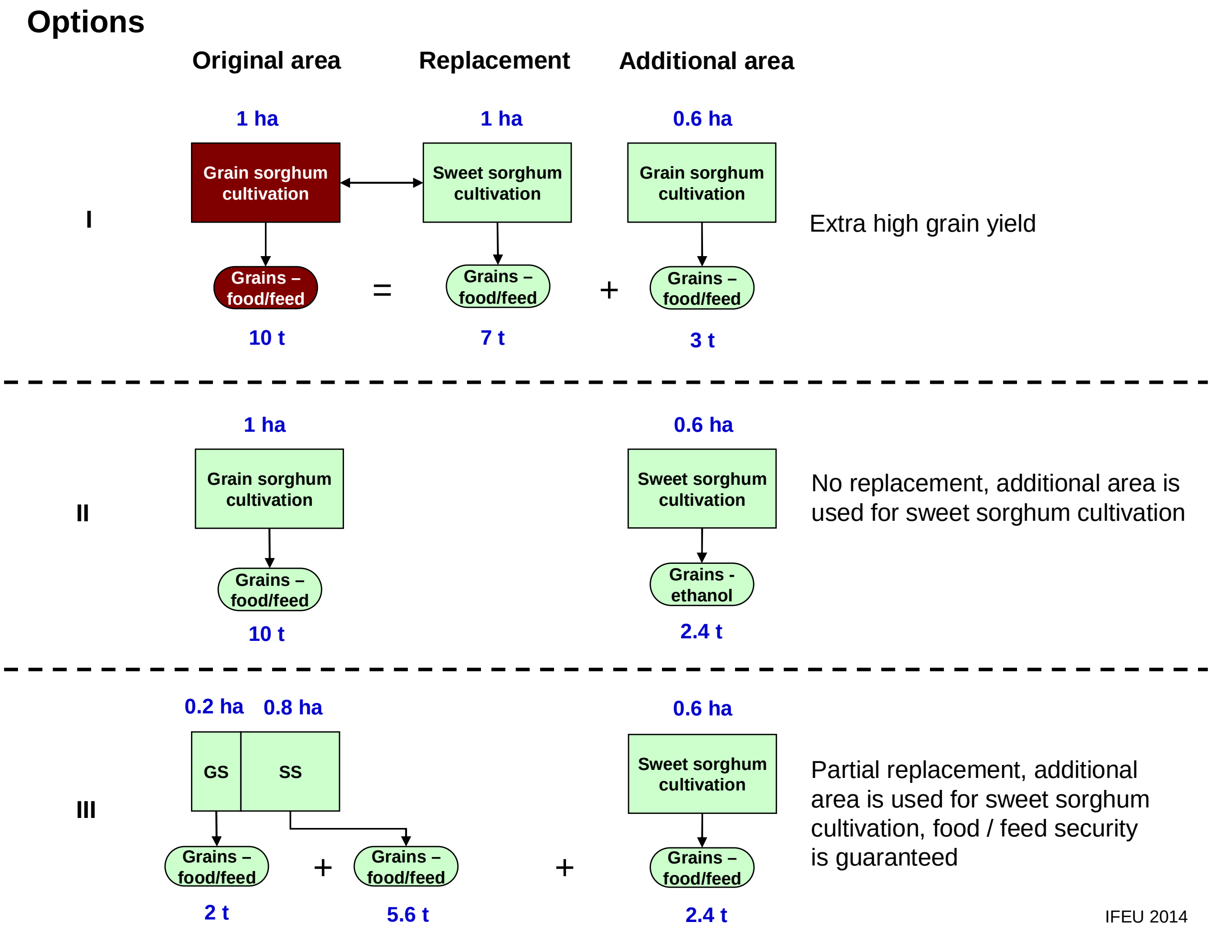

Fig. 3-5 Schematic overview of the two land use options of the extra high scenario. Blue numbers are examples for illustration, see text.

Option II

The same production area as in option I is assumed (Fig. 3-5, option II). Grain sorghum is not replaced and sweet sorghum is only grown on the additional area. Grains of grain sorghum are used as food / feed to guarantee food / feed security, whereas grains and juice of sweet sorghum are processed to ethanol in a central ethanol production unit, which corresponds to the processing described in the cane fallow scenario (see Fig. 3-1 and corresponding descriptions). For example: high grain yield of grain sorghum cultivation is about 10 t and grain yield of sweet sorghum cultivation on the additional area is about 2.4 t, if high case sweet sorghum cultivation as described in the grain to food scenario (grain yield: 4 t / ha / year is taken as a basis.

Option III

Another option, assuming again the same production area as in option I, contains a partial replacement of grain sorghum (Fig. 3-5, option III). Thus, sweet sorghum is cultivated on parts of the original grain sorghum cultivation area and on the additional area. The proportion was chosen in the way that grains out of sweet and grain sorghum cultivation still guarantee food / feed security. Thus, grains from grain and sweet sorghum are used as food or feed and the juice of sweet sorghum is processed in a central ethanol production unit which corresponds to the processing described in the cane fallow scenario 2015 (see Fig. 3-2 and corresponding descriptions). For example: if grain yield of sweet sorghum that is cultivated on the additional area is about 2.4 t, sweet sorghum can be grown on 0.8 ha (if high yield sweet sorghum as described in option I is taken as a basis) and grain sorghum on 0.2 ha (if extra high yield grain sorghum as described in option I is taken as a basis) of the original area to gain still a grain yield of 10 t in total.

3.1.3 Syrup production scenario

In some cases, infrastructure for biomass transportation to large centralised production units may be insufficient or not existent. Therefore, partially decentralised processing might be another option to grow and use sweet sorghum. Additionally, central ethanol producers often face the difficulty of a rather narrow production window where large amounts of sweet sorghum need to be processed. In such cases the syrup production from sweet sorghum juice might be an advantage. Since the syrup can be stored slightly longer than the sweet sorghum juice, the ethanol production facility can ease production and expand the production window. In this scenario the sweet sorghum stalks are milled at village level and the juice is further processed into syrup, which is transported to central ethanol units. The grains are separated before harvest and used as feed or food, replacing cereals. The leaves are used as feed, replacing also cereals. The bagasse which is obtained during stalk milling is used at village level for heat production that is needed to concentrate the juice into syrup. If there is surplus bagasse, it is used as animal feed, replacing cereals. The syrup is transported to a centralised ethanol production unit and it is treated just as the juice in the cane fallow scenario. For the central ethanol unit, external energy carriers need to be used since the bagasse from syrup production is left in the villages. External energy carriers can either be fossil energy carriers such as coal and oil or rice straw. An overview of the syrup scenario is given in Fig. 3-6.

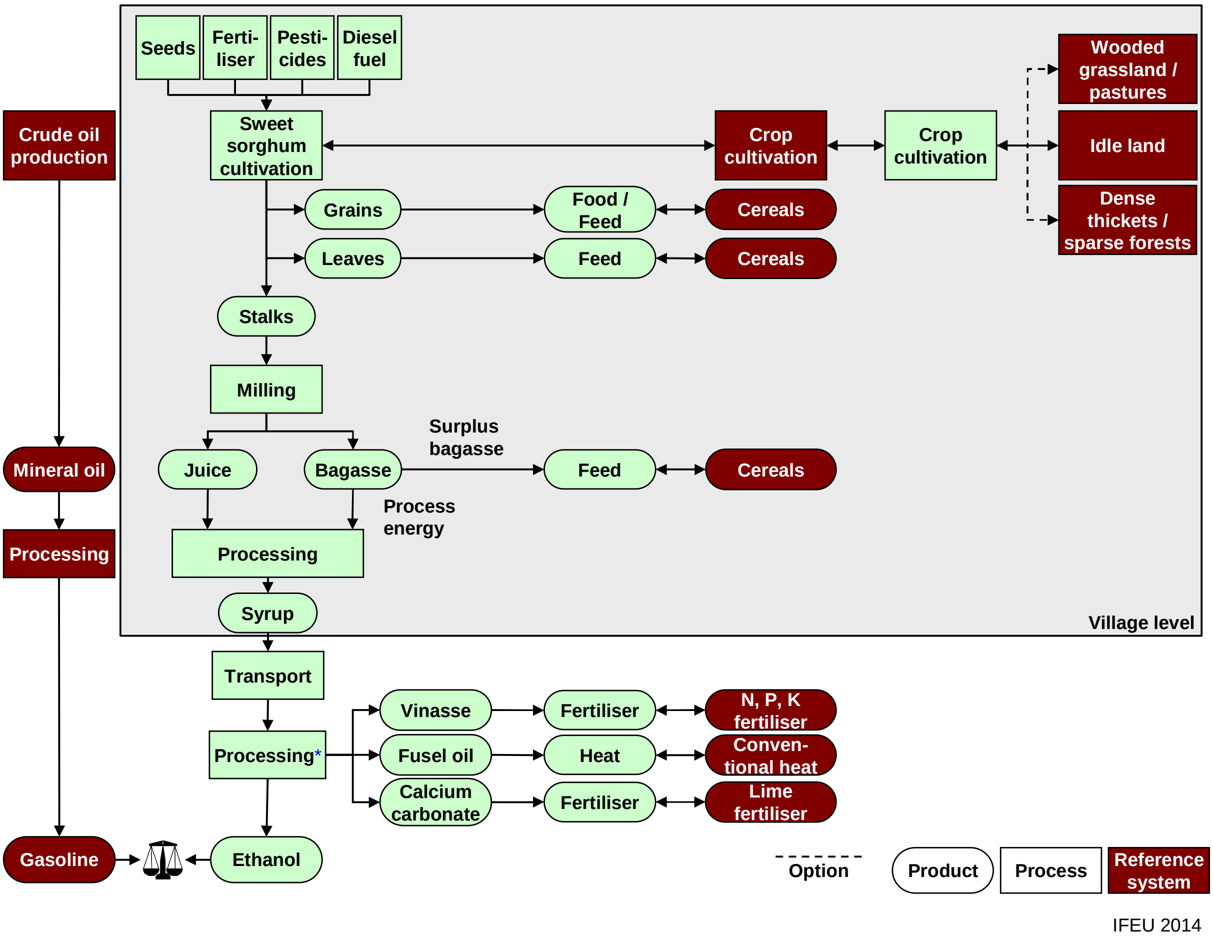

Fig. 3-6 Schematic overview of the syrup production scenario for a decentralised production; numbers indicate scenario numbers (for a summary of assessed scenarios see Table 3-1). *For the ethanol production unit in the syrup scenario external energy carriers are needed which can either be fossil energy carriers (4 I) or rice straw (4 II).

3.2 Biomass sorghum scenarios

Besides sweet sorghum, biomass sorghum is also considered in this project. Biomass sorghum is cultivated mainly to gain high biomass yields for biogas production.

The target systems are centralised, mechanised systems in industrialised settings. The focus lies on high biomass yields, whereas sugar content and grain yields are of less importance. Accordingly, the crop is used as a whole. Several options of energy production from biomass sorghum were assessed in order to give a bandwidth on different use options and to include both first and second generation technologies. The main focus was laid on biogas and biomethane production. Alternatively, the combustion of the biomass and the production of fuel is analysed with the focus on second generation technologies. Two options were assessed here: a) second generation ethanol produced from lignocellulose and b) biomass gasification with the synthesis of the gas into biofuel.

Biomass sorghum is mainly cultivated on land which becomes free due to the intensification of existing land use. Also idle land can be used to grow biomass sorghum. In the further course of the report all these land use options are referred to as “idle land”. Forest conversion is forbidden in all countries within Europe. Thus, no sensitivity analyses for alternative land use options were conducted.

The yield differences due to multiple climatic conditions in the temperate zone were assessed via sensitivity analyses.

3.2.1 Biogas and biomethane production

An overview of biogas and biomethane production is given in Fig. 3-7. For the biogas production, the biomass sorghum is chopped and ensilaged after harvest. Subsequently, the silage is fermented into biogas. Biomass sorghum can be fermented together with co-substrates such as manure or corn. However, the main objective is to assess the use of biomass sorghum from a certain area. Therefore, biomass sorghum digestion was assessed without any co-substrate. The biogas is either used for heat and power (5 I A) or only for power production (5 I B), replacing conventionally produced heat and power or power only, respectively.

Alternatively, the biogas can be further processed into biomethane and used

- for heat and power production, which replaces conventional heat and power (5 II A), or
- as a transport fuel replacing conventional gasoline (5 II B) and natural gas (5 II C), respectively.

In all processes, digestate is produced as a by-product. It is used as fertiliser replacing mineral fertilisers.

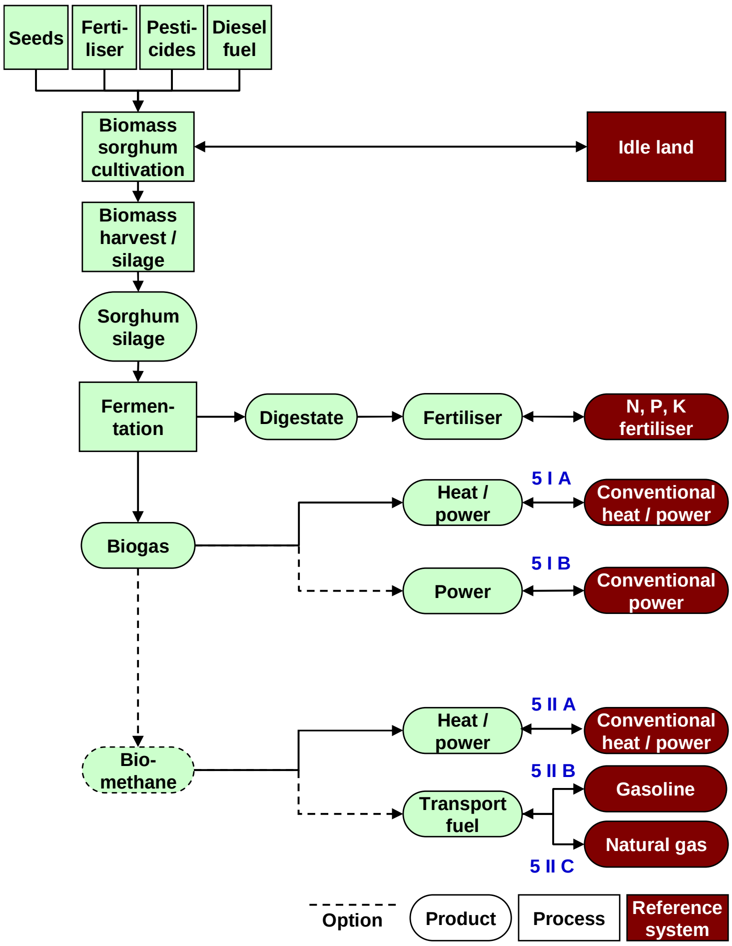

Fig. 3-7 Schematic overview of biogas production from biomass sorghum for the temperate climate; numbers indicate scenario numbers (for a summary of assessed scenarios see Table 3-2).

3.2.2 Second generation ethanol

An alternative to the conversion of biomass sorghum into biogas or biomethane is the production of ethanol from the lignocellulosic fraction of biomass sorghum (5 a). An overview of this scenario is given in Fig. 3-8. The biomass is harvested and pre-treated in order to render the cellulose and hemicellulose accessible for a subsequent hydrolysis step. After the hydrolysis of the cellulose and hemicellulose for breaking down the long chains into C6 sugars (e.g. glucose) and C5 sugars (e.g. xylose), the substrate is fermented. The ethanol is used as transport fuel, replacing conventional gasoline.

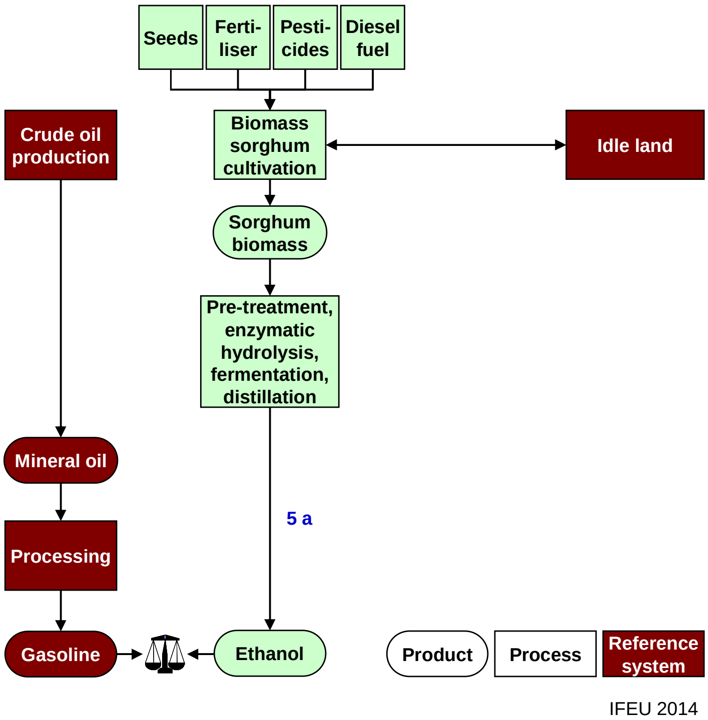

Fig. 3-8 Schematic overview of second generation ethanol production from biomass sorghum lignocellulose for the temperate climate; numbers indicate scenario numbers (for a summary of assessed scenarios see Table 3-2).

3.2.3 Direct combustion

Another option to convert biomass sorghum into energy is direct combustion (Fig. 3-9). Since this process requires comparatively dry biomass, direct combustion is especially feasible in the southern regions of Europe such as in the southern part of Spain, Italy or Greece. Here, the stalks remain on the field after harvest for drying. After collection, they can be directly used for combustion in the direct combustion process.

During the combustion process, heat and power are produced that replace conventionally produced heat and power (5 b I). Furthermore, either power or heat can be produced separately. Power production replaces conventional power (5 b II) while heat production either replaces natural gas (5 b III A) or fuel oil (5 b III B).

In all processes ash is produced as a by-product which has to be disposed in landfills.

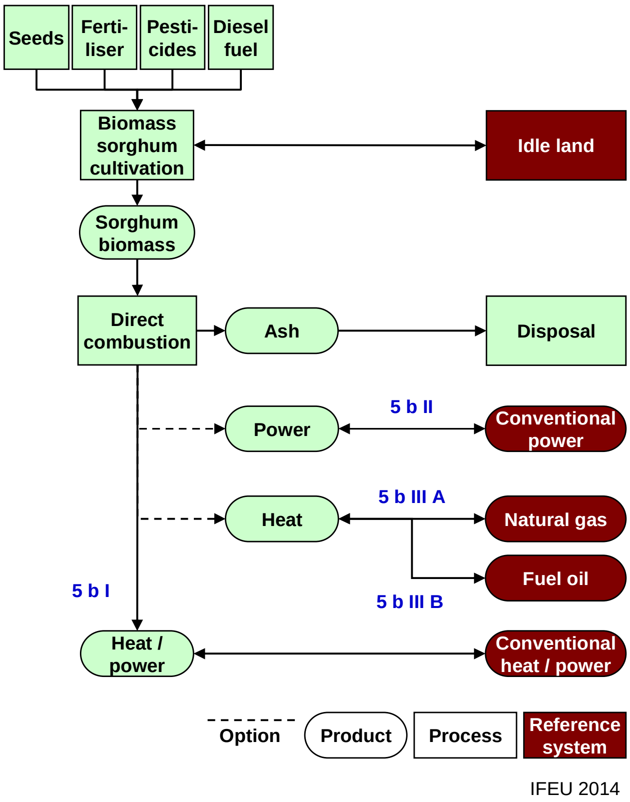

Fig. 3-9 Schematic overview of direct combustion of biomass sorghum for the temperate climate; numbers indicate scenario numbers (for a summary of assessed scenarios see Table 3-2).

3.2.4 Gasification

Besides direct combustion, dry biomass is also needed for biomass sorghum gasification (Fig. 3-10).

For biomass gasification, two options are analysed: first the direct gasification (5 c I), second the gasification with a prior pyrolysis of the biomass (5 c II).

For both options, the biomass needs to be comparatively dry as a precondition. For drying the biomass could either be longer left on the field or waste heat from the gasification process could be used as energy supply in the case of direct gasification. For the pyrolysis, however, external energy supply is needed. As a next step, the biomass or the pyrolysis oil is gasified into a synthesis gas. It is a mixture of hydrogen and carbon monoxide. After cleaning the gas, it is synthesised into the so-called BtL fuels. The standard synthesis is the Fischer-Tropsch synthesis where FT diesel is produced as a main product. If there is surplus bioenergy from the process, it is fed into the grid and replaces conventional energy.

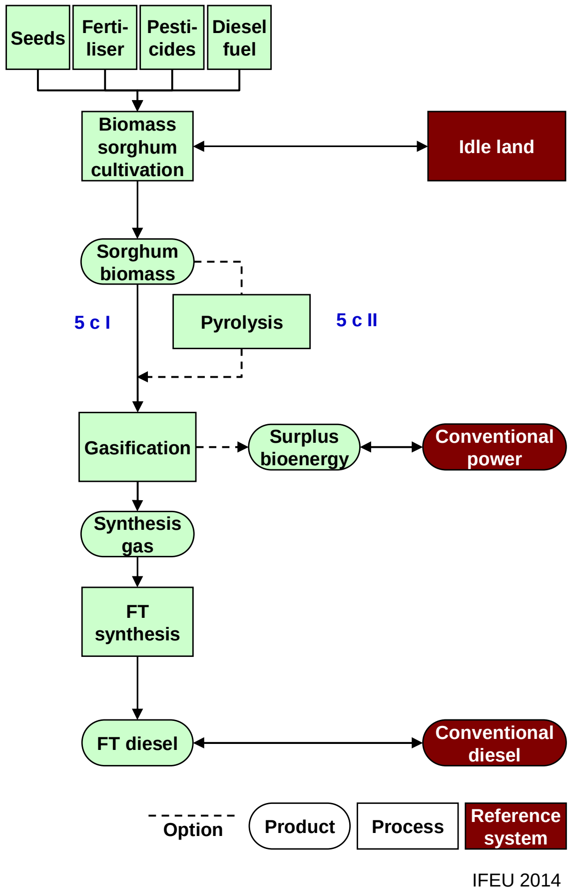

Fig. 3-10 Schematic overview of FT diesel production from biomass sorghum gasification for the temperate climate; numbers indicate scenario numbers (for a summary of assessed scenarios see Table 3-2).

3.3 Summary: scenario overview

Table 3-1 and Table 3-2 summarise all scenarios selected for the integrated assessment. Further sensitivity analyses were assessed in the preceding assessments of individual sustainability aspects (environmental and economic assessment as well as SWOT analysis, which includes social aspects /Reinhardt et al. 2014/, /Basavaraj, Parthasarathy Rao et al. 2014/, /Rutz & Janssen 2012a/).

Table 3-1 Overview of all sweet sorghum scenarios. Bold: Main scenarios.

	Sweet sorghum				
	Scenario	Option	Use of surplus bagasse	Option**	Use of leaves
1	**Cane fallow**	1 I	**Bioenergy**	1 I a	**Fertiliser (left on field)**
				1 I b	Together with bagasse
		1 II	Feed	1 II a	Fertiliser (left on field)
				1 II b	Together with bagasse
2	Cane fallow 2015	2 I	Bioenergy		Fertiliser (left on field)
		2 II	Feed		
3	**Grain to food**	3 I	**Bioenergy**	3 I a	**Fertiliser (left on field)**
				3 I b	Feed
		3 II	Feed	3 II a	Fertiliser (left on field)
				3 II b	Feed
4	**Syrup**	4 I*	**Feed**		**Feed**
		4 II*	Feed		

* For the ethanol production unit in the syrup scenario external energy carriers are needed which can either be fossil energy carriers (4 I) or bagasse from joint processes (4 II).

** The option numbers listed here are combinations of the alternative use pathways of surplus bagasse and of leaves.

Table 3-2 Overview of all biomass sorghum scenarios. Bold: Main scenario.

	Biomass sorghum				
	Conversion process	Option	Main product / method	Option*	Use of main product
5	**Biogas production**	5 I	**Biogas**	5 I A	**Heat and power**
				5 I B	Power
		5 II	Biomethane	5 II A	Heat and power
				5 II B	Transport fuel replacing gasoline
				5 II C	Transport fuel replacing natural gas
Alternatives					
5 a	2G ethanol production	5 a	Ethanol		Transport fuel
5 b	Direct combustion	5 b I	Heat & power		Heat and power
		5 b II	Power		Power
		5 b III	Heat	5 b III A	Natural gas
				5 b III B	Fuel oil
5 c	Gasification	5 c I	Direct gasification		Transport fuel
		5 c II	Gasification with prior pyrolysis		Transport fuel

* The option numbers listed here are combinations of the alternative methods of biomass conversion and of the use pathways of the main product.

4 Results

4.1 Summary: Environmental assessment

This subchapter summarises the results of the environmental assessment report /Reinhardt et al. 2014/. For further details please refer to the original report.

4.1.1 Global / regional environmental impacts

The results of the life cycle assessment can be summarised as follows:

I) General aspects of sweet sorghum and biogas production scenarios

The production and use of sweet and biomass sorghum as energy crops can cause a wide spectrum of potential impacts ranging from significant environmental benefits to distinctly detrimental environmental impacts compared to conventional energy carriers. In the cane fallow, grain to food and biogas production scenarios, results for the impact categories depletion of non-renewable energy resources and greenhouse effect are mostly advantageous compared to fossil equivalents, whereas the results for the other investigated impact categories (acidification, terrestrial and aquatic eutrophication, ozone depletion and human toxicity (in case of the sweet sorghum scenarios) cause additional environmental burdens (see Fig. 4-1 and Fig. 4-2). For the syrup production scenario, however, mostly disadvantageous results can be observed for all investigated impact categories. Thus, to improve bioethanol and biogas production in all scenarios, optimisation is necessary to reduce disadvantages and increase advantages.

Some life cycle stages are particularly relevant to numerous environmental impact categories and therefore represent starting points for optimising bioethanol production. Most important for sweet sorghum and biogas production scenarios are the following life cycle stages (see Fig. 4-3 and Fig. 4-4, respectively):

- Fertilisation (especially nitrogen) and field emissions (influenced by fertilisation)
- Credits given for the avoided expenses for the use of conventional energy carriers.
- For most sweet sorghum scenarios also the use of the by-products are important life cycle steps. For biogas production scenarios, digestate storage and digestate incorporation into the soil are decisive life cycle steps.

For both sweet sorghum (except for syrup production) and biogas production scenarios counts that **high biomass yields** can help to save greenhouse gases and fossil energy carriers. Thus, one way to optimise bioethanol production includes aiming at higher yields. Since all categories in all sweet sorghum and biogas production scenarios are strongly influenced by the amount of applied mineral fertilisers (especially N fertiliser), another optimisation potential is to **reduce the nutrient content** in the harvested biomass while still sustainable cultivation practices are guaranteed.

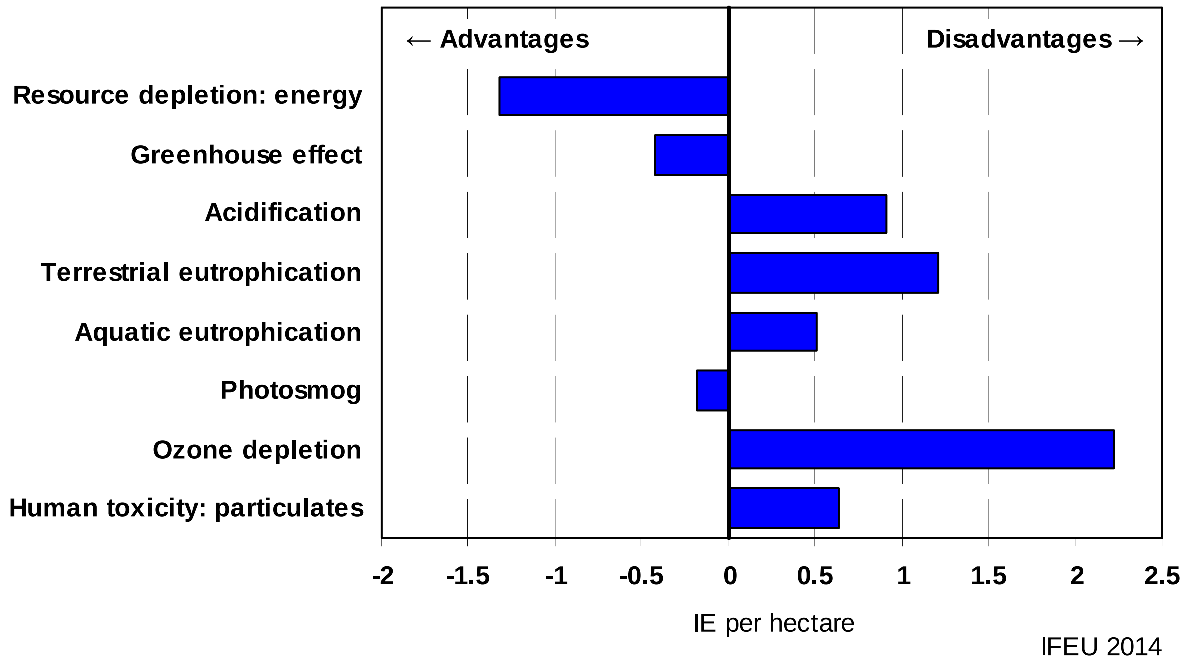

Fig. 4-1 Net results for sweet sorghum bioethanol production in the cane fallow scenario per hectare per year normalised to inhabitant equivalents (IE).

How to read the first bar in Fig. 4-1:

If bioethanol is produced from 1 ha sweet sorghum and replaces fossil gasoline, as much of non-renewable energy resources are saved as about 1.3 European inhabitants consume each year.

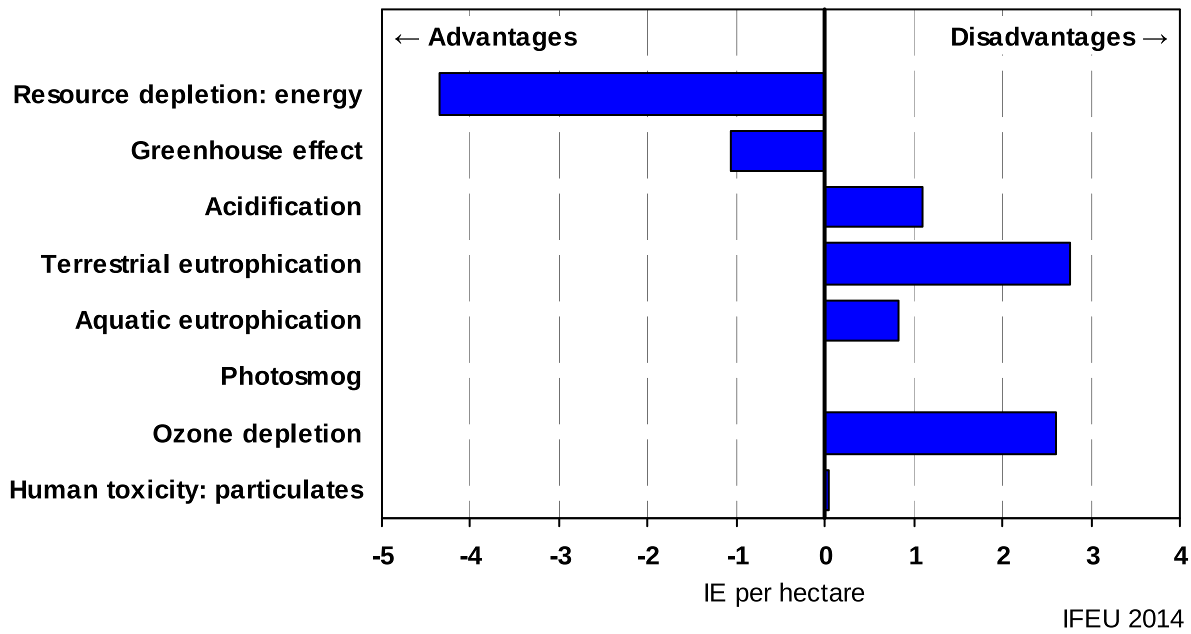

Fig. 4-2 Overview of net results for the biogas scenario per hectare per year normalised to inhabitant equivalents (IE). Results include all investigated environmental impact categories and are based on typical cultivation and conversion conditions.

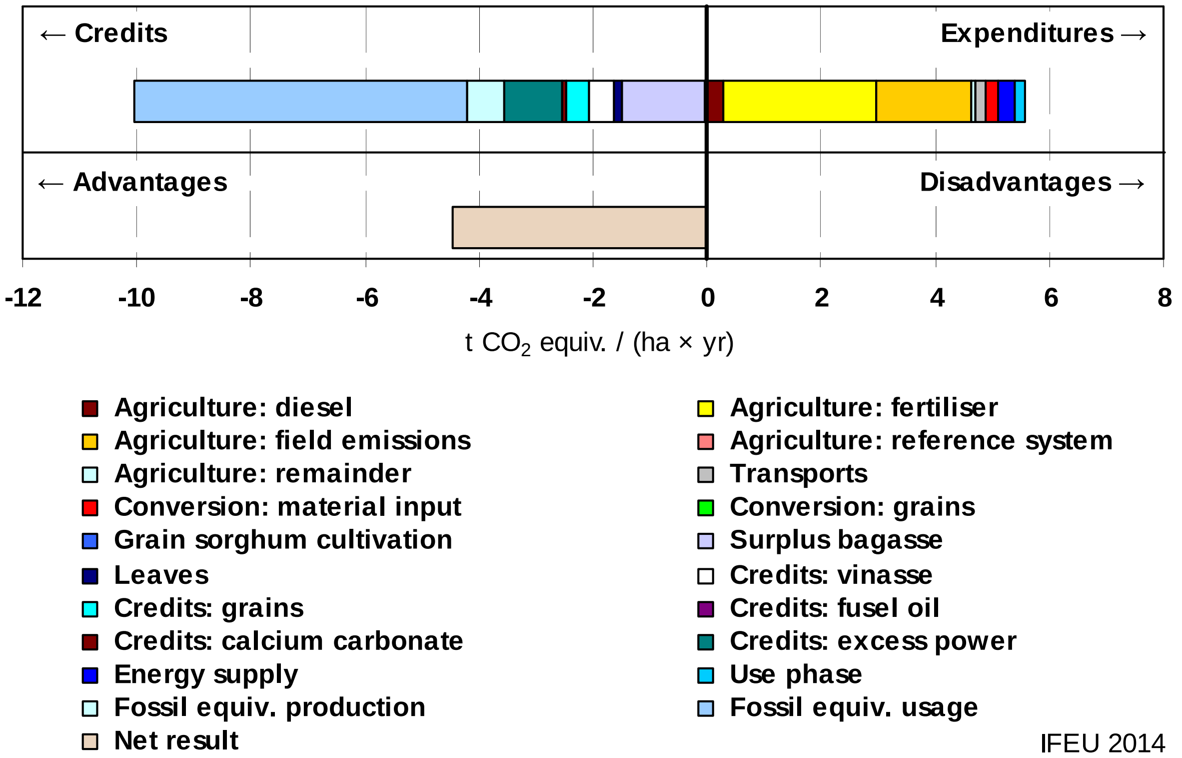

Fig. 4-3 Sweet sorghum to bioethanol: Contributions of individual life cycle steps (coloured sections) to the overall net result (light brown bar) of sweet sorghum ethanol production in the cane fallow scenario for the environmental impact category greenhouse effect. Results are based on typical cultivation and conversion conditions.

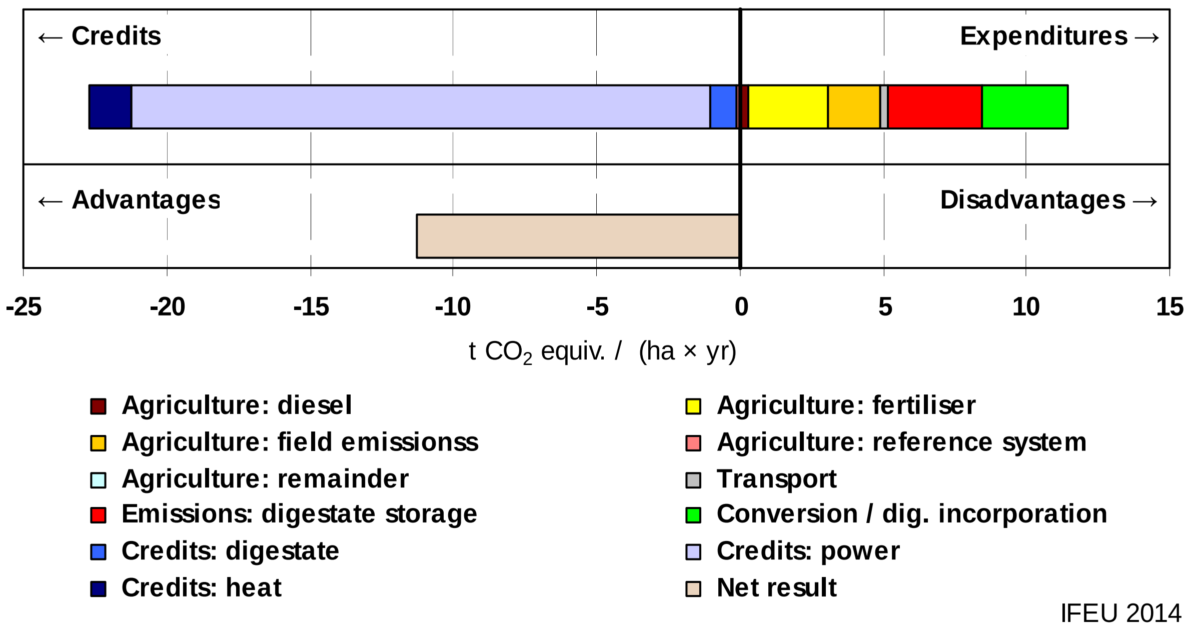

Fig. 4-4 Biomass sorghum to biogas: Contributions of individual life cycle steps (coloured sections) to the overall net result (light brown bar) of biogas production in the environmental impact category greenhouse effect. Results are based on typical cultivation and conversion conditions.

The **transportation distance** has only little influence on the outcome of the overall results in all investigated impact categories and for all sweet sorghum and biogas production scenarios.

Variability throughout the whole life cycles of energy sorghum cultivation and use lead to considerable bandwidths of possible environmental impacts (see Fig. 4-5 and Fig. 4-6 exemplarily for greenhouse effect). Thus, all life cycle steps, which have been identified as important for the overall result, should be optimised thoroughly.

II) Specific results for sweet sorghum scenarios

- The overall bandwidth of results and thus the **optimisation potential** throughout the whole life cycle is higher for the cane fallow than for the grain to food and the syrup production scenario (Fig. 4-5).
- Since the impact of the **conversion efficiency** on the overall results is relatively small for the sweet sorghum scenarios, the conversion efficiency holds only a small potential for optimising bioethanol production.
- The different use options of the **by-products** represent a huge optimisation potential in the sweet sorghum scenarios (mainly cane fallow). It is suggested that in future leaves and surplus bagasse should be used for bioenergy production while grains should be processed into ethanol.
- As long as there are no optimisation arrangements in the syrup production scenario to reduce especially the expenditures (e.g. by reducing the nutrient content of harvested biomass or by decreasing expenses from external energy carriers), aiming at higher yields should not be pursued in the first place.
- In the syrup production scenario **external energy carriers** are needed to convert sugar juice into ethanol since the bagasse has already been used to boil down the sugar juice into syrup. From a climate protection point of view a renewable energy resource out of residual products such as rice straw should be used for energy provision where possible.
- If **land cover** changes are involved, the outcome of the greenhouse gas balance depends largely on the carbon stocks of the area. If a piece of land is developed for sweet sorghum cultivation, a reduction of the carbon inventory of this area must be prevented.
- If sweet sorghum is cultivated in **traditional grain sorghum cultivation** regions, there is no big difference in the overall results if grain sorghum is totally or only partially replaced.

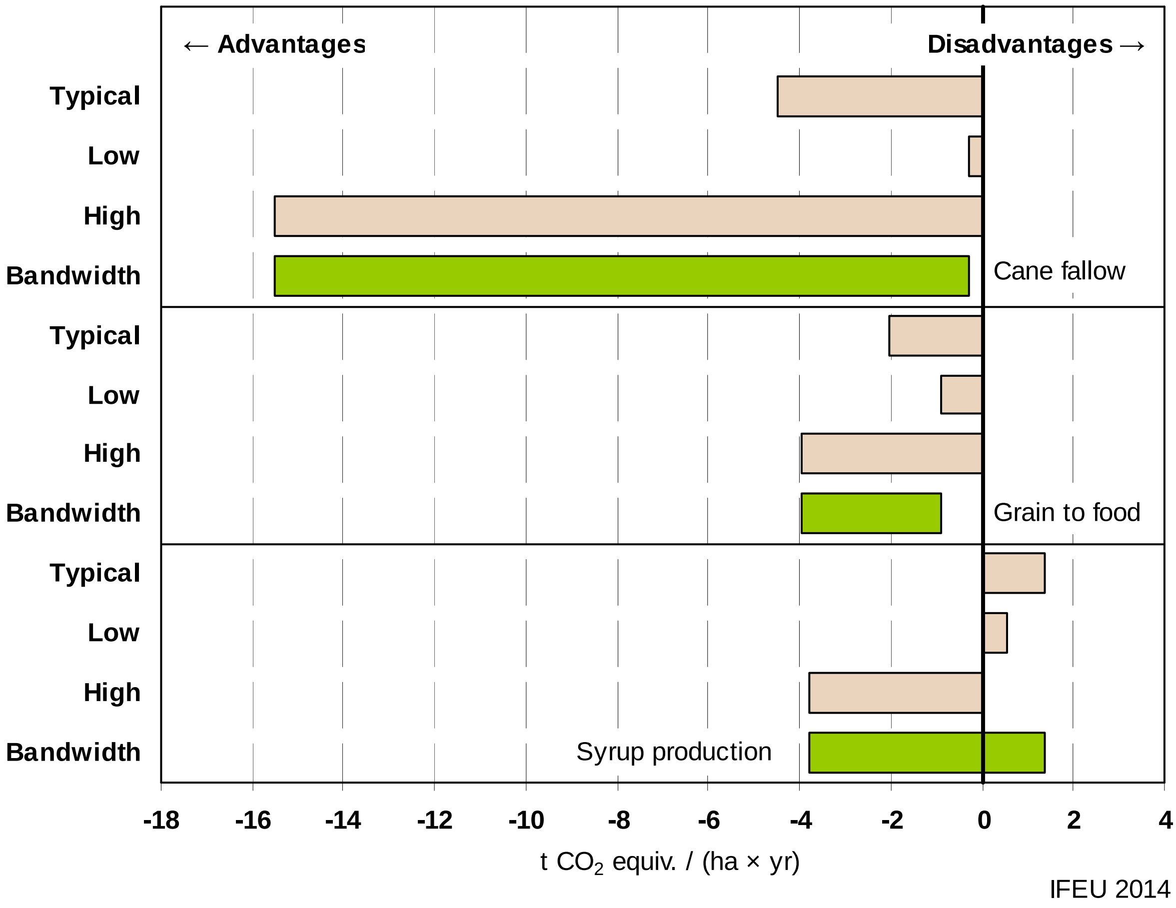

Fig. 4-5 Bandwidths of net results (typical, low, high) in the impact category greenhouse effect for the sweet sorghum scenarios cane fallow, grain to food and syrup production.

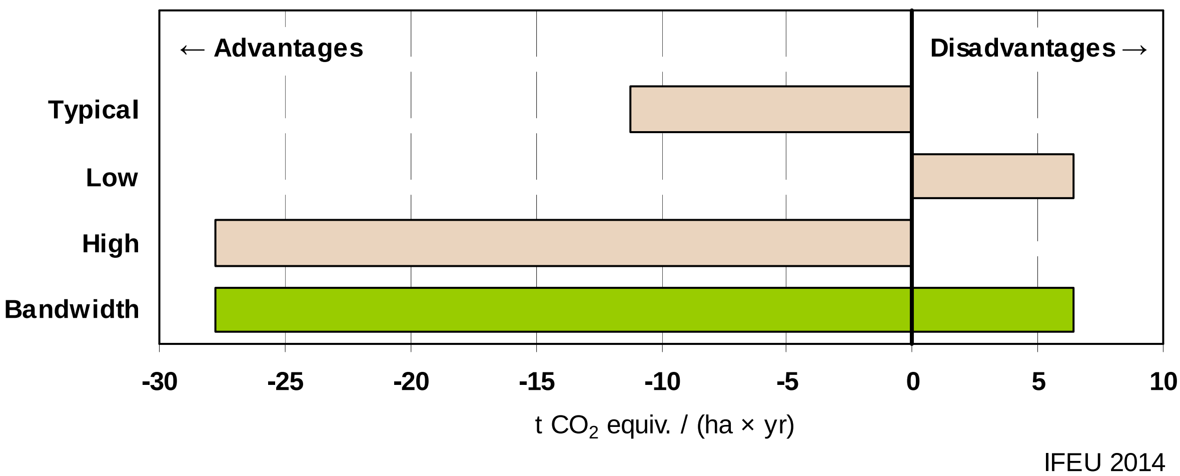

Fig. 4-6 Bandwidths of net results (typical, low, high) for biogas production for the impact category greenhouse effect.

III) Specific results for biomass sorghum scenarios

- To gain optimised conversion conditions for biogas production, **digestate storage tanks** should be covered and closed gas-tight. Additionally, the digestate should be incorporated into the soil within 1 hour.
- The more fossil carbon, emitted during the combustion of the fossil energy carrier, can be saved, the more advantageous is the outcome in most investigated impact categories. However, since the **energy carrier** can mostly not be influenced by the plant operator, the optimisation potential is relatively low.
- From an environmental perspective, **biogas and its use in a CHP** unit should be favoured over the other biogas use options, as far as biogas is produced under the same conditions as biomethane. In case biogas is further refined into **biomethane**, the use of biomethane in a combined heat and power unit should be favoured over a use as a natural gas substitute or fuel.
- A direct combustion of biomass sorghum and its use in a CHP unit performs best compared to all other use options in almost all categories. Also 2nd generation ethanol as a fuel cannot reach those levels of environmental advantages (see also /Reinhardt 2013/). Thus, from an environmental protection point of view the direct combustion should be favoured over the processing of biomass sorghum into biogas, but only if both heat and power can be produced and used (Fig. 4-7).

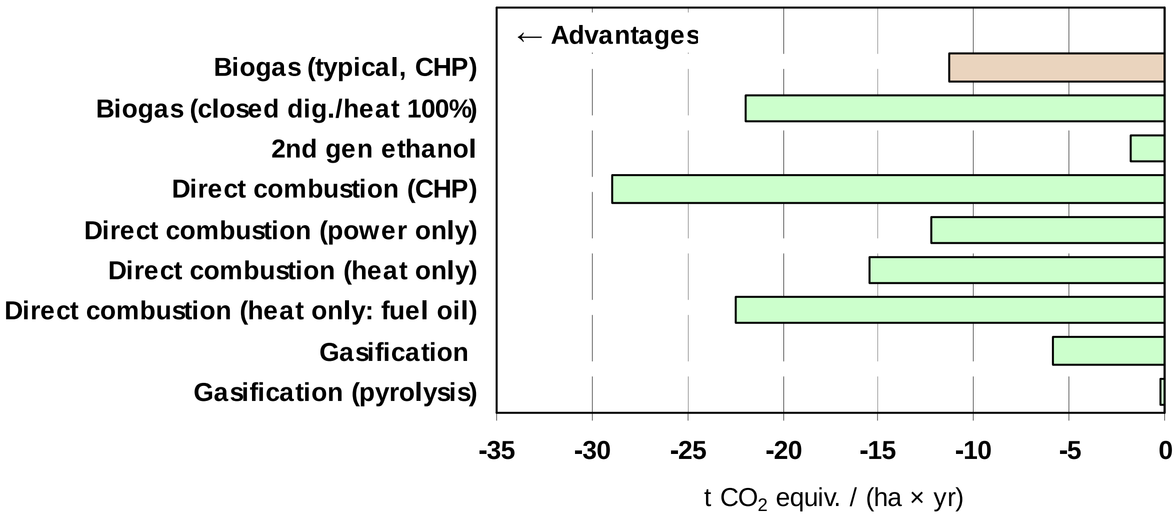

Fig. 4-7 Comparison of all investigated alternative scenarios on bioenergy production from biomass sorghum with biogas production for the environmental impact category greenhouse effect. Results are based on typical cultivation conditions. For detailed descriptions of alternative scenarios see subchapters 3.2.2 to 3.2.4.

4.1.2 Local environmental impacts

The methodological approach developed for the assessment of local environmental impacts in SWEETFUEL is labelled a Life Cycle - Environmental Impact Assessment (LC-EIA). The main idea of this approach is to apply major elements of EIA to a complete life cycle on a

generic basis /Rettenmaier et al. 2013/, /Kretschmer et al. 2012/. Due to this approach, it is possible to supplement the Life Cycle Assessment (LCA) by elements of EIA.

The main features of the LC-EIA approach can be summarised as follows (for further details see /Reinhardt et al. 2014/):

- The intensity and resolution of the environmental effects can be arranged between the classical project-related EIA and the strategic environmental assessment (SEA).
- The outcomes of the LC-EIA are fully compatible to LCA. Results of the LC-EIA give a new quality to the environmental impact category "land use" within the standardised methodology of LCA, by not only balancing the area needed for the application of a new technology but additionally giving information on the quality of the land use change and its possible impacts on local environmental factors.
- LC-EIA is broadening the scope of EIA (as well as SEA) in terms of assessment of a whole life cycle. The local approach of classical EIA usually prevents the inclusion of local environmental effects outside of certain administrative boundaries and thus possibly neglects important environmental effects, e.g. on biodiversity.
- Due to the generic, technology-focussed approach, different scenarios can be assessed and compared more quickly and easily.
- Therefore, an assessment of overall sustainability of a new technology can be carried out more easily and the optimisation of technology implementation by finding the best options or possibilities to remedy environmental effects can be done more effectively.
- Within the framework of SWEETFUEL and other related projects a comparable methodology for the analysis of biomass production and conversion can be used.

In the following, the main results of the LC-EIA are summarised. Subchapter 4.1.2.1 focuses on the main results regarding the cultivation and use of sweet sorghum while subchapter 4.1.2.2 presents the main results regarding the cultivation and use of biomass sorghum. An overall conclusion and a reflection of the LC-EIA results in the broad context of the SWEETFUEL project is given in chapter 5.

4.1.2.1 Sweet sorghum scenarios

Local environmental impacts are primarily dominated by 'biomass provision'. The other life cycle stages such as the provision of fertilisers or biomass conversion in ethanol facilities play only a subordinate role. Where sweet sorghum is cultivated on what was previously agricultural land, field crops are displaced. Assuming constant demand they must then be cultivated elsewhere. From an accounting perspective, for this purpose only land comes into question that has not been used agriculturally yet (see subchapter 3.1). These areas are referred to as the agricultural reference system. During the conversion and subsequent agricultural exploitation of these areas a variety of local environmental impacts occur, depending on the agricultural reference system. Sweet sorghum cultivation therefore indirectly leads to field conversion, which is thus also referred to as indirect land use change (iLUC).

- If the reference system is based on 'idle land', land use changes and land cultivation can negatively impact the soil (e.g. erosion, compaction, nutrient extraction), the hydrologic

balance (for example nutrient input, pesticide input, water demand), and flora, fauna and biodiversity (e.g. habitat destruction, soil compaction, pesticides) (Table 4-1).

- If the reference system is based on habitats with a comparatively high ecological value such as pastures or wooded areas, for example, the local impacts on flora, fauna and biodiversity can be much more serious, whereby additional negative impacts on local climate regulation and the landscape may occur.

From a purely qualitative perspective, the environmental impacts caused by sweet sorghum cultivation are very similar across all the investigated sweet sorghum scenarios (given the same reference system). In comparison, from a quantitative perspective, the local environmental impacts of the 'grain to food' scenario are substantially less grave than the local environmental impacts of the other two scenarios (‘cane fallow’ and ‘syrup production’). The reason for this is the considerably lower coverage of cultivated area by the indirect land use change: only approximately 0.2 ha of compensation area are required to cultivate 1 ha of sweet sorghum in the 'grain to food' scenario compared to 1 ha respectively in the 'cane fallow' and 'syrup production' scenarios.

Table 4-1 Risks associated with the cultivation of sweet sorghum compared to the reference system idle land

Type of risk	Affected environmental factors								
	Soil	Ground water	Surface water	Plants/ Biotopes	Animals	Climate/ Air	Land-scape	Human health and recrea-tion	Bio-diversity
Soil erosion	negative[1]/ neutral[2]		negative[1]/ neutral[2]						
Soil compaction	negative	negative		negative	negative				negative
Loss of soil organic matter	negative[1]/ neutral			negative[1]/ neutral[2]	negative[1]/ neutral[2]				negative[1]/ neutral[2]
Soil chemis-try / fertiliser	negative	negative							
Nutrient leaching		negative							
Eutrophi-cation	negative	negative	negative	negative	negative				negative
Water de-mand		negative		neutral	neutral				neutral
Weed con-trol / pesti-cides’		negative	negative	negative	negative				negative
Loss of landscape elements				neutral	neutral	neutral	neutral	neutral	neutral
Loss of habitat types				neutral/ negative	neutral/ negative				neutral/ negative
Loss of species				neutral/ negative	neutral/ negative				neutral/ negative

Foot notes:
1: Negative if sweet sorghum leaves are removed from field after harvest
2: Neutral if sweet sorghum leaves are left on the field after harvest

In order to fundamentally reduce the local environmental impacts of sweet sorghum cultivation, the following demand arises: care should be taken that the substitute areas for field crop cultivation (for example soya or peanuts in the 'cane fallow' scenario, grain sorghum in the 'grain to food' scenario and a variety of field crops in the 'syrup production' scenario) are of comparatively low ecological value. Under no circumstances sweet sorghum should be cultivated on areas classified as biodiversity hot spots, or on land that has a high carbon inventory, performs a special hydrologic balance function, or is characterised by a remarkable landscape.

As already noted briefly above, less grave local environmental impacts arise from other life cycle stages, for example from the use of agricultural materials and fuels or from transport infrastructure conditions:

- Local environmental impacts created by sweet sorghum cultivation's material and fuel demand at the material and fuel production location comprise, among other things, the water demand at that location, exhaust gas emissions, disposable wastes and wastewaters. Because only a small proportion of the overall production at the respective material and fuel production locations is used for sweet sorghum cultivation, the local environmental impacts occurring at those locations are only of subordinate relevance to the analysis of sweet sorghum cultivation.
- Because in all three scenarios sweet sorghum is cultivated on land previously used agriculturally, it can be assumed that sufficient road infrastructure already exists and can be utilised, so that no local environmental impacts occur in these areas. Depending on the location of the substitute area, where either soya / peanuts ('cane fallow'), grain sorghum ('grain to food) or possibly other field crops ('syrup scenario') are cultivated, additional road infrastructure must be built. Inasmuch as additional road infrastructure must be built, local environmental impacts on flora, fauna and biodiversity (habitat destruction and fragmentation), as well as on the soil and the hydrologic balance (surface sealing), must be anticipated.
- Due to the sugar content in the sweet sorghum stalks their storage tolerance is strongly limited which requires immediate processing. In contrast to the central ethanol plant ("cane fallow" and "grain to food" scenarios, respectively), in the syrup production scenario additional - however insignificant - impacts are expected caused by the need for syrup storage facilities. The construction of the small tanks to store the syrup produced at village level imposes negative impacts on soil, water, animals and plants due to clearing, sealing and compaction of soil. On the other hand, due to the concentration of the sweet sorghum juice in the scenario "syrup production", less biogenic material needs to be transported to the central ethanol plant compared to the scenarios "cane fallow" and "grain to food", which both encompass direct delivery of sweet sorghum stalks to the ethanol plant.
- Compared to conventional gasoline, the energy content of ethanol is significantly lower. The consequence of this is an overall increase in refuelling frequency and thus an increase in traffic volume, which is in turn associated with a greater noise nuisance and exhaust emissions that might lead to local environmental impacts on the soil, flora, fauna, air quality and human health.

Life cycle stage „biomass conversion“: With respect to the construction of the central bioethanol plant major impacts on soil, water, flora, fauna, biodiversity and landscape are to be expected due to clearing, sealing and material inputs needed. During operation of the bioethanol plant, environmental impacts on water, soil and air are to be expected due to the water demand and the wastewater discharge, the release of gases and fine dust as well as potential accidents. Since ethanol substitutes for conventionally produced gasoline, the sweet sorghum conversion can be compared to the conversion of crude oil in a crude oil refinery. Greater emissions of unfavourable gases as well as a higher risk of hazardous accidents due to the production of dangerous substances, the long-distance transportation of oil and the processing at high pressure and temperature conditions can be identified.

It can be summarised that, depending upon life cycle stages, different local environmental impacts develop that differ in their respective intensity – from less serious to extremely unfavourable.

4.1.2.2 Biomass sorghum scenarios

In Europe, conversion of forest areas is prohibited by law and conversion of grasslands only possible to a small degree. 'Idle land' is therefore adopted exclusively as the agricultural reference scenario for biomass sorghum cultivation.

As discussed above for the sweet sorghum scenarios, the local environmental impacts in the biomass sorghum scenarios are essentially determined by the cultivation of the biomass. These are cultivation-related impacts on the soil (for example erosion, compaction, nutrient extraction), the hydrologic balance (for example nutrient input, pesticide input, water demand) and flora, fauna and biodiversity (for example habitat destruction, soil compaction, pesticides). In addition, extra local environmental impacts, some quite serious, may occur, in particular with regard to soil quality and local biodiversity, as a result of increasing land pressure or monocultures. Developments in this direction are likely to occur in two cases:

- Increase in conversion efficiency with the consequence that larger facilities are built as a general rule. Since larger facilities require more charging material, more biomass sorghum must be cultivated. However, due to logistical and cost reasons this should occur within a given radius around the facility.
- Biomass sorghum is harvested comparatively wet for biogas and biomethane production, meaning that from an economical perspective the harvested crop displays only low transportability. For large, and therefore efficient, biogas facilities, large quantities of biomass sorghum must therefore be cultivated spatially close to the biogas facility.

In contrast to this, less grave local environmental impacts arise from other life cycle steps, in particular from the use of agricultural materials and fuels, as well as from transport infrastructure conditions:

- Among other things, the local environmental impacts ensuing from the production of materials and fuel comprise water demand, exhaust gas emissions, disposable wastes and wastewaters. However, these local environmental impacts are of only subordinate relevance.

- Because Europe represents the spatial context for biomass sorghum production, it is assumed that sufficiently well-developed transport infrastructure already exists, meaning that no local environmental impacts occur as a result of road building.
- If biogas or biomethane are produced from biomass sorghum, the relatively wet-harvested biomass is ensilaged in bunker silos and then transported as needed to the biogas facility. Relatively little infrastructure is associated with this process. The situation is different if second generation ethanol or synthetic fuels are produced, or biomass sorghum is exploited for energy production (scenarios: '2G ethanol', 'direct combustion' and 'gasification'). Here, biomass sorghum is harvested dry and large warehouses or stores are required. Their construction leads to environmental impacts on flora and fauna (habitat destruction), as well as on the soil and the hydrologic balance (soil compaction, sealing).
- If second generation ethanol is produced from biomass sorghum ('2G ethanol' scenario), the result is an overall increase in refuelling frequency and thus an increase in traffic volume as a result of the lower energy content of ethanol compared to conventional gasoline. This is associated with a greater noise nuisance and exhaust emissions that might lead to local environmental impacts on the soil, flora, fauna, air quality and human health.

In contrast to this, the 'biomass conversion' life cycle stage displays greater local environmental impacts: When building the various biomass sorghum exploitation technologies (a biogas and a 2G bioethanol facility, a CHP plant for direct combustion and a BtL facility for the gasification scenario), (serious) impacts, on the soil, the hydrologic balance, flora, fauna, biodiversity, and the landscape must be anticipated. As a result of the operation of these facilities also local environmental impacts on the soil, the hydrologic balance and air quality can be expected due to the water demand, the production of wastewater, waste disposal, exhaust gas and particulate emissions as well as the possibility of accidents.

Thus, it can be summarised that, depending upon life cycle phase, different local environmental impacts develop that differ in their respective intensity – from less serious to extremely unfavourable.

4.2 Summary: Economic assessment

This subchapter summarises the results of the economic assessment report /Basavaraj, Parthasarathy Rao et al. 2014/. For further details please refer to the original report.

Sweet sorghum (*Sorghum bicolor* (L.) Moench) is a promising energy crop due to its efficiency in both, high water use and nutrient uptake. Furthermore, the production of food, feed and fuel can be combined in one crop /Basavaraj et al. 2012a/, /Basavaraj et al. 2013a/. This is an important asset on the background of the currently increasing discussion on energy production and food security /Basavaraj et al. 2012b/, /Basavaraj et al. 2013b/, /Basavaraj et al. 2013c/.

Economic feasibility of ethanol from sweet sorghum is analysed for different scenarios namely ethanol from sweet sorghum stalk, stalk+ grain, grain for food, and syrup at village level to ethanol along with the impacts of by-products on use pathways. The analysis is carried out under varying values of key production and processing parameters by defining low, typical and high case values. The key parameters are varied within a given bandwidth under each case related to feedstock yield, sugar content in sweet sorghum stalk, processing efficiency and ethanol / power recovery etc.

4.2.1 Sweet sorghum to ethanol

Comparison of calculated net variable cost of ethanol (after allowing credits for by-products) generated from sweet sorghum stalk, stalk + grain, grain for food and syrup scenarios with market price of ethanol indicates that the ethanol output in the scenario from stalk + grain under typical and high case is competitive and a realistic scenario in 2020. Also, ethanol production under the grain to food scenario is competitive in all cases. Under the grain to food scenario the value of grain significantly reduces the cost of ethanol production after due credit is given to grain value. With the on-going debate on food vs. fuel, sweet sorghum as a feedstock is found to be economically promising when the grain is utilized for food and stalk to ethanol. Ethanol production using syrup route is most uneconomical while production from stalk is competitive under the high case scenario only. For the syrup route the extraction of syrup at village level is still not commercially viable adding to the overall cost of production. In all cases feedstock costs is the major contributor to the variable production costs of ethanol followed by processing costs, labour and other maintenance and operational costs. Interest costs etc. make up the rest (Fig. 4-8). Feedstock costs however, tend to come down as we move from low to high case due to higher yields under the high case compared to the low case.

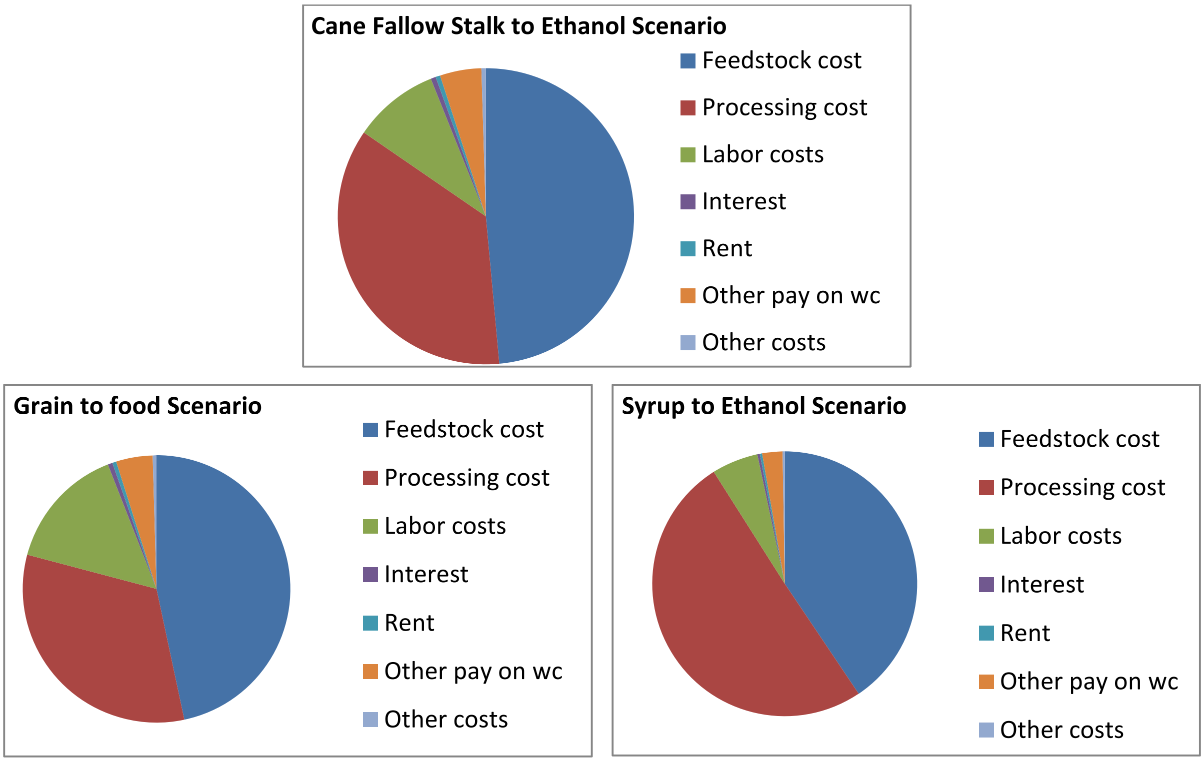

Fig. 4-8 Breakup of operational costs for selected sweet sorghum scenarios, typical case

Among the different by-products generated while producing ethanol from stalk only or stalk + grain scenarios, electricity generation from surplus bagasse, excess power and CaO account for a major share followed by vinasse, fusel oil etc. Under the stalk + grain scenario, spent grain additionally accounts for a small share in the total value of by-products. As we move from low to high case the share of electricity from surplus bagasse declines significantly as the available quantity of surplus bagasse declines. Under the food to grain scenario grain value makes a significant contribution to the by-product value followed by all others like in the stalk only scenario. The use of surplus bagasse as feed does not alter the economics significantly as the value of bagasse as feed is lower than when it is used to generate electricity. The contribution of leaves left on the field via fertilizer though important is small in all scenarios.

A fifteen year cash flow analysis shows that the NPV (net present value) of investment for the stalk only scenario is negative under the low and typical cases and positive under the high case. For the stalk + grain scenario, the NPV is positive under typical and high cases with an IRR (internal rates of return) ranging from 70 % to 148 %. Under the grain to food scenario the NPV's are positive with IRR ranging from 67 % in the typical case to 120 % in the high case. The IRRs are lower when surplus bagasse is used for feed. In the case of syrup to ethanol scenario the NPV's are negative in all cases.

Break-even price analysis (i.e., the price where the project NPV becomes zero) is calculated over all the cases by simulating ethanol price. The break-even price ranges from 0.86 € / litre under the low case to 0.44 € / litre under the high case for the stalk to ethanol scenario. The break even prices are much higher under the syrup to ethanol scenario ranging from 1.43 € / litre under low case to 0.63 € / litre under high case.

The cost of ethanol production for the 4 scenarios, i.e., stalk to ethanol, stalk + grain to ethanol, grain to food and syrup to ethanol is 649, 422, 58 and 850 in € per tonne respectively under the typical case.

4.2.2 Biomass sorghum to biogas and biomethane

Comparison of calculated total variable cost of biogas and bio methane generated from sorghum biomass shows it has a competitive edge over its counterpart in the market. The variable cost of producing biogas under the typical scenario is 0.09 € / kWh. It is the same for biomethane. The market price of power in 2012 is 0.2 € / kWh implying biogas from biomass sorghum is more competitive at current market prices.

A fifteen year cash flow analysis shows that the return on investment is positive under biomass sorghum to biogas scenarios. See Fig. 4-9 for a breakup of operational costs. The internal rate of return (IRR) for the three cases (low, typical and high) under this scenario is observed as 24 %, 44 % and 57 % respectively. The break-even price is consequently much higher than the actual cost of production.

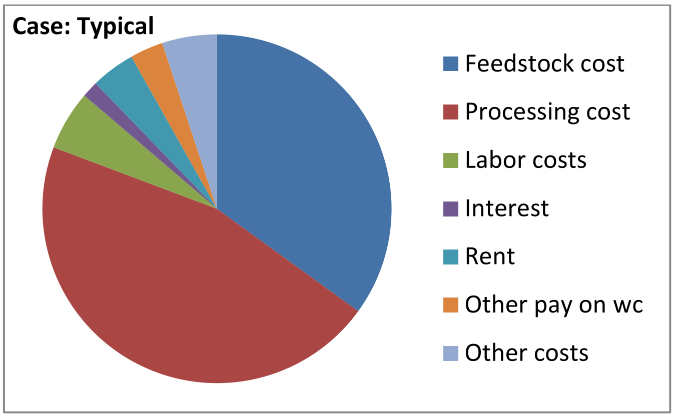

Fig. 4-9 Breakup of operational costs for biogas production from biomass sorghum, typical case

4.2.3 Biomass sorghum to alternate products

Biomass sorghum is also used to produce second generation ethanol although the technology for this is not fully developed. Price data for the enzyme used for processing of second generation ethanol is not readily available. Hence, based on information gathered from industry, price ranging from 200 € / tonne to 500 € / tonne was used. Variable cost analysis indicates that the cost of production of 2^{nd} generation ethanol is competitive at the lower end of the price of enzyme assumed for this study but at the higher end of enzyme price it is not competitive. Economic feasibility analysis also indicated non-viability of 2^{nd} generation ethanol under the assumed price band of the enzyme used for processing. For 2^{nd} generation ethanol to become viable and competitive the processing cost has to come down in the near future.

Biomass sorghum can also be used to produce FT diesel through direct gasification. Economic assessment found variable costs ranging from 1.28 to 1.22 € / litre as we move from

low to high case. The costs are higher under the gasification with prior pyrolysis. With world diesel prices at 0.85 € / litre the production FT diesel through gasification is not economical. Consequently the returns from the investment i.e., net present value is negative. The break even prices range from 1.2 to 1.5 € / litre as we move from high to low case.

4.3 Summary: SWOT analysis

This subchapter summarises the results of the SWOT analysis report /Rutz & Janssen 2012a/. For further details please refer to the original report.

The SWOT analysis collects and presents qualitative arguments for the cultivation of sweet and biomass sorghum for the conversion into ethanol as energy carrier. This is important as current discussions on the sustainability of biofuel value chains mainly focus on environmental and quantifiable aspects. The evaluation of socio-economic and qualitative impacts is generally more challenging /Rutz et al. 2011/, /Rutz & Janssen 2012b/, /Rutz & Janssen 2012c/ and thus, a SWOT analysis is a good method to present a comprehensive picture of these aspects.

The results of this SWOT analysis contain important information on social sustainability aspects but also several qualitative technical aspects of the sorghum to energy value chain. In total, more than 450 arguments have been collected and categorised into strengths, weaknesses, opportunities and threats. Thereby, a clear categorisation was not always possible and repetitions of similar arguments occur in some tables. General arguments given for and against sweet sorghum as energy crop are exemplarily shown in Table 4-2. The analysis can be further extended and completed with additional arguments. For this report, further aspect from a separate ethical assessment (see subchapter 4.3.1) and from /Rutz & Janssen 2014/ were taken into account. For the integrated sustainability assessment, arguments on social sustainability were grouped and categorised. This lead to the selection of seven most important social indicators and a qualitative rating for the assessed scenarios (see also Table 4-3).

The aim to show different qualitative aspects of sorghum cultivation and processing was successfully achieved. The SWOT analysis shows a very broad picture of many aspects associated with some key value chains of sorghum use for ethanol and other biofuels. This shall help stakeholders and decision makers building their own opinion about this topic.

Table 4-2 SWOT for sweet sorghum as energy crop. S: sorghum / energy sorghum, SS: sweet sorghum, BS: biomass sorghum

S1 **High genetic variability** of S provides good breeding opportunities in order to create new improved varieties.	W1 Specific **S varieties** for ethanol production are insufficient. Availability of commercial seeds of well-defined SS cultivars is limited.
S2 S is permitting **multiple breeding generations** per year due to a short growth cycle (3-4 months).	W2 **Specific traits** important for the ethanol industry (e.g. yield of juice, sugar, ligno-cellulose, grain, total biomass) still need to be defined for rapid genetic improvements. Thereby culture and conditions in growing countries and regions have to be taken into account.
S3 **Genetics of S are relatively well known**, genetic diversity is extensive and maintained.	W3 For the improvement of the S value chain, research on **new cultivars** is needed.
S4 S can grow in a **broad environmental range** from tropical to temperate regions. S could be a promising energy crop in both developed and developing countries as well as for small and large scale value chains.	W4 Genetic improvement and crop management of S for **sugar yield increases** has lagged behind other crops.
S5 S as energy crop can be cultivated and further processed at very **different scales**, thus smallholders, but also industry could benefit.	W5 Lack of better understanding of **interaction of genetic factors** (associated with sugar and juice potential) **with environmental factors.**
S6 S is characterized by **high water, radiation and nutrient use efficiency** in comparison to other energy crops (e.g. maize, sugarcane)	W6 There exists a knowledge gap on S **biotic and abiotic stress management** (e.g. weeds, insects, pathogens, soil, water).
S7 S is also suitable for **cultivation on marginal soils**, thus reducing potential LUC and ILUC impacts. However, yields are lower on marginal soils.	W7 Breeding efforts risk being mainly achieved for cultivars in **developed countries** (temperate to sub-tropical regions), but not for cultivars in developing countries (sub-tropical to tropical regions) due to the lack of resources.
S8 As an **efficient C4 plant**, S is one of the most efficient crops to convert atmospheric CO_2 into sugar and starch.	W8 **Intellectual Property** (IP) issues hinder free sharing of germplasm among S researchers.
S9 S is an **annual crop with a short growth cycle**, which can be easily integrated in many cultivation systems. In tropical climates the short growth cycle facilitates several harvests per year, creating opportunities for double cropping.	W9 The release of new industrially developed hybrids risks of being **not affordable for small-scale farmers**.
S10 In tropical and sub-tropical climates S is very suitable to be **integrated with sugarcane cultivation**. This leads to strong interest of sugarcane producers (e.g. in Argentina, Colombia) in S cultivation.	W10 Introduction of newly developed S cultivars may pose **risks for traditional cultivation** activities of the rural population.
S11 The **crop rotation cycle** of S is very flexible facilitating many different crop sequences.	W11 **S as energy crop is still relatively new** to many farmers. If not actively promoted there is a threat to be not sufficiently recognized by farmers.
S12 S is suitable for **intercropping**.	W12 Large scale S cultivation for industry needs **many hectares** that are difficult to be organized for a centralised industrial plant.
S13 S can be well adapted to **no-till planting**.	W13 Large-scale industrial S producers may not be interested in the production of both food and ethanol and thus may have a negative impact on (local) **food security**.
S14 **Full mechanization** of S cultivation is possible, thus, allowing for industrialized value chains.	W14 **Environmental risks** of large-scale S cultivation may include (depending on the cultivation system) negative impacts on biodiversity, soil erosion, soil compaction, soil fertility as well as surface and ground water resources. Monocultures have negative impacts on the landscape.
S15 **All aboveground parts of the plant (stalk, leafs, grain) are valuable products**. Since the potential use of S is very broad, it can be used for the production of food (sugar, grains), 1^{st} and 2^{nd} generation ethanol, biomaterials, electricity from bagasse combustion, thermochemical biofuels and products, biogas, feed and fodder.	W15 As SS is a new crop, wrong agricultural practices could lead to environmental problems (to high application of fertilizers and pesticides/herbicides, wrong irrigation, etc.)
S16 **Commercial technologies are available** for ethanol production from S.	W16 **Sugars of SS rapidly degrade**. The fresh stalks have to be processed quickly and cannot be stored for a long period.
S17 Bagasse and leaves can be used as **fuel** for process energy and power generation, thus creating a good GHG balance.	W17 Simple and cheap methods to **stabilise SS juice** have not yet been developed.
S18 Bagasse and leaves can be used as **fodder**, which is an opportunity to subsistence agriculture of small-scale farmers.	W18 **Harvesting technologies** for separate seed, stalk and leaf harvest are not yet mature. If no new harvesting technologies for separate seed, stalk and leaf harvest is developed, SS risks of being only sugar or starch crop and not both.

Table 4-2 (continued)

S19 Small-scale farmers could sell the juice or even the syrup or ethanol, while using grains and leaves as **food / fodder** for their own needs. Benefits for small-scale farmers include income generation. S20 S ethanol can contribute to **fossil energy and GHG savings** compared to conventional fuels. S21 Small-scale cultivation of S in rural communities can **benefit local energy supply** through production of ethanol in micro-distilleries and use of ethanol in adapted generators. S22 S can contribute to **food security** (grains). S23 S is a **climate-change ready crop**. S24 S can be cultivated as a **ratoon crop** (even two ratoon crops are feasible e.g. in the Philippines). S25 S is **photo sensitive** under certain conditions providing high biomass production. S26 **Harvest time** as well as **sugar** and **juice behaviour** is not the same for all genotypes.	W19 Technologies for **small-scale ethanol production** (micro-distilleries) are under development (pilot installations exist) and not yet commercially mature. W20 **Generators operating on ethanol** are available, but not very common. W21 S has **poor tolerance to cold** in temperate climate. W22 S has **short harvesting season**, usually 20-40 days, resulting in a limited feedstock supply period through the year. W23 Grains from some high biomass yielding natural S varieties have **too high tannin contents** for food or feed. W24 **Resources invested** in studying SS is very little compared to investments in e.g. maize or sugarcane.
O1 Generally, the global **demand for biofuels** is increasing (e.g. through mandates and targets), thus creating market opportunities for bioethanol from S. O2 Emergence of **new market opportunities for ethanol** fuel (e.g. aviation, heavy vehicles, households, rural electrification, military vehicles) may provide opportunities for S ethanol. O3 **Increasing global investment in the agricultural sector** may also support global S cultivation. O4 Technology development on ethanol production from sugars and ligno-cellulosic feedstock may **reduce production costs** and improve the efficiency of the S value chain. O5 GMO free S cultivation may be beneficial to access **European markets**. O6 **Regulations and standards** (quality and sustainability) for ethanol blending in gasoline exist in many countries, thus ensuring market opportunities for ethanol production. O7 **Variable sugar / ethanol production** of industrial sugar-bio refineries is generally possible and would be an opportunity to sell products to the best market prices. O8 **Diversification of crops** mitigates risks of the sugar industry associated to the reliance on only few crops. O9 The **trend of increasing fossil fuel prices** increases competitiveness of biofuels, including ethanol from S. O10 **Biofuel promoting policies** currently provide strong incentives for the development of the ethanol sector worldwide. O11 The introduction of **policies on climate change** mitigation and adaptation creates opportunities for the use of new energy crops such as S. O12 **Policies on rural development** which focus on the support of small-scale farmers may also support S production through e.g. out grower schemes.	T1 Current and future **prices for ethanol** from S could be too high when compared with other current and future products (fossil fuels, 2nd generation fuels), especially in subsidised fossil fuel markets. T2 Increasing **global prices of agricultural commodities** may also affect S and reduce the competitiveness of S ethanol. T3 Limited information is available on **cost of production of S ethanol** in comparison with other crops. T4 **Changes in macro-economic factors** (economic growth, unemployment, interest rates, exchange rates) may negatively affect the prospects of S ethanol. T5 Move towards alternative transport, including **electric vehicles**, may affect biofuel markets worldwide. T6 Most experience on ethanol production in tropical and subtropical regions was made with **sugarcane** and not with S. S risks of remaining a niche crop. T7 Limited market opportunities exist for value-added **co-products** of S compared to e.g. DDGS from corn based ethanol production. T8 Changes in **ethanol-promoting policies** as well as trade policies may negatively affect the prospects of S ethanol. T9 As long as no breakthrough in **international climate change policies** can be achieved, the support for and demand of biofuels will be limited. T10 Instable **political and economic framework conditions** in developing countries hinder fast promotion of S, especially in tropical and subtropical regions. T11 If **research on S is not financially supported** only limited improvements in S breeding and crop management can be achieved. Lack of financial support especially in developing countries for S research do not allow efficient and fast progress in breeding of new varieties which are adapted to specific climates in many developing countries. T12 Limited access to **capital markets** as bankers lack understanding of S potential as biofuel feedstock. T13 General **negative image of imported biofuels** into the EU may affect bioethanol production from S in other continents.

Table 4-2 (continued)

O13 Globally the importance for **increased research initiatives on agricultural commodities** is acknowledged. This may also lead to available funding to further improve S varieties. O14 **Support for biofuels from ligno-cellulosic feedstock** (e.g. through the "double counting" under the RED) may stimulate S as energy crop in temperate regions. O15 Global **sustainability certification schemes** for biofuels are established (e.g. Bonsucro, ISCC, RSB) facilitating proof of sustainability to positively influence public perception. O16 **Discussions on food-fuel conflicts** create opportunities for double purpose crops such as S (ethanol, grains). This may also improve public acceptance for ethanol from S. O17 **Increased droughts and increasing water scarcity** due to climate change favour water use efficient plants such as S. O18 For most crops **yield increases** are achieved over time due to cultivation improvements. This may facilitate competitiveness of S ethanol. O19 Alternative valorisation chains are under development for S based **hydrogen production**. O20 Alternative valorisation chains are under development for S based **biomaterials production** (building material, car industry). O21 Opportunities exist for breeding high yielding varieties of S for **staggered sowing and for post rainy season**. O22 Opportunities exist for valuation/quantification of **environmental benefits** to be incorporated with economic and sustainability perspectives. O23 **Incentives** to the industry focused on bioenergy, such as **land use or tax rates**. O24 **Alternative products** of SS can be potable alcohol (a high proof alcohol that is drinkable), syrup as a sweetener from the juice, and beer. Stalks can be alternatively used as cooking fuel. The farmer has generally different market choices.	T14 General increasing **resource competition** (land, water) for food, fuel, and fibres may lead to conflicts and reduce available land for S cultivation. T15 **Barriers to entry and licensing issues** in developing countries act as a threat for viability of ethanol production from centralized production systems. T16 **Lack of policy support** in the initial years will lead to industry exiting the business. T17 **Social instability** may affect land productivity in general. T18 **Lack of adequate infrastructure** may limit the S from field to refinery. T19 Large-scale industrial S production may lead to **land use conflicts** between industrial operators and small-scale farmers.

4.3.1 Complementary results: Ethical assessment

A separate assessment of potential ethical issues around the SWEETFUEL project has been conducted /Bursztyn 2014/. Its results were taken into account for the assessments of social sustainability partially supporting and partially extending results of the SWOT analysis.

The importance of ethics as an issue to be considered in research projects is growing. Ethics committees are now part of the institutional framework of the most important academic and non-academic research institutions. This means that together with the definition and implementation of projects their implications must be considered. Moreover researchers are facing the need to submit their activities to the evaluation and compliance to ethical and deontological regulations. Their responsibility now is not only reaching the results proposed in the pro-

jects, but also foreseeing the consequences and preventing negative side effects. There is an overall consensus among researchers that such considerations are necessary.

Ethical aspects have been assessed by a conclusive evaluation using questionnaires supported by case studies.

Several ethical issues were addressed in questionnaires to all members of the SWEETFUEL consortium about their perceptions and opinions about ethical implications of their activities. Please see the report for a detailed evaluation of these questionnaires /Bursztyn 2014/.

Apart from the interaction and survey on the views of the members of the consortium, two case studies were previously set by the SWEETFUEL project: India & Brazil. In both cases research was already being carried on previous to SWEETFUEL project and both had their own collection of material to be developed (Brazil – EMBRAPA, India – ICRISAT). Nevertheless their implications are rather different.

Some aspects raised during the visit to both institutions deserve to be highlighted:

- In India, sweet sorghum is very disseminated among farmers; in Brazil sorghum is a known crop, complementary to other crops (such as maize), but for feeding cattle (grains).
- In India, SS is produced in small scale by small holders; in Brazil, the target of EMBRAPA are large scale sugarcane farmers.
- In India the use of ethanol blended with gasoline is recent and still small. A governmental recommendation from 2012 set the rate of 5 %, but this rate is still to be reached.
- In Brazil ethanol (from sugarcane) is a national policy since the 1970s, both for the supply of ethanol vehicles and to blend with gasoline (25 %). Since 2013 all cars made in Brazil for the national market are flex-fuel.
- In India the “risks” of disruption for the peasants’ economy are to be considered, as they must manage trade-offs between self-consumption and market strategies; in Brazil this is not a risk, but rather an opportunity, as SS is meant to be complementary to sugarcane in large scale farms. But there are risks associated to the increase in the production of sugarcane in Brazil, as is the case of deforestation. One can consider that the introduction of sweet sorghum may slow the pressure on forests.
- Both ICRISAT and EMBRAPA don’t aim at making profit from the outcomes of their research.

4.4 Integrated sustainability assessment

The integrated assessment of sustainability is a structured way of comparing several sustainability aspects into a holistic picture with the aim to provide decision support to politicians and stakeholders. This methodology has been successfully applied in several projects before /Reinhardt et al. 2012/, /Kretschmer et al. 2013a/, /Rettenmaier et al. 2014/. The integrated assessment of sustainability consists of the following steps:

- Selection of relevant scenarios and indicators (subchapter 4.4.1)
- Addition of suitable additional indicators such as CO_2-avoidance costs (subchapter 4.4.2)
- Compilation of data (subchapter 4.4.3)
- Categorisation of quantitative data (subchapter 4.4.4)
- Analysis of comparisons of energy sorghum scenarios to a conventional provision of equivalent products (subchapter 4.4.5)
- Analysis of comparisons of energy sorghum scenarios to each other (subchapter 4.4.6)

4.4.1 Selection of indicators

Various aspects of environmental, economic and social sustainability have been studied in individual assessments, which form the basis of this integrated sustainability assessment. These are the environmental and economic assessment as well as SWOT analysis, which includes social aspects /Reinhardt et al. 2014/, /Basavaraj, Parthasarathy Rao et al. 2014/, /Rutz & Janssen 2012a/. Additionally, technological aspects are taken into account originating from /Braconnier et al. 2013/. The impact of the SWEETFUEL life cycles and the conventional reference systems on all these aspects is quantified or qualitatively rated using various indicators. The suitability and scientific validity of the indicators has been verified in the individual assessments. In the integrated sustainability assessment, those indicators were selected that provide the most relevant information for decisions between the assessed options. Partially, related specific (qualitative) indicators were merged into a more general indicator if values showed similar patterns. For an overview and a short description of the indicators see Table 4-3.

Table 4-3 Overview of sustainability indicators

Impact category	Short description
Technology	
Cultivation experience	Experience of farmers with optimal timing, fertilisation etc.
Harvest technology (maturity)	Technical maturity / availability of adapted harvesters.
Conversion technology (maturity)	Technical maturity of fuel / energy production processes.
GMO plant use	Potential risks through use of genetically modified plants (++ indicates: not used).
Breeding potential	Potential to improve plant properties by conventional breeding.
Storage facilities	Need for construction of short-term and seasonal storage facilities for biomass.
Environment	
Resource depletion: energy	Depletion of non-renewable energy resources, i.e. fossil fuels such as mineral oil, natural gas, coal and uranium ore.
Climate change	Global warming 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.
Acidification	Shift of the acid / base equilibrium in soils by acidifying gases like sulphur dioxide, nitrogen oxides and ammonia (keyword 'acid rain').
Aquatic eutrophication	Input of nutrients into surface water (marine and freshwater) directly or via input into soils and gaseous emissions. E.g. nitrogen and phosphorous species contribute to this (keyword 'algal bloom').
Photosmog	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').
Human toxicity (particulate matter emissions)	Damage to human health due to air pollutants such as fine, primary particles and secondary particles (mainly from NO_X, NH_3 and SO_2, keyword 'winter smog' or 'London smog').
(Stratospheric) Ozone depletion	Loss of the protective ozone layer in the stratosphere by certain gases such as CFCs or nitrous oxide (keyword 'ozone hole').
Direct land use	Occupation of agricultural land by production of crops.
Net land use	Direct land use minus agricultural land that may not be cultivated anymore elsewhere because co-products of the assessed process like feed replace dedicated feed crops.
Water	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.

Table 4-3 (continued)

Impact category	Short description
Economy	
Total capital investment	Sum of invested capital for the biorefinery facility including utilities.
NPV	The net present value is the sum of expenses and future returns discounted at a rate of 10 % per year (in this case).
Profit	Profits for the conversion plant operator. Negative values indicate support that would be necessary to reach a break-even (no profit / no loss) based on prices indicated in /Basavaraj, Parthasarathy Rao et al. 2014/.
IRR (Internal Rate of Return)	The Internal Rate of Return is defined as the discount rate at which the NPV is just equal to zero. The higher the IRR, the more favourable the investment project appears.
CO_2 avoidance costs	Losses (or profits if indicator result is negative) per unit of avoided greenhouse gas emissions. This indicator is not defined if no greenhouse gas emissions are avoided.
Energy resource savings costs	Losses per unit of saved non-renewable energy resources (analogous to CO_2 avoidance costs).
Society	
Food security	Influence on local food security via food or feed production.
Income for farmers / local community	Income in the agricultural sector through (by-) product sales.
Access to land, land rights	Availability of land and legal / contractual basis of land use.
Access to jobs	Job creation / conservation, here mostly related to biorefineries.
Acceptance by farmers	Perception and preferences among farmers.
Acceptance by general society	Perception and preferences in the general public. This also includes aspects like expected national revenues.
Innovation	Innovation by development and implementation of new processes.

4.4.2 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.

CO_2 avoidance costs[1] are based on greenhouse gas emission savings and the price support per tonne of biomass that is needed to make an investment attractive (i.e. an internal rate of return of 10 % is reached). As another example, energy resource savings costs are derived in the same way from the indicator "Resource savings: energy" (energy demand from non-renewable resources).

1 The name of this indicator is applied here because of its common use. Nevertheless, greenhouse gases besides CO_2 are taken into account as well for its calculation.

Such indicators can give additional information but may also lead to wrong conclusions if they are not interpreted carefully (see subchapter 2.2.3 for details). In this case, it is very important that both avoidance / savings costs indicators can only indicate the efficiency of reaching a certain target (e.g.: How expensive is it to avoid greenhouse gas emissions under certain conditions?) but not the efficacy of reaching it (e.g.: How certain is that such emissions are avoided at all?). For political decisions, however, the latter question should be more important.

4.4.3 Overview of data

Available data for all scenarios and indicators under typical conditions is shown in Table 4-4 and Table 4-5. N/D indicates that there is no data on a particular aspect. In contrast, N/A indicates that the indicator is not applicable under those particular conditions. This is for example the case for CO_2 avoidance costs if there are no greenhouse gas emission savings or for the IRR if there is no overall profit. Further data for the sub-scenarios “low” and “high” is shown in Table 7-2 in the annex.

Table 4-4 Overview of selected indicators and results for sweet sorghum scenarios in comparison to conventional systems under typical conditions. GMO: genetically modified organism, NPV: net present value, IRR: internal rate of return, N/A: not applicable, N/D: no data, *: see text (subchapter 4.4.5).

			Sweet sorghum scenarios											
			Cane fallow	Cane fallow (Leaves to energy)	Cane fallow (Surplus bagasse to feed)	Cane fallow (Max. feed)	Cane fallow 2015 (no grain use)	Cane fallow (land use change)	Grain to food	Grain to food (Leaves to feed)	Grain to food (Surplus bagasse to feed)	Grain to food (Max. feed)	Syrup production	Syrup production (fuel: rice straw)
		Grain use	Ethanol	Ethanol	Ethanol	Ethanol	**Fertil.**	Ethanol	**Food**	Food	Food	Food	Food	Food
		Surplus bagasse use	Energy	Energy	**Feed**	Feed	Energy	Energy	Energy	Energy	**Feed**	**Feed**	Feed	Feed
		Leaves use	Fertil.	**Energy**	Fertil.	**Feed**	Fertil.	Fertil.	Fertil.	**Feed**	Fertil.	**Feed**	Feed	Feed
Area	**Indicator**	**Unit**												
Technology	Cultivation experience	–	-	-	-	-	-	-	-	-	-	-	-	-
	Harvest technol. (maturity)	–	-	-	-	-	+	-	-	-	-	-	N/A	N/A
	Conversion technol. (maturity)	–	+	+	+	+	+	+	+	+	+	+	+	+
	GMO plant use	–	++	++	++	++	++	++	++	++	++	++	++	++
	Breeding potential	–	+	+	+	+	+	+	+	+	+	+	+	+
	Storage facilities	–	-	- -	-	- -	0	-	-	- -	-	- -	N/A	N/A
Environment	Resource depletion: energy	GJ / (ha × yr)	-109	-163	-84	-88	-84	-109	-67	-70	-36	-39	8	-30
	Climate change	t CO_2 eq. / (ha × yr)	-4.5	-7.2	-3.8	-4.4	-2.6	3.2	-2.0	-2.5	-1.2	-1.6	1.4	-1.2
	Acidification	kg SO_2 eq. / (ha × yr)	44	43	36	32	39	44	30	27	19	16	22	30
	Terrestrial eutrophication	kg PO_4 eq. / (ha × yr)	7.1	7.0	6.0	5.3	6.1	7.1	4.6	4.0	3.2	2.7	3.1	3.4
	Aquatic eutrophication	kg PO_4 eq. / (ha × yr)	19	20	18	18	16	19	12	12	11	11	19	19
	Photosmog	kg ethene eq. / (ha × yr)	-3.6	-4.0	-3.5	-3.6	-1.8	-3.6	-1.3	-1.3	-1.1	-1.2	-0.7	-1.5
	Human toxicity	kg PM10 eq. / (ha × yr)	25	21	23	21	22	25	16	14	13	11	18	23
	Ozone depletion	g R11 eq. / (ha × yr)	154	169	118	100	144	154	111	98	65	52	44	59
	Direct land use	ha × yr / (ha × yr)	1	1	1	1	1	1	1	1	1	1	1	1
	Net land use	net ha × yr / (ha × yr)	0.9	0.9	-0.1	N/D	1.0	0.9	0.2	N/D	-1.1	N/D	N/D	N/D
	Water	–	-	-	-	-	-	- -	0 *	0 *	0 *	0 *	-	-
	Soil	–	-	- -	-	-	-	- -	0 *	0 *	0 *	0 *	- -	- -
	Fauna	–	-	-	-	-	-	- -	0 *	0 *	0 *	0 *	-	-
	Flora	–	- -	- -	- -	- -	- -	- -	- *	- *	- *	- *	- -	- -
	Landscape	–	-	-	-	-	-	- -	0 *	0 *	0 *	0 *	-	-
Economy	Total capital investment	Million € / plant	58	58	58	58	58	58	58	58	58	58	58	58
	NPV	Million € / plant	225	N/D	181	N/D	-68	225	214	N/D	164	N/D	-147	N/D
	Profit	€ / (ha × yr)	453	N/D	364	N/D	-196	453	464	N/D	356	N/D	-424	N/D
	IRR	%	70%	N/D	59%	N/D	N/A	70%	67%	N/D	54%	N/D	N/A	N/D
	CO_2 avoidance costs	€ / t CO_2 eq.	-101	N/D	-96	N/D	77	N/A	-228	N/D	-303	N/D	N/A	N/D
	Energy resource savings costs	€ / GJ	-4	N/D	-4	N/D	2	-4	-7	N/D	-10	N/D	N/A	N/D
Society	Food security	–	0	0	+	+	0	-	+	+	++	++	++	++
	Income for farmers / local community	–	+	+	+	+	0	0	+	+	+	+	++	++
	Access to land, land rights	–	-	-	-	-	-	-	0	0	0	0	0	0
	Access to jobs	–	+	+	+	+	+	0	+	+	+	+	++	++
	Acceptance by farmers	–	0	0	0	0	0	0	+	+	+	+	+	+
	Acceptance by general society	–	0	0	+	+	0	0	+	+	+	+	++	++
	Innovation	–	0	+	+	+	-	+	++	++	++	++	+	+

Table 4-5 Overview of selected indicators and results for biomass sorghum scenarios in comparison to conventional systems under typical conditions. For abbreviations see Table 4-4.

Area	Indicator	Unit	Biomass sorghum scenarios: Biogas (CHP)	Biogas (Power)	Biomethane (CHP)	Biomethane (fuel)	Biomethane (natural gas)	2^{nd} gen. ethanol	Direct combustion (CHP)	Direct combustion (power)	Direct combustion (heat)	Gasification	Gasification (Pyrolysis)
Technology	Cultivation experience	–	-	-	-	-	-	-	-	-	-	-	-
	Harvest techn. (maturity)	–	+	+	+	+	+	+	+	+	+	+	+
	Conversion techn. (maturity)	–	+	+	+	+	+	-	0	0	0	- -	- -
	GMO plant use	–	++	++	++	++	++	++	++	++	++	++	++
	Breeding potential	–	++	++	++	++	++	++	++	++	++	++	++
	Storage facilities	–	0	0	0	0	0	0	0	0	0	0	0
Environment	Resource depletion: energy	GJ / (ha × yr)	-357	-336	-385	-165	-162	-71	-546	-304	-351	-148	-51
	Climate change	t CO_2 eq. / (ha × yr)	-11.2	-9.8	-17.9	-10.1	-5.7	-1.8	-28.9	-12.2	-22.4	-5.9	-0.2
	Acidification	kg SO_2 eq. / (ha × yr)	53	54	43	71	97	80	28	37	72	35	53
	Terrestrial eutrophication	kg PO_4 eq. / (ha × yr)	16.1	16.2	13.9	12.6	16.5	10.3	5.5	6.7	8.5	8.0	9.6
	Aquatic eutrophication	kg PO_4 eq. / (ha × yr)	31	31	32	32	32	30	23	23	23	23	23
	Photosmog	kg ethene eq. / (ha × yr)	-0.8	-0.3	-3.3	-17.5	-3.6	-4.8	-7.5	-1.8	-5.9	-2.0	-1.9
	Human toxicity	kg PM10 eq. / (ha × yr)	1	2	1	29	54	52	-7	3	40	17	37
	Ozone depletion	g R11 eq. / (ha × yr)	180	180	176	162	183	253	230	235	234	169	172
	Direct land use	ha × yr / (ha × yr)	1	1	1	1	1	1	1	1	1	1	1
	Net land use	net ha × yr / (ha × yr)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Water	–	-	-	-	-	-	-	-	-	-	-	-
	Soil	–	- -	- -	- -	- -	- -	-	-	-	-	-	-
	Fauna	–	-	-	-	-	-	-	-	-	-	-	-
	Flora	–	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -
	Landscape	–	0	0	0	0	0	0	0	0	0	0	0
Economy	Total capital investment	Million € / plant	2	N/D	N/D	N/D	N/D	112	N/D	N/D	N/D	56	56
	NPV	Million € / plant	4	N/D	3	N/D	N/D	-105	N/D	N/D	N/D	-363	-847
	Profit	€ / (ha × yr)	1575	N/D	1118	N/D	N/D	-762	N/D	N/D	N/D	-1313	-3062
	IRR	%	44%	N/D	34%	N/D	N/D	N/A	N/D	N/D	N/D	N/A	N/A
	CO_2 avoidance costs	€ / t CO_2 eq.	-140	N/D	-62	N/D	N/D	417	N/D	N/D	N/D	223	12774
	Energy resource savings costs	€ / GJ	-4	N/D	-3	N/D	N/D	11	N/D	N/D	N/D	9	60
Society	Food security	–	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Income for farmers / local community	–	+	0	+	+	+	+	+	N/D	N/D	+	+
	Access to land, land rights	–	-	-	-	-	-	-	-	N/D	N/D	-	-
	Access to jobs	–	+	+	+	+	+	+	+	N/D	N/D	+	+
	Acceptance by farmers	–	+	+	+	+	+	0	0	N/D	N/D	0	0
	Acceptance by general society	–	0	-	+	+	+	+	0	N/D	N/D	+	+
	Innovation	–	+	0	++	++	++	++	+	N/D	N/D	++	++

4.4.4 Categorisation

For comparability to qualitative indicators, quantitative indicators are categorised and the table is coloured accordingly (Table 4-4 and Table 4-5). Results are rated advantageous (green) if the assessed scenario shows lower burdens or higher advantages than the respective conventional reference scenario under typical conditions. Depending on the indicator, this can be at either negative net results (for indicators showing burdens) or at positive net results (for indicators showing advantages). Disadvantageous results are analogously coloured red. The investment sum is not categorised because there is no reference value. Net land occupation is categorised in three steps: If there is no reduction compared to direct land occupation (1 net ha x yr / (ha x yr)), the result is rated disadvantageous (red). If net land occupation is negative, it is rated advantageous (green) and otherwise it is rated neutral (yellow).

4.4.5 Comparison energy sorghum vs. conventional products

The data tables (Table 4-4 and Table 4-5) show, which advantages or disadvantages of energy sorghum cultivation and use exist compared to providing conventional equivalent products, which are mostly of fossil origin. As there is no scenario without disadvantages, political processes with all involved stakeholders are needed to decide, which disadvantages are acceptable in return for the advantages.

Several typical patterns of results can be identified in the data:

For sweet sorghum and biomass sorghum

- Regarding global and regional environmental impacts, a specific pattern of impacts can be observed: Savings in greenhouse gas emissions, non-renewable energy consumption and photosmog are contrasted by additional environmental burdens regarding acidification, eutrophication, human toxicity through inhalation of particulate matter and ozone depletion.
- Economic indicators generally point into the same direction as they display various facets of the same aspect profitability.

For sweet sorghum

- Differences in technological aspects mostly arise from varying by-product use in sweet sorghum scenarios.
- For sweet sorghum, net land use shows variable outcomes depending on the use of co-products.

For biomass sorghum

- In biomass sorghum scenarios, differences in technological aspects are mostly related to the used conversion technology and its requirements.

Table 4-6 Overview of results per net area occupation for sweet sorghum scenarios in comparison to conventional systems. For abbreviations see Table 4-4.

Area	Indicator	Unit	Sweet sorghum scenarios: Cane fallow	Cane fallow (Leaves to energy)	Cane fallow 2015 (no grain use)	Cane fallow (land use change)	Grain to food
		Grain use	Ethanol	Ethanol	**Fertil.**	Ethanol	**Food**
		Surplus bagasse use	Energy	Energy	Energy	Energy	Energy
		Leaves use	Fertil.	**Energy**	Fertil.	Fertil.	Fertil.
Technology	Cultivation experience	–	-	-	-	-	-
Technology	Harvest technology (maturity)	–	-	-	+	-	-
Technology	Conversion technology (maturity)	–	+	+	+	+	+
Technology	GMO plant use	–	++	++	++	++	++
Technology	Breeding potential	–	+	+	+	+	+
Technology	Storage facilities	–	-	- -	0	-	-
Environment	Resource depletion: energy	GJ / (net ha × yr)	-125	-188	-84	-125	-402
Environment	Climate change	t CO_2 eq. / (net ha × yr)	-5.2	-8.3	-2.5	3.6	-12.2
Environment	Acidification	kg SO_2 eq. / (net ha × yr)	51	50	39	51	177
Environment	Terrestrial eutrophication	kg PO_4 eq. / (net ha × yr)	8.1	8.1	6.1	8.1	27.2
Environment	Aquatic eutrophication	kg PO_4 eq. / (net ha × yr)	22	23	16	22	70
Environment	Photosmog	kg ethene eq. / (net ha × yr)	-4.2	-4.6	-1.8	-4.2	-7.5
Environment	Human toxicity	kg PM10 eq. / (net ha × yr)	29	24	22	29	96
Environment	Ozone depletion	g R11 eq. / (net ha × yr)	177	195	144	177	662
Environment	Direct land use	ha × yr / (net ha × yr)	1.2	1.2	1.0	1.2	6.0
Environment	Net land use	net ha × yr / (net ha × yr)	1	1	1	1	1
Environment	Water	–	-	-	-	- -	-
Environment	Soil	–	-	- -	-	- -	-
Environment	Fauna	–	-	-	-	- -	-
Environment	Flora	–	- -	- -	- -	- -	- -
Environment	Landscape	–	-	-	-	- -	-
Economy	Total capital investment	Million € / plant	58	58	58	58	58
Economy	NPV	Million € / plant	225	N/D	-68	225	214
Economy	Profit	€ / (net ha × yr)	523	N/D	-195	523	2770
Economy	IRR	%	70%	N/D	N/A	70%	67%
Economy	CO_2 avoidance costs	€ / t CO_2 eq.	-101	N/D	77	N/A	-228
Economy	Energy resource savings costs	€ / GJ	-4	N/D	2	-4	-7
Society	Food security	–	0	0	0	-	+
Society	Income for farmers / local community	–	+	+	0	0	+
Society	Access to land, land rights	–	-	-	-	-	0
Society	Access to jobs	–	+	+	+	0	+
Society	Acceptance by farmers	–	0	0	0	0	+
Society	Acceptance by general society	–	0	0	0	0	+
Society	Innovation	–	0	+	-	+	++

For some sweet sorghum scenarios, net land use deviates strongly from direct land use and even leads to negative results in some cases. The reason is that some by-products are used as feed or food and replace feed / food, which is conventionally cultivated separately. These areas for separate feed / food cultivation are not needed any more if feed / food are instead provided by sweet sorghum. Originally, the unit of reference “per ha per yr of direct land use” for all quantitative impacts has been chosen because the used agricultural land is the limiting factor for energy sorghum cultivation. The most efficient climate change mitigation is thus achieved by those scenarios, which show the highest greenhouse gas emission savings per area of land used. If net land use deviates strongly from direct land use, all other impacts should be compared on the basis of net land use rather than direct land use because the former is limiting overall achievable benefits (Table 4-6). However, these figures should be interpreted carefully for the following reasons:

- Figures for net land use are less certain than figures for direct land use. They vary in their quality depending on whether the replacement is direct (sweet sorghum vs. grain sorghum in “Grain to food” scenarios) or indirect (feed replaces variable conventional feed sources on the regional market).
- Net land use can only be smaller than direct land use if alternative cultures are replaced in reality. This means for example, that feed is really cultivated separately in the respective region and is not a co-product of another process, a residue like food waste or similar. Furthermore, the separate feed production needs to be given up instead of increasing meat or dairy production.
- In the case of very small or negative results for net land use, it does not make sense to express other impacts per net land use because land use is not limiting any more. This is reflected in meaningless results of other indicators per net land use, which tend towards infinity (for very small net land use) or change their sign (for negative net land use). Thus, respective scenarios were omitted in Table 4-6.
- In some cases, figures related to net land use are more decisive: Although qualitative results are formally independent of reference units, some ratings are based on the precondition that idle land is taken into use for cultivation. This especially applies to local environmental impacts, which are mostly negative if idle land is taken into use. Thus, these ratings are most relevant on a net land use basis if similar cultures are replaces (e.g. grain sorghum by sweet sorghum). For consistency, respective ratings on a direct land use basis are modified to reflect lower net impacts in the “Grain to food“ scenarios (marked with asterisks).

In summary, all energy sorghum scenarios show advantages and disadvantages, which requires a political decision process. Yet, it is possible under certain conditions to achieve sweet sorghum cultivation without additional land because co-products can be used to replace area-intensive conventional cultures.

4.4.6 Benchmarking of energy sorghum scenarios

Not all energy sorghum scenarios, which provide advantages over conventional products, can be realised on a big scale because land availability is limited. Thus, the best of these competing scenarios have to be identified. In theory, that scenario is best, which is clearly better than all other scenarios in all indicators under all conditions. However, such a scenario does not exist among the assessed energy sorghum cultivation and use scenarios. Thus, each candidate scenario has some disadvantages compared to several alternatives. These conflicts are important to know for decision makers but not immediately available from the result tables (Table 4-4 and Table 4-5). For this purpose, candidate scenarios are compared to all other scenarios in a benchmarking process. In this process, suitable benchmarks (candidate scenarios) and a comparison metric is identified. This metric should provide information on:

- whether a scenario is better or worse than the benchmark regarding a certain indicator,
- whether this holds true in the high and low cases, too, if data is available (see Table 7-2 in the annex),
- whether the differences are robust.

The metric is described in detail in subchapter 2.2.4. It provides the following results from very advantageous (++) to very disadvantageous (--) compared to the benchmark. As the reference always is another energy sorghum scenario, which was selected as benchmark, the rating does not state whether advantages compared to the conventional reference (e.g. fossil fuels) occur. For example, a (-) for “Cane fallow 2015 (no grain use)” compared to “Cane fallow” in Table 4-7 means that the early implementation scenario without grain use is worse than the mature scenario with grain use regarding the achieved mitigation of climate change (per ha per yr), although both achieve considerable mitigations compared to gasoline etc..

No difference (0) between two scenarios means for quantitative indicators that the difference is smaller than 5 % of the overall range of results among all scenarios. This threshold is chosen to reflect variability and uncertainty. However, a threshold cannot reflect aspects of uncertainty arising from data quality issues. In this regard, all comparisons between scenarios containing agricultural systems regarding the impacts on aquatic eutrophication, photosmog and ozone depletion have to be interpreted carefully. These impacts strongly depend on few input parameters, which are associated with a relatively high uncertainty.

All quantitative indicators used in the benchmarking process are expressed per directly used agricultural area as this is the limited resource, about which the scenarios are competing. Although qualitative results do not have units, this is important because a different unit of the input (e.g. per t of ethanol) would lead to different results. Net land occupation is given as indicator instead of using it as unit of reference because results are not very certain as discussed in subchapter 4.4.5.

Besides the definition of a suitable comparison metric, the decision context specifies which scenarios have to be compared to each other and which benchmark is suitable for each comparison. The following decision contexts and scenario selections were identified:

- Which scenario is best for cultivating sweet sorghum as part of sugarcane crop rotation schemes?
    - → Comparison of all "Cane fallow" scenario variants with the main scenario "Cane fallow" as benchmark (Table 4-7).
- Which scenario is best for cultivating sweet sorghum instead of grain sorghum?
    - → Comparison of all "Grain to food" scenario variants with the main scenario "Grain to food" as benchmark (Table 4-8).
- Which are general advantages and disadvantages of the three sweet sorghum cultivation and use approaches "Cane fallow", "Grain to food" and "Syrup production" (as a guideline in other decision contexts)?
    - → Comparison of all respective main scenarios with "Cane fallow" as benchmark (Table 4-9).
- Which scenario is best for cultivation and use of biomass sorghum?
    - → Comparison of all biomass sorghum scenarios with the main scenario "Biogas (CHP)" as benchmark (Table 4-10), which highlights differences between those scenarios studied in detail. Furthermore, comparison to the most efficient scenario "Direct combustion (CHP)" as benchmark (Table 4-11), to highlight overall perspectives.

All results, conclusions and recommendations resulting from the shown comparison tables are discussed in detail in chapter 5.

Table 4-7 Results of benchmarking process with scenario "Cane fallow" as benchmark. The scenarios are compared based on direct land use (per ha per yr). For abbreviations see Table 4-4.

Benchmark: Cane fallow **Basis: Direct land use**		**Sweet sorghum scenarios**					
		Cane fallow	Cane fallow (Leaves to energy)	Cane fallow (Surplus bagasse to feed)	Cane fallow (Max. feed)	Cane fallow 2015 (no grain use)	Cane fallow (land use change)
	Grain use	Ethanol	Ethanol	Ethanol	Ethanol	**Fertil.**	Ethanol
	Surplus bagasse use	Energy	Energy	**Feed**	Feed	Energy	Energy
	Leaves use	Fertil.	**Energy**	Fertil.	**Feed**	Fertil.	Fertil.
Technology							
	Cultivation experience		0	0	0	0	0
	Harvest technology (maturity)		0	0	0	++	0
	Conversion technology (maturity)		0	0	0	0	0
	GMO plant use		0	0	0	0	0
	Breeding potential		0	0	0	0	0
	Storage facilities		0	0	0	0	0
Environment							
	Resource depletion: energy		+	0	0	0	0
	Climate change		+	0	0	-	- -
	Acidification		0	+	+	0	0
	Terrestrial eutrophication		0	+	+	+	0
	Aquatic eutrophication		0	0	0	+	0
	Photosmog		0	0	0	-	0
	Human toxicity		0	0	+	0	0
	Ozone depletion		-	+	+	0	0
	Net land use		0	++	N/D	-	0
	Water		0	0	0	0	-
	Soil		-	0	0	0	-
	Fauna		0	0	0	0	- -
	Flora		0	0	0	0	0
	Landscape		0	0	0	0	- -
Economy							
	Total capital investment		0	0	0	0	0
	NPV		N/D	0	N/D	-	0
	Price support		N/D	0	N/D	-	0
	IRR		N/D	-	N/D	N/A	0
	CO_2 avoidance costs		N/D	0	N/D	0	N/A
	Energy resource savings costs		N/D	0	N/D	-	0
Society							
	Food security		0	++	++	0	- -
	Income for farmers / local comm.		0	0	0	- -	- -
	Access to land, land rights		0	0	0	0	0
	Access to jobs		0	0	0	0	- -
	Acceptance by farmers		0	0	0	0	0
	Acceptance by general society		0	++	++	0	0
	Innovation		++	++	++	- -	++

Table 4-8 Results of benchmarking process with scenario "Grain to food" as benchmark. The scenarios are compared based on direct land use (per ha per yr). For abbreviations see Table 4-4.

	Benchmark: Grain to food Basis: Direct land use	**Sweet sorghum scenarios**			
		Grain to food	Grain to food (Leaves to feed)	Grain to food (Surplus bagasse to feed)	Grain to food (Max. feed)
	Grain use	**Food**	Food	Food	Food
	Surplus bagasse use	Energy	Energy	**Feed**	**Feed**
	Leaves use	Fertil.	**Feed**	Fertil.	**Feed**
Technology	Cultivation experience		0	0	0
	Harvest technology (maturity)		0	0	0
	Conversion technology (maturity)		0	0	0
	GMO plant use		0	0	0
	Breeding potential		0	0	0
	Storage facilities		0	0	0
Environment	Resource depletion: energy		0	-	0
	Climate change		0	0	0
	Acidification		0	+	++
	Terrestrial eutrophication		0	+	++
	Aquatic eutrophication		0	0	0
	Photosmog		0	0	0
	Human toxicity		0	0	+
	Ozone depletion		+	++	++
	Net land use		N/D	++	N/D
	Water		0	0	0
	Soil		0	0	0
	Fauna		0	0	0
	Flora		0	0	0
	Landscape		0	0	0
Economy	Total capital investment		0	0	0
	NPV		N/D	0	N/D
	Price support		N/D	0	N/D
	IRR		N/D	-	N/D
	CO_2 avoidance costs		N/D	0	N/D
	Energy resource savings costs		N/D	0	N/D
Society	Food security		0	++	++
	Income for farmers / local comm.		0	0	0
	Access to land, land rights		0	0	0
	Access to jobs		0	0	0
	Acceptance by farmers		0	0	0
	Acceptance by general society		0	0	0
	Innovation		0	0	0

Table 4-9 Results of benchmarking process with scenario "Cane fallow" as benchmark. The scenarios are compared based on direct land use (per ha per yr). For abbreviations see Table 4-4.

Benchmark: Cane fallow Basis: Direct land use		Sweet sorghum scenarios		
		Cane fallow	Grain to food	Syrup production
	Grain use	Ethanol	**Food**	Food
	Surplus bagasse use	Energy	Energy	Feed
	Leaves use	Fertil.	Fertil.	Feed
Technology	Cultivation experience		0	0
	Harvest technology (maturity)		0	N/A
	Conversion technology (maturity)		0	0
	GMO plant use		0	0
	Breeding potential		0	0
	Storage facilities		0	0
Environment	Resource depletion: energy		0	- -
	Climate change		0	- -
	Acidification		0	+
	Terrestrial eutrophication		0	+
	Aquatic eutrophication		0	0
	Photosmog		0	0
	Human toxicity		0	0
	Ozone depletion		0	++
	Net land use		++	N/D
	Water		+	0
	Soil		+	0
	Fauna		0	0
	Flora		0	0
	Landscape		0	0
Economy	Total capital investment		0	0
	NPV		0	- -
	Price support		0	- -
	IRR		-	N/A
	CO_2 avoidance costs		0	N/D
	Energy resource savings costs		0	N/D
Society	Food security		++	++
	Income for farmers / local comm.		0	++
	Access to land, land rights		++	++
	Access to jobs		0	++
	Acceptance by farmers		++	++
	Acceptance by general society		++	++
	Innovation		++	++

Table 4-10 Results of benchmarking process with scenario "Biogas (CHP)" as benchmark. The scenarios are compared based on direct land use (per ha per yr). For abbreviations see Table 4-4.

Benchmark: Biogas (CHP) Basis: Direct land use		Biomass sorghum scenarios: Biogas (CHP)	Biogas (Power)	Bio-methane (CHP)	Bio-methane (fuel)	Bio-methane (natural gas)	2nd gen. ethanol	Direct comb. (CHP)	Direct comb. (power)	Direct comb. (heat)	Gasifi-cation	Gasifi-cation (Pyro-lysis)
Technology	Cultivation experience		0	0	0	0	0	0	0	0	0	0
	Harvest technology (maturity)		0	0	0	0	0	0	0	0	0	0
	Conversion technology (maturity)		0	0	0	0	- -	- -	- -	- -	- -	- -
	GMO plant use		0	0	0	0	0	0	0	0	0	0
	Breeding potential		0	0	0	0	0	0	0	0	0	0
	Storage facilities		0	0	0	0	0	0	0	0	0	0
Environment	Resource depletion: energy		0	0	-	-	- -	+	-	0	-	- -
	Climate change		0	+	0	-	-	+	0	+	-	-
	Acidification		0	+	- -	- -	- -	+	+	- -	+	0
	Terrestrial eutrophication		0	+	+	0	+	++	++	+	+	+
	Aquatic eutrophication		0	0	0	0	0	+	+	+	+	+
	Photosmog		0	+	++	+	+	++	+	++	+	+
	Human toxicity		0	0	- -	- -	- -	+	0	- -	- -	- -
	Ozone		0	0	+	0	- -	- -	- -	- -	0	0
	Net land use		0	0	0	0	0	0	0	0	0	0
	Water		0	0	0	0	0	0	0	0	0	0
	Soil		0	0	0	0	+	+	+	+	+	+
	Fauna		0	0	0	0	0	0	0	0	0	0
	Flora		0	0	0	0	0	0	0	0	0	0
	Landscape		0	0	0	0	0	0	0	0	0	0
Economy	Total capital investment		N/D	N/D	N/D	N/D	- -	N/D	N/D	N/D	- -	- -
	NPV		N/D	0	N/D	N/D	- -	N/D	N/D	N/D	- -	- -
	Price support		N/D	-	N/D	N/D	- -	N/D	N/D	N/D	- -	- -
	IRR		N/D	-	N/D	N/D	N/A	N/D	N/D	N/D	N/A	N/A
	CO_2 avoidance costs		N/D	0	N/D	N/D	0	N/D	N/D	N/D	0	-
	Energy resource savings costs		N/D	0	N/D	N/D	- -	N/D	N/D	N/D	- -	- -
Society	Food security	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Income for farmers / local communities		- -	0	0	0	0	0	- -	- -	0	0
	Access to land, land rights		0	0	0	0	0	0	++	++	0	0
	Access to jobs		0	0	0	0	0	0	- -	- -	0	0
	Acceptance by farmers		0	0	0	0	- -	- -	- -	- -	- -	- -
	Acceptance by general society		- -	++	++	++	++	0	0	0	++	++
	Innovation		- -	++	++	++	++	0	- -	- -	++	++

Table 4-11 Results of benchmarking process with scenario "Direct combustion (CHP)" as benchmark. The scenarios are compared based on direct land use (per ha per yr). For abbreviations see Table 4-4.

Benchmark: Direct combustion (CHP) Basis: Direct land use		Biomass sorghum scenarios										
		Biogas (CHP)	Biogas (Power)	Bio-methane (CHP)	Bio-methane (fuel)	Bio-methane (natural gas)	2^{nd} gen. ethanol	Direct comb. (CHP)	Direct comb. (power)	Direct comb. (heat)	Gasifi-cation	Gasifi-cation (Pyro-lysis)
Technology	Cultivation experience	0	0	0	0	0	0		0	0	0	0
	Harvest technology (maturity)	0	0	0	0	0	0		0	0	0	0
	Conversion technology (maturity)	++	+	+	+	+	-		0	0	-	-
	GMO plant use	0	0	0	0	0	0		0	0	0	0
	Breeding potential	0	0	0	0	0	0		0	0	0	0
	Storage facilities	0	0	0	0	0	0		0	0	0	0
Environment	Resource depletion: energy	-	-	-	-	-	-		-	-	-	-
	Climate change	-	-	-	-	-	-		-	-	-	-
	Acidification	-	-	-	-	-	-		-	-	-	-
	Terrestrial eutrophication	- -	-	-	-	-	-		-	-	-	-
	Aquatic eutrophication	-	-	-	-	-	-		0	0	0	0
	Photosmog	- -	-	-	+	-	-		-	-	-	-
	Human toxicity	-	-	-	-	-	-		-	-	-	-
	Ozone depletion	++	+	+	+	+	-		0	0	+	+
	Net land use	0	0	0	0	0	0		0	0	0	0
	Water	0	0	0	0	0	0		0	0	0	0
	Soil	-	-	-	-	-	0		0	0	0	0
	Fauna	0	0	0	0	0	0		0	0	0	0
	Flora	0	0	0	0	0	0		0	0	0	0
	Landscape	0	0	0	0	0	0		0	0	0	0
Economy	Total capital investment							N/D				
	NPV							N/D				
	Price support							N/D				
	IRR							N/D				
	CO_2 avoidance costs							N/D				
	Energy resource savings costs							N/D				
Society	Food security	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Income for farmers / local communities	0	-	0	0	0	0		-	-	0	0
	Access to land, land rights	0	0	0	0	0	0		+	+	0	0
	Access to jobs	0	0	0	0	0	0		-	-	0	0
	Acceptance by farmers	++	+	+	+	+	0		0	0	0	0
	Acceptance by general society	0	-	+	+	+	+		0	0	+	+
	Innovation	0	-	+	+	+	+		-	-	+	+

5 Conclusions, recommendations and outlook

In this chapter, overall conclusions are drawn from all results on sustainability aspects of the SWEETFUEL project (subchapter 5.1). Recommendations for decision makers are given (subchapter 5.2). Finally, limitations and further need for research are discussed in an outlook in subchapter 5.3.

5.1 Conclusions

Two groups of scenarios were analysed in the SWEETFUEL project: scenarios on bioethanol production from sweet sorghum, which can be cultivated in many tropical, sub-tropical and semi-arid regions, and scenarios on biogas production from biomass sorghum, which is primarily suited for temperate climate. All scenarios share some implications on sustainability (subchapter 5.1.1) but differ in others. As sweet sorghum and biomass sorghum do not compete with each other, this assessment focuses on the decision-relevant comparison within these groups (subchapters 5.1.2 and 5.1.3).

5.1.1 General

- The whole life cycles of energy sorghum cultivation and use mostly lead to a combination of **environmental advantages** (non-renewable energy resources, climate change, photosmog) **and disadvantages** (acidification, eutrophication, human toxicity through particulate matter emissions, ozone depletion). Furthermore, local environmental impacts are mostly negative, too, when compared to idle land (see Table 4-4 and Table 4-5).

  This is a typical pattern that is similarly observed for most energy crops. Effective biomass production, especially with annual or annually cultivated crops, can only be achieved with intensive agriculture including appropriate fertilisation, which is the major cause for the observed negative impacts. Any weighting of these advantages and disadvantages necessarily involves subjective preferences. Thus, the precondition for any energy sorghum use is that society accepts the environmental disadvantages in return for the advantages.
- Several scenarios that depict the use of mature technology turn out to be **highly profitable** (see Table 4-4 and Table 4-5) under the conditions set for the economic assessment (see subchapter 7.4 in the annex for an overview and /Basavaraj, Parthasarathy Rao et al. 2014/ for details).
- Social impacts vary but are mostly positive as long as conflicts about land rights and access to land can be solved (see Table 4-4 and Table 4-5).
- Despite these general patterns, quantitative **results** for environmental impacts and economic profitability **can vary widely**. Non-optimal scenarios can even deviate from the

general pattern and cause e.g. additional greenhouse gas emissions and high economic losses (see Table 7-2 in the annex and subchapter 4.1.1). The high importance of implementation conditions emphasises the need for **optimisation**. The following examples for important optimisation potentials can be deduced from specific analyses of individual processes and life cycle steps primarily in LCA and economic assessment (see subchapter 4.1.1 for details):

- Yields can and should be increased by breeding highly productive sweet and biomass sorghum cultivars and by improving the agricultural management.
- The nitrogen and thus protein content should be reduced by breeding and management if biomass is used for energy or fuel production. In these cases, protein content is not a quality criterion but only causes high fertiliser demands and thus costs and environmental damages.

- Besides variability that depends on choices of the involved shareholders, all results for future scenarios are necessarily associated with **uncertainty due to external factors**, which can hardly be influenced or optimised. For example, obtainable product prices may deviate strongly from the prices set for the economic assessment scenarios (see appendix 9.5 in /Basavaraj, Parthasarathy Rao et al. 2014/) and replaced conventional energy sources may deviate strongly depending on developments in the energy sector (see subchapter 4.2.1.3 in /Reinhardt et al. 2014/). Robustness of results was verified by calculating bandwidths of results under conditions that experts consider not typical but yet plausible (see Table 7-2 in the annex) and by sensitivity analyses e.g. on break-even prices (see subchapter 4.2) or on replaced conventional energy sources (see subchapter 4.1.1). These analyses show the range of conditions under which conclusions based on the presented results are valid.
- The variability of results, which on many internal and external parameters, makes it necessary to analyse each specific concept of energy sorghum cultivation individually in an adapted assessment. The main focus of such an assessment on environmental, economic and / or social aspects has to be adjusted depending on the concept.
- **Land availability** is a general limitation for cultivation of all energy crops and thus also for energy sorghum. Conflicts about land can be mitigated if land can be used that is not or not very well suited for established crops. This does not only refer to marginal land that would otherwise be entirely abandoned but also includes gradual advantages through specific plant properties. For energy sorghum in particular, these advantages are for example that most cultivars are resistant against infestation with the western corn rootworm (*Diabrotica virgifera virgifera*) and drought tolerant /Braconnier et al. 2013/, /Gloyna et al. 2011/, /Khawaja 2014/. Opportunities for cultivation in areas where e.g. maize cannot be cultivated every year to manage pests or where other crops produce low yields should thus be used. Further advantages for the energy sorghum variant sweet sorghum arise from its character as a multi-purpose plant as discussed below. In this regard, especially the option to directly replace grain sorghum by sweet sorghum (“grain to food” scenario) reduces the risk of land use conflicts significantly.

- In general, energy sorghum cultivation and partially also its use are **innovative processes**. This involves little existing cultivation experience and medium to high potentials for further improvements of properties by breeding without the need to use genetically modified crops (see Table 4-4, Table 4-5 and /Braconnier et al. 2013/).
  On the one hand, the innovative character creates opportunities, which is a central motivation for this project. On the other hand, innovation can always be an obstacle for implementation. Such obstacles require active management if energy sorghum should be implemented on a large scale.

5.1.2 Sweet sorghum

Three different approaches of sweet sorghum cultivation and use were assessed in several scenarios each: Cultivation on fallows between cycles of sugarcane with a focus on fuel production also from grains ("Cane fallow"), substitution of grain sorghum cultivation with co-production of food and fuel ("Grain to food"), and non-mechanised cultivation with a focus on keeping a big part of the fuel value chain in the villages through concentrating sugar juice to syrup ("Syrup production"). In all scenarios, the main product is ethanol.

- **"Cane fallow" scenarios** are generally advantageous regarding climate change mitigation, energy resource savings and profitability under most assessed conditions (see Table 4-7 and Table 4-4). However, additional land is required because fallow periods between sugarcane cultivation cycles are mostly already used for other purposes such as peanut cultivation. If this leads to additional use of idle land elsewhere, local environmental impacts are negative but at least to some extent reversible. If instead land of higher ecological value (e.g. forests or grasslands) is converted into e.g. peanut cultivation area (scenario "land use change"), this has severe consequences on climate, soils, water, biodiversity and landscape. Furthermore, social impacts are mixed because the "Cane fallow" scenarios involves additional land use by industrial players, which may increase the risk of land right conflicts.

  Thus, sweet sorghum cultivation between sugarcane cultivation cycles is an efficient way of biofuel production as long as there is sufficient idle land in the region to avoid land use changes with severe consequences.

  An early implementation scenario ("Cane fallow 2015"), in which grains are not harvested but ploughed in due to a lack of harvesting technology, is less advantageous for the environment than the mature "Cane fallow" scenario but at least does not cause substantial further disadvantages. However, it is expected to be unprofitable under most conditions. Therefore, an early implementation of the scenario "Cane fallow" should be pursued on a smaller scale to gain cultivation experience even without using the grains while technology and concepts are being developed further.

- "**Grain to food" scenarios** contribute to climate change mitigation and energy resource savings while being profitable under most assessed conditions (see Table 4-4). Furthermore, social impacts are mostly positive. As sweet sorghum produces almost as much grains as the replaced grain sorghum, only little extra land is needed to maintain grain production levels (net land use). That way, high benefits can be achieved per net land

occupancy (see Table 4-6). If surplus bagasse is used as feed and replaces feed production elsewhere (in this example wheat), then net area occupancy could even become negative. As the replacement of feed is indirect and subject to market dynamics, those numbers are very uncertain but the general conclusion is clear: Adopting integrated production using sweet sorghum, it is possible to produce the same amounts of food and feed, which are currently produced separately, on a smaller total area and to additional obtain fuel from the same land on top. A similar potential for net land use reductions has already been observed for few other biofuel production systems such as sugar beet ethanol /Rettenmaier et al. 2008/. However, intensification of agriculture also has downsides, which are observed for most biofuels: Environmental impacts such as acidification and eutrophication increase e.g. through higher yields and thus increased fertiliser use. Overall, replacement of grain sorghum is an option for sweet sorghum cultivation if (little) additional land is available to maintain food production levels or can be made available e.g. through substitution of local feed cultivation by surplus bagasse (see Table 4-8).

- **“Syrup production”** differs from the other approaches as it does not generate any environmental advantages due to its low energy efficiency and lack of process integration (process steps occur in different places and thus waste heat cannot be used efficiently). Advantages can only be achieved if further renewable energy sources such as rice straw are used to produce energy for the ethanol plant. Furthermore, the assessed business model is not profitable (see Table 4-4). In contrast, “Syrup production” scenarios are preferable over the other approaches from a social point of view (see Table 4-9).

  Although the grassroots approach of these scenarios seems appealing and it yields benefits to the local population, it is very hard to make this approach environmentally and economically sustainable. And after all, long term social advantages depend on environmental and economic sustainability. If there is unused biomass such as rice straw (continuously) available as an energy source, this sweet sorghum scenario might still be feasible. However, alternative agriculture-based rural development concepts should be examined before this approach is implemented.

- In the “Cane fallow” and “Grain to food” scenarios, the co-product **surplus bagasse** (left after the energy demand of ethanol production is satisfied by bagasse combustion) can either be **used for further energy generation or as feed**. Both options result in rather similar environmental impacts and revenues per directly used agricultural area considering regional variability and uncertainty (see Table 4-7 and Table 4-8). Advantages for the one or the other option depend on competing options of power and feed production in any particular region and their respective prices and environmental impacts. However, there is a striking difference in net area occupancy as discussed above. Even if bioenergy production should be a preference of society, the use of surplus bagasse as feed could still be the better option if the land becoming available through replacing separate feed production is used for bioenergy provision. Thus, surplus bagasse should be used as feed unless regional market conditions are strongly in favour of bioenergy production.

  Similar advantages and disadvantages can be found for the **use of grains for food or fuels**. Yet, implementation of the respective scenarios “Grain to food” and “Cane fallow” is primarily dependent ethical and cultural criteria because of priority for sufficient food

production and market conditions. Nevertheless, also in this respect there are indirect linkages of energy / fuel and feed / food markets through multi-purpose crops. This connection and its region-specific effects on sustainability require additional research.

- The **use of leaves** for energy production is highly advantageous in terms of environmental impacts as long as enough organic matter remains on the land to preserve soil quality. It might however be associated with technical and logistical challenges (see Table 4-7). The use of leaves as feed e.g. for goats may be an option in a rural setting but environmental benefits are expected to be rather marginal and may vary considerably depending on the replaced source of feed (see Table 4-7). The economic value of leaves is generally low no matter if they are used as fertiliser or feed. Therefore, leaves should be combusted for energy production if logistically feasible and permitted by soil quality.
- **CO_2 avoidance costs and energy resource savings costs** turned out to be less decisive indicators because many scenarios are profitable and thus costs are negative (see Table 4-4). In that case, this indicator reflects additional profits for the involved companies instead of costs to be paid for by the general society. For companies, other indicators such as the internal rate of return are more important than CO_2 avoidance costs, which are more relevant for political decisions. The important conclusion for politics is that greenhouse gas emission savings and energy resource savings can be achieved without public costs other than e.g. support for research and dissemination.
- The different scenarios reveal a contrast between a smallholder-oriented but inefficient approach (“Syrup production”) with high (short term) social advantages and an industrialised and efficient one (“Cane fallow”) with low social advantages as two extremes of a continuous spectrum. As the ethical assessment shows (see subchapter 4.3.1 for details), it depends on context and structures in the society concerned if an efficient industrialised approach is likely to cause **ethical conflicts**. If this is prone to be the case as e.g. in India, then a compromise has to be found that is efficient enough to reach a sustainable outcome on all dimensions. This is important because long term advantages in the social domain depend on environmental and economic sustainability instead of wasting resources.

5.1.3 Biomass sorghum

Biomass sorghum cultivated in temperate climates is expected to be predominantly used as energy crop for biogas production. In contrast to sweet sorghum, biomass sorghum is a single-purpose plant, which is harvested as whole plant. Additionally, direct combustion and several scenarios on 2^{nd} generation fuel production are analysed as alternative biomass use options (for all investigated options see Table 3-2).

- All assessed biogas and biomethane scenarios show very similar **qualitative impact patterns** (see Table 4-5): They are profitable under all assessed conditions, generally cause environmental benefits regarding climate change, energy resource savings and photosmog but cause additional environmental burdens in all other impact categories. Social impacts are mostly positive although land availability may be an issue. In terms of technology, cultivation experience is still lacking but otherwise all processes are estab-

lished. However, quantitative differences mainly in respect to environmental impacts can be large and under some boundary conditions, even additional greenhouse gas emissions can occur. Thus, biomass sorghum for biogas production is an innovative crop, which can be fed into established value chains. Its benefits and problems throughout the whole life cycle are qualitatively similar to those of existing biogas production from cultivated crops such as maize. Yet, concrete implementation and agricultural practise can make a big difference especially with respect to environmental impacts.

- It depends on market conditions whether the energy consuming **upgrading of biogas to biomethane** pays off both economically and environmentally. Biomethane is fed into the natural gas grid and can thus be used flexibly and rather efficiently. However, if biogas is used in combined heat and power production (CHP) and there is a local demand for the produced heat (see Table 4-5 and Table 7-2 high case), then biogas use is as efficient as biomethane use and upgrading of biogas to biomethane would only cause additional energy consumption, costs and emissions. Thus, upgrading for use in a CHP close to heat customers is advantageous in many rural settings without existing heat demand (see Table 4-10). Heat use options therefore have to be analysed carefully before installing new biogas plants. If there is heat demand, a direct use of biogas instead of upgrading to biomethane should be preferred at least for environmental and economic reasons although the public may be in favour of the contrary.

  Another important market influence to consider is whether biomethane replaces power and heat from mixed sources as discussed above including environmentally harmful coal or if fossil natural gas is replaced directly (see Table 4-10). Additionally, a replacement of petroleum-based fuels could take place if biomethane-powered cars replace conventional cars. Results show that environmental impacts improve the more of harmful coal rather than relatively clean natural gas is replaced. Petroleum ranges between these two extremes. As national and European energy markets are concerned, biomethane use options and thus its environmental impacts are influenced by strategic political decisions. Thus, these environmental implications should be taken into account in political decision processes.

- Further specific **optimisation options of biogas production** have been identified in the environmental assessment (see subchapter 4.1). For example, it is crucial to cover the storage area for the digestate gas-tight because of emissions of the greenhouse gas methane. Up to now, this is mandatory in big biomethane plants in Europe but still optional for small biogas units. Furthermore, digestate should be incorporated into the soil straight after spreading it as fertiliser on fields because this avoids ammonia emissions, which are relevant for several environmental impacts. If these steps are not optimised, this can lead to additional greenhouse gas emissions compared to energy provision from fossil resources. Individual farmers and owners of biogas plants and their practise therefore determine if and to which extent the overall aim of climate change mitigation is reached.

- **Alternative use options of biomass sorghum** are direct combustion for energy generation or 2nd generation fuel production (bioethanol or synthetic Fischer-Tropsch diesel). All these technologies are less mature than biogas / biomethane production. Direct combustion is possible with limited modifications to well established technology while there is on-

ly one industrial scale 2nd generation ethanol plant so far and Fischer-Tropsch diesel processes have only been demonstrated on smaller scales. For this reason, the implementation of these alternatives contributes to innovation but is met by farmers with scepticism.

- **Direct combustion** in a CHP plant achieves the best environmental performance of all biomass sorghum use options (see Table 4-11). The main reason is that the conversion steps to biogas or biomethane, which necessarily cause losses, are omitted. Furthermore, soil erosion may be reduced because biomass sorghum is harvested later after it has partially dried on the field. Harvest in a comparatively dry state also reduces or spares technical drying. Still, it was observed in the SWOT assessment that its image in the general society is not as good as for other biomass use options. A screening economic analysis of this scenario yields the result that there should be conditions under which direct combustion is profitable. If biomass is combusted in a power plant or heat plant instead of a CHP, environmental benefits are lower but still in the range of those achievable with biogas production and use. Future biomass sorghum cultivation should therefore aim at direct combustion instead of biogas / biomethane from an environmental point of view. Public awareness of this fact should be raised and implementation programs should be initiated.
- In the near future, **2nd generation fuels from biomass sorghum** cannot compete with biogas / biomethane production and use or direct combustion in respect to achievable climate change mitigation, energy resource savings and profits (see Table 4-10). Regarding other environmental impacts such as acidification and eutrophication, there are advantages compared to biogas production but not compared to direct combustion (see Table 4-11). This is due to the energy, material and capital intensive conversion processes. Economically, especially the required enzymes cause a large share of the variable costs for 2nd generation ethanol but these costs have the potential to decline significantly in the future. Thus, competitiveness may be reached in the medium term. On the long run, this conversion may pay off from an environmental point of view as power production from fossil resources can potentially be largely replaced by renewable power but there is no such option in sight for fuels. Instead, the increasing use of unconventional fossil petroleum will increase the environmental footprint of fossil fuels.

In summary, both sweet sorghum and biomass sorghum can be cultivated and used according to concepts that lead to many environmental, economic and social advantages if sufficient land is available. Necessary optimisations to reach these positive outcomes are highlighted in this report. However, environmental disadvantages such as increased nutrient inputs into ecosystems, which are typical for biofuels from cultivated biomass anyway, come also along with energy sorghum. In contrast to many other biofuels including most 2nd generation ethanol from residues, ethanol production from the multi-purpose crop sweet sorghum can under some conditions result in a net release of area, e.g. if all co-products are used to substitute existing food or feed production. For all these reasons, energy sorghum is a promising new alternative among biofuel and bioenergy crops. Yet, not all energy sorghum pathways are sustainable *per se* and thus implementation programs – at least when publicly funded – have to be accompanied by specific sustainability analyses.

5.2 Recommendations

Based on the results of the environmental and economic assessments, the SWOT analysis and the ethical assessment, as well as the conclusions discussed above, a number of recommendations for individual stakeholders, especially decision makers in science, industry and politics, can be derived. Those recommendations, which are specific to either biomass or sweet sorghum, are discussed first in subchapters 5.2.1 and 5.2.2. Recommendations for both energy sorghum variants then follow in subchapter 5.2.3.

5.2.1 Specific recommendations for sweet sorghum

The following specific recommendations refer to various areas of the entire life cycle:

- Because especially large sustainability benefits are associated with the use of the co-products, care should be taken that as much of the plant as possible is machine-harvestable. Technical advances in **harvesters** should therefore be supported, with a focus on harvesting both co-products, grains and leaves.
- Where grain of sweet sorghum is not demanded for food purpose, distilleries crushing sugarcane for ethanol should **utilise both stalk and grain** of sweet sorghum by increasing the crushing window during the lean periods. Use of both stalk and grain for ethanol is more profitable than stalk alone. Concepts and programs for the use of both grain and stalk should be implemented.
- When planning a new ethanol plant, a **concept for full utilisation of the leaves and the surplus bagasse** should be compiled as any use of these co-products improves both profitability and environmental impacts. Even if ethanol plants should be profitable without using the co-products, investors should opt for their use as higher environmental benefits is this case come along with increased profitability. To increase incentives, ethanol plants with an integrated use of by-products should e.g. be given priority consideration in authorisation practice. Whether surplus bagasse should be used for energy generation or as feed should be decided based on regional markets and / or conditions. Priority should however be given to the use as feed if regional availability of land for feed production is an issue.
- The cultivation of sweet sorghum on land with natural vegetation often influences the carbon stock and biodiversity of the land negatively and should therefore be avoided. Initiatives and programmes supporting the establishment of sweet sorghum as an energy crop should therefore promote **integration in existing cultivation systems, or cultivation on low-carbon soils, or soils of relatively little ecological value**, and to this end raise incentives and query farmers and investors about convincing concepts. This also applies to the case of sweet sorghum cultivation in sugarcane cycles or, even more so, instead of grain sorghum, because indirect land use changes are actually occurring in practise, whose negative impacts must be minimised.

- **Syrup processing**: Converting juice to syrup at village level is **neither economical nor environmentally beneficial** unless significant improvements compared to the assessed scenarios are realised. If decentralised syrup production from sweet sorghum still should be followed further, particular attention should be paid to the concept for provision of the energy source for centralised processing of the syrup to ethanol. Only those concepts should be promoted or approved that can demonstrate a positive energy and greenhouse gas balance.
- In order to ensure that the **leaf harvest** is sustainable, i.e. the organic soil substance is not negatively impacted, an appropriate research project should be established with the aim of identifying how the maximum sustainable leaf harvest can be determined across a variety of sites. In addition, a process for implementing the results in the field must be developed.

5.2.2 Specific recommendations for biomass sorghum

Specific recommendations for the cultivation and use of biomass sorghum apply predominantly to the following two areas:

Biogas production

- Combined production and utilisation of **power and heat** should be preferred over power production only. Instead, biogas plants are often built in areas where there are no noteworthy heat consumers. This is neither sustainable from an environmental nor from an economical perspective. Thus, a heat utilisation concept should be taken into account at the planning stage. To increase incentives, biogas plants with a conclusive heat use concept should be given priority consideration in authorisation practice.
- In terms of the production of biogas from biomass sorghum, a legal obligation should be introduced to cover the digestate store gas-tight.
- **Emissions from the application of digestate** to the field should be minimised. To this end, the digestate should be worked into the soil in the shortest possible time (e.g. one hour) after application. Legal regulations and monitoring of this practise should be introduced where not yet in place. Furthermore, a research project should be established with the aim of identifying whether and under which conditions it is beneficial to add nitrification inhibitors to the digestate in order to reduce emissions following application of the digestate.

Alternative use options

- **Direct combustion** of biomass sorghum for combined heat and power production is the environmentally most beneficial use option and is profitable. As this scenario was not in the primary focus of this study, further research should be supported on implementation barriers, issues of nutrient recycling from ashes and long term perspectives in a changing energy system.

- Production of **2nd generation ethanol** is promising to become economically viable in the medium term and more environmentally advantageous than competing direct combustion in the long term. Thus, maturation and optimisation of the technology should be further supported in individual industrial scale plants. Given the currently achievable environmental and social benefits as well as the associated avoidance costs, it does not seem justified for society to finance a large scale implementation of this technology e.g. via direct subsidies or mandatory blending quota – at least not if mainly annually cultivated biomass is used.
- As **2nd generation ethanol and synthetic FT fuels** are rather medium to long term options, biomass sorghum should not be developed with high priority as feedstock for such fuels but may find an additional market in this use option later.

5.2.3 General recommendations for energy sorghum

The general recommendations for both investigated energy sorghum variants biomass and sweet sorghum are relevant to a variety of areas of the entire life cycle and affect both environment and economics positively:

- Support for breeding programmes for general **yield** optimisation differentiated into geographical, climatic and soil conditions, in order to reap the full benefits of the sorghum variants;
- Promotion of techniques for optimising cultivation methods (e.g. improved fertiliser and pesticide application) for **yield stability or the optimised use of resources**;
- Reduction in applied **mineral fertiliser**:
    - Continuation of appropriate breeding programmes for reducing the nutrient content in the harvested biomass that is intended for energy use.
    - Establishing research projects for optimising suitable cultivation methods (e.g. optimising the time of harvesting) for reducing the nutrient content in the harvested biomass that is intended for energy use.
    - Integration of sweet sorghum and biomass sorghum cultivation respectively in existing, established crop rotation systems should be aimed for, because sorghum is capable of utilising nutrients from deeper layers, which remained unused in the previous cultivation systems. Appropriate research projects should be established, in particular with the aim of identifying promising multi-crop rotations.

Furthermore, limited land availability causes competition between various land use options, which also affects energy sorghum cultivation. This **competition about land** needs to be politically managed to avoid a high risk of environmental, social and on the long run also economically unsustainable developments:

- In the mid- to long-term, biomass and land use allocation plans should be developed at national and pan-national level. Due to the fact that environmental implications including resource scarcity in particular do not possess an adequate price, market mechanisms cannot replace these plans.

- Based on these national plans, regional plans which include regulations for project planning should be developed. In this context, the cultivation of crops adapted to local conditions should be supported. For instance, the environmental impacts of the cultivation of a crop with a high water demand depend on water availability at the specific location. Furthermore, regional planning is vital due to the fact that also public funds to date have created market actors with considerable local demand for biomass and significant market power. Further ethanol producing facilities could potentially exacerbate the process. This can create distortion of competition and thus create displacement effects that can be environmentally and socially unsustainable. In some regions, especially land rights of smallholders need to be protected. With appropriate planning, unfavourable developments can be, and must be, avoided.
- As long as no appropriate planning is in place, preventive measures should include binding land use and cultivation-related sustainability criteria for uniform application across all purposes, i.e. for bio-based materials, chemicals, fuel and energy carriers as well as feed / food production.
- The political decision process in each concerned region should take into account **how far** unavoidable **environmental disadvantages** mainly caused by intensive agriculture **are acceptable** in return for the advantages. This understanding is needed as a basis for the development of above mentioned land use allocation plans.

Further aspects

- **Knowledge transfer** in terms of experience in cultivating energy sorghum should be supported.
- **Quality control**: All appropriate support programmes or implementation concepts and programmes should be accompanied scientifically in order to identify the impacts on sustainability and to facilitate optimisation in the course of the running project.
- An early **involvement of stakeholders** should be ensured in planning processes especially for bigger industrial projects that will affect agriculture in the region. This helps avoiding conflicts and increases the public acceptance.

5.3 Outlook

This study comprehensively assesses the cultivation and use of sweet sorghum and biomass sorghum in various climatic zones compared to conventional provision of various alternative products. It is based on established methodologies such as life cycle assessment (LCA) or cost benefit analysis in combination with new methodologies such as life cycle environmental impact assessment (LC-EIA) and integrated sustainability assessment. The derived conclusions and recommendations show that this combination of methodologies is a practicable approach to assess the sustainability of potential future implementations of new technologies.

However, there are several possibilities how the implementation of the assessed systems can indirectly affect sustainability of further systems, which could only be addressed concisely and qualitatively. Especially the following aspects require further research in the future beyond the specific impacts of energy sorghum analysed here:

In most scenarios, the basket of products produced from energy sorghum, requires more agricultural land for its provision than the provision of alternative conventional (reference) products, because conventional energy and fuels are provided from fossil resources. This net land occupation has several implications beyond the life cycles of energy sorghum and its reference products. Depending on land availability, this concerns detrimental effects of extending agricultural land at the expense of natural ecosystems or alternative land use options that are could be implemented instead. These topics are very important for the sustainability of any non-food crop. However, further research is required to be able to quantify all of these effects:

- Global and regional land availability is dependent on many factors including demographics, affluence (with important effects on meat consumption) and global non-food land use in the sectors of bioenergy, biofuels, bio-based materials and nature conservation. Prognoses and scenarios vary considerably from study to study (see e.g. /Kretschmer et al. 2013b/, /Bringezu et al. 2012/, /Leopoldina 2012/).
- Direct or indirect land use changes and thus potentially severe consequences may result from using more land for sorghum cultivation than available regionally and globally. These effects are hard to quantify and allocate to specific causes due to complex market interactions already in retrospective but even more so for the future. For further reading, please refer e.g. to /Fehrenbach et al. 2009/, /EC 2010a/, /NL Agency 2010/, /Edwards et al. 2010/.
- If land for non-food use is available, there may still be more advantageous use options of the limited resource agricultural land than energy sorghum cultivation. These land use options range from established first generation biofuels from oil seed crops via second generation fuels to innovative biorefinery concepts producing several products including e.g. novel bio-based polymers from short rotation coppice. Currently, there is a dynamic development with many new approaches in all involved sectors, which are envisioned to be ready for the market within the next ten years. Such alternatives have been compared for example in /Rettenmaier et al. 2014/.

Results of this further research will be needed by decision makers to manage conflicts about agricultural land among competing non-food use options in the medium to long term. For such conflict management, land use allocation plans and biomass allocation plans are promising instruments. The integration of energy sorghum cultivation into such plans furthermore requires a full sustainability assessment for any concretely planned and publicly supported large scale energy sorghum cultivation project additional to the more general level research suggested above.

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7 Annex

The annex contains various supplementary material including input data, further results and further descriptions of the methodology.

7.1 Scenario data

This subchapter contains an overview of important agricultural and conversion data for the environmental assessment (Table 7-1). The cultivation of biomass and sweet sorghum is assessed in the way that full expenditures of crop cultivation are ascribed to the harvested crop based on a sustainable cultivation practise. This includes that as many nutrients are replaced by fertilisation as are lost by harvesting and emissions to air and water and exceed the deposition of nutrients from the atmosphere (in case of nitrogen) /Müller-Lindenlauf et al. 2014/.

Table 7-1 Selected data used for SWEETFUEL scenario calculations and certain outputs for the typical dataset.

	Units (per ha × year)	Sweet sorghum Cane fallow	Sweet sorghum Grain to food	Sweet sorghum Syrup	Biomass sorghum
Agricultural inputs					
Seeds	kg	7	7	7	8
Pesticides	kg	5	5	2.5	5
Fertiliser*					
N	kg	350	260	350	356
P_2O_5	kg	120	90	120	125
K_2O	kg	380	285	380	450
Diesel fieldwork	L	90	85	90	110
Yields					
Biomass	t (dry matter)	20	15	20	25
Extraction efficiency	%	95	95	85	-
Sugar	t	3.1	2.0	2.8	-
Outputs					
Ethanol (from stalks)	t	1.6	1.0	1.2	-
Ethanol (from grains)	t	1.2	-	-	-
Surplus bagasse	t	3.7	4.5	5.5	
Biogas – power	kWh	-	-	-	23,300
– heat	MJ	-	-	-	17,100

* N-fertiliser demand was calculated as follows: (nutrient content in biomass) × (biomass yield) / (1 - losses through ammonia emissions, denitrification & nitrate leaching) - (atmospheric deposition$_{net}$)

7.2 Additional results

Besides typical scenarios, bandwidth from high to low have been defined to cover variability in parameters such as agricultural yields, sugar content and conversion efficiencies. This leads to a bandwidth of results depicted in Table 7-2. For results under typical conditions refer to Table 4-4 and Table 4-5.

* (continued) Nutrient contents in biomass and yields for sweet and biomass sorghum are based on experimental data. In $deposition_{net}$, losses due to ammonia emissions, denitrification & nitrate leaching are already taken into account. Losses are based on model calculations and statistics and atmospheric deposition is based on literature sources /Müller-Lindenlauf et al. 2014/. The following losses were used for nitrogen emissions: Ammonia 3.29 %, nitrate leaching 15 % for annual crops, denitrification losses 10 %. The losses relate to typical agricultural practise expected for 2020. This methodological approach results in higher fertiliser values compared to field trials, but delivers a realistic description of a sustainable agricultural practise.

Table 7-2 Bandwidths of results for the main sweet and biomass sorghum scenarios in comparison to conventional systems. For abbreviations see Table 4-4. *: see subchapter 4.4.5.

			Low				High			
			Sweet sorghum			Biomass	Sweet sorghum			Biomass
			Cane fallow	Grain to food	Syrup production	Biogas (CHP)	Cane fallow	Grain to food	Syrup production	Biogas (CHP)
Area	**Indicator**	**Unit**								
Technology	Cultivation experience	–	-	-	-	-	-	-	-	-
	Harvest techn. (maturity)	–	-	-	N/A	+	-	-	N/A	+
	Conversion techn. (maturity)	–	+	+	+	+	+	+	+	+
	GMO plant use	–	++	++	++	++	++	++	++	++
	Breeding potential	–	+	+	+	++	+	+	+	++
	Storage facilities	–	-	-	N/A	0	-	-	N/A	0
Environment	Resource depletion: energy	GJ / (ha × yr)	-47	-44	3	-168	-222	-95	25	-568
	Climate change	t CO_2 eq. / (ha × yr)	-1.4	-1.0	0.5	6.4	-10.8	-3.4	3.7	-27.8
	Acidification	kg SO_2 eq. / (ha × yr)	25	23	10	43	68	35	47	-7
	Terrestrial eutrophication	kg PO_4 eq. / (ha × yr)	3.7	3.5	1.3	10.9	11.4	5.5	6.6	7.8
	Aquatic eutrophication	kg PO_4 eq. / (ha × yr)	10	9	11	20	31	14	31	36
	Photosmog	kg ethene eq. / (ha × yr)	-1.0	-0.7	-0.2	2.5	-8.3	-2.1	-2.0	-4.5
	Human toxicity	kg PM10 eq. / (ha × yr)	14	13	8	11	39	19	37	-31
	Ozone depletion	g R11 eq. / (ha × yr)	86	85	16	114	245	133	105	203
	Direct land use	ha × yr / (ha × yr)	1	1	1	1	1	1	1	1
	Net land use	net ha × yr / (ha × yr)	1.0	0.2	N/D	1.0	0.8	0.2	N/D	1.0
	Water	–	- -	- *	- -	- -	-	0 *	-	-
	Soil	–	- -	- *	- -	- -	-	0 *	-	-
	Fauna	–	-	-	-	-	-	0 *	-	-
	Flora	–	- -	- -	- -	- -	-	-	-	-
	Landscape	–	-	-	-	-	0	0	0	0
Economy	Total capital investment	Million € / plant	58	58	58	2	58	58	58	2
	NPV	Million € / plant	-91	-78	-305	2	536	423	-123	6
	Profit	€ / (ha × yr)	-132	-112	-441	561	1474	1225	-623	2194
	IRR	%	N/A	N/A	N/A	24%	148%	120%	N/A	57%
	CO_2 avoidance costs	€ / t CO_2 eq.	95	108	N/A	N/A	-137	-358	N/A	-79
	Energy resource savings costs	€ / GJ	3	3	N/A	-3	-7	-13	N/A	-4
Society	Food security	–	0	+	++	N/A	0	+	++	N/A
	Income for farmers / local community	–	+	+	++	+	+	+	++	+
	Access to land, land rights	–	-	0	0	-	-	0	0	-
	Access to jobs	–	+	+	++	+	+	+	++	+
	Acceptance by farmers	–	0	+	+	+	0	+	+	+
	Acceptance by general society	–	0	+	++	0	0	+	++	0
	Innovation	–	0	++	+	+	0	++	+	+

7.3 Methodology environmental assessment

This subchapter contains a summary of the methodology used for the environmental assessment. For the complete methodology please refer to /Reinhardt et al. 2014/.

7.3.1 Life cycle assessment (LCA)

A general introduction of the methodology of a life cycle assessment (LCA) can be found in /Reinhardt et al. 2014/. In the following the settings for the life cycle impact assessment (LCIA) (subchapter 7.3.1.1) applied for the environmental assessment, system boundaries (subchapter 7.3.1.2), further methodological issues (subchapter 7.3.1.3) and the origin of the data are considered (subchapter 7.3.1.4).

7.3.1.1 Settings for Life cycle Impact Assessment (LCIA)

The impact categories considered in the screening LCA performed by /Reinhardt et al. 2014/, the life cycle inventory (LCI) parameters and the respective characterisation factors are shown in Table 7-3. All impact categories are standard categories in life cycle assessments /JRC-IES 2010/. The procedures and general data for the calculations are documented in detail in /Borken et al. 1999/. In case of the category greenhouse effect the conversion of other trace gases (e.g. methane, nitrous oxide) into carbon dioxide equivalents (CO_2 equiv.) was calculated by using GWP100 factors /IPCC 2007/.

Some impact categories, which are disregarded by /Reinhardt et al. 2014/, are excluded because they are i) irrelevant for the SWEETFUEL systems (e.g. ionising radiation) or ii) still under methodological development (e.g. human and ecotoxicity, water depletion and land use; classified as level III or II/III in the ILCD Handbook). Moreover, LCI data quality for 2020 is limited particularly for human toxicity and ecotoxicity, which cover very many substances. The data available today is not suitable to derive results that are balanced enough for decision support. Therefore, this category as a whole is excluded from the LCA and instead, one aspect of human toxicity, i.e. health risks due to particulate matter emissions, is covered as a midpoint indicator and important impacts on biodiversity are covered within the LC-EIA part (see subchapter 7.3.2).

Table 7-3 Indicators, important LCI parameters and characterisation factors for the respective impact categories (/CML 2004/, /IPCC 2007/, /Klöpffer & Renner 1995/, /Leeuw 2002/, /Ravishankara et al. 2009/, /IFEU 2014/ on the basis of /IPCC 2007/).

Impact category	Category indicator	Life cycle inventory (LCI) parameter	Formula	Character. factor
Depletion of non-renewable energy resources	Cumulative primary energy use from non-renewable sources	Crude oil Natural gas Hard coal Lignite Uranium ore	—	—
Greenhouse effect	CO_2 equivalents (carbon dioxide equivalent)	Carbon dioxide fossil Nitrous oxide Methane biogenic* Methane fossil**	CO_2 N_2O CH_4 CH_4	1 298 25 27.75
Acidification	SO_2 equivalents (sulphur dioxide equivalent)	Sulphur dioxide Nitrogen oxides Ammonia Hydrochloric acid	SO_2 NO_X NH_3 HCl	1 0.7 1.88 0.88
Terrestrial eutrophication	PO_4^{3-} equivalents (phosphate equivalent)	Nitrogen oxides Ammonia	NO_X NH_3	0.13 0.346
Aquatic eutrophication	PO_4^{3-} equivalents (phosphate equivalent)	Nitrate Nitrogen Phosphorous	NO_3^- N P	0.095 0.42 3.07
Photochemical ozone formation	C_2H_4 equivalents (ethylene equivalents)*	Non-methane hydrocarbons Methane	NMHC CH_4	1 0.006
(Stratospheric) Ozone depletion	CFC-11 equivalents	Nitrous oxide (Dinitrogen oxide)	N_2O	0.017
Human toxicity	PM_{10} equivalents	Particulate matter (≤10 µm) Sulphur dioxide Nitrogen oxides Non-methane hydrocarbons Ammonia	- SO_2 NO_X NMHC NH_3	1 0.54 0.88 0.012 0.64

*without CO_2 effect; **with CO_2 effect

Regarding ozone depletion, an ODP factor for nitrous oxide from a study by /Ravishankara et al. 2009/ is used although it is not yet commonly accepted because it is the only one available.

Normalisation

Normalisation helps to better understand the relative magnitude of the results for the different environmental impact categories. It transforms a category indicator result by dividing it by a selected reference value, e.g. a certain emission caused by the system is divided by this emission per capita in a selected area.

In the SWEETFUEL LCA study, the environmental advantages and disadvantages for the European scenarios can be related to the environmental situation in the EU27. The reference

information is the yearly average energy demand and the average emissions of various substances per inhabitant in Europe, the so-called inhabitant equivalent (IE).

Due to the insecurity related to future emissions of various substances, the inhabitant equivalents will be calculated based on 2005 emissions. These values are subsequently used to normalise data which are calculated for 2015 and 2020 (time frame for SWEETFUEL systems). To ensure comparability, results for the non-European scenarios are also normalised using the EU inhabitant equivalents for EU27.

Weighting

Weighting will not be applied. Weighting uses numerical factors based on value-choices to compare and sometimes also aggregate indicator results, which are not comparable on a physical basis.

7.3.1.2 System boundaries

The LCA for this project covers the entire value chain from feedstock production to the distribution and usage of the final products including land use change effects with associated changes in carbon stocks.

Systematic exclusion of activity types

Infrastructure is excluded from the system. This applies to production and processing equipment, vehicles such as tractors, buildings and streets connected with the crops' production and use. In many LCAs assessing bioenergy systems it was shown that infrastructure accounts for less than 10 % of the overall results (see /Nitsch et al. 2004/, /Fritsche et al. 2004/ and /Gärtner 2008/). However, this only applies to the environmental impacts. In contrast, investment and capital costs for process equipment or buildings are an important part of the economic assessment.

7.3.1.3 Further methodological issues

Biogenic carbon

There are two possible sources for carbon dioxide (CO_2) emissions: (recent) biogenic or fossil carbon stocks. For biofuels, the amount of CO_2 released into the atmosphere from direct biofuel combustion equals the amount of CO_2 that has been taken up by the plants recently (short carbon cycle). This release of biogenic CO_2 is considered carbon neutral, i.e. it does not promote greenhouse effect. Therefore, only fossil carbon is taken into account for calculating greenhouse gas balances in SWEETFUEL, which is the standard approach among LCA practitioners.

Direct land use change and changes in organic carbon stocks

Changes in direct land use and related changes in organic carbon stocks of above- and below-ground biomass, soil organic carbon, litter and dead wood will be covered by LCA /IPCC 2006/. Changes in organic carbon stocks may result from extraction of woody biomass or straw for bio-refining, which formerly remained on the field / in the forest. The carbon stock changes and resulting release of greenhouse gases (mainly in the form of CO_2) are integrat-

ed into the GHG balances by using the above mentioned methodologies if alternative land use options lead to different carbon stocks. The methodologies described by the IPCC guidelines for national greenhouse gas inventories /IPCC 2006/ and the guidelines for the calculation of land carbon stocks for the purpose of Annex V to EU RED /EC 2010b/ will be used.

Carbon sequestration, which could also result from a land use change, will not be taken into account. This is because the potential to sequester carbon in soil is very site-specific and highly dependent on former and current agronomic practices, climate and soil properties /Larson 2005/. Moreover, it is impossible to assure that the carbon is sequestered permanently. As there is no scientific consensus about this issue, carbon sequestration in agricultural soils will not be accounted for.

Indirect effects

New systems using biomass can indirectly affect environmental indicators by withdrawing resources from other (former) uses. One of the most common indirect effects is indirect land use change: Biomass formerly used for other purposes (e.g. as food or feed) has to be produced elsewhere if it is now used for biorefineries. This can cause a clearing of (semi-)natural ecosystems (=indirect land use change) and hence changes in organic carbon stocks and damages to biodiversity.

Withdrawing biomass from other uses may affect not only land use patterns but also other goods and services. For example, if a SWEETFUEL bioethanol plant is less efficient compared to another energetic biomass use option (e.g. CHP plants) in terms of replacement of crude oil equivalents but more efficient from an economic point of view and hence withdraw biomass from direct energetic use pathways, the crude oil production may even increase.

7.3.1.4 Data origin and data quality

Since sweet sorghum is cultivated in many different regions, for the SWEETFUEL project a multitude of data and information with respect to agricultural production and reference systems are needed. Those data were provided by the project partners.

Data on equivalent products of the outputs and their production chains were deduced by IFEU /IFEU 2014/.

7.3.2 Life cycle environmental impact assessment (LC-EIA)

A comprehensive assessment of environmental impacts also has to take into consideration local impacts on environmental factors like e.g. biodiversity, water and soil. A general introduction to LC-EIA methodology and the derivation of the life cycle environmental impact assessment approach is given in /Reinhardt et al. 2014/. In the following, the LC-EIA approach in the SWEETFUEL project is summarised.

For the purpose of this project, which encompasses neither an actual site-specific production of sweet sorghum nor the construction of a plant, it is not appropriate to perform a full-scale EIA according to regulatory frameworks, which is always project and site specific. Nevertheless, elements of environmental impact assessment (EIA) are used to characterise the environmental impacts associated with the SWEETFUEL concepts at a generic level.

The elements of EIA used in this project are shown in Fig. 7-1.

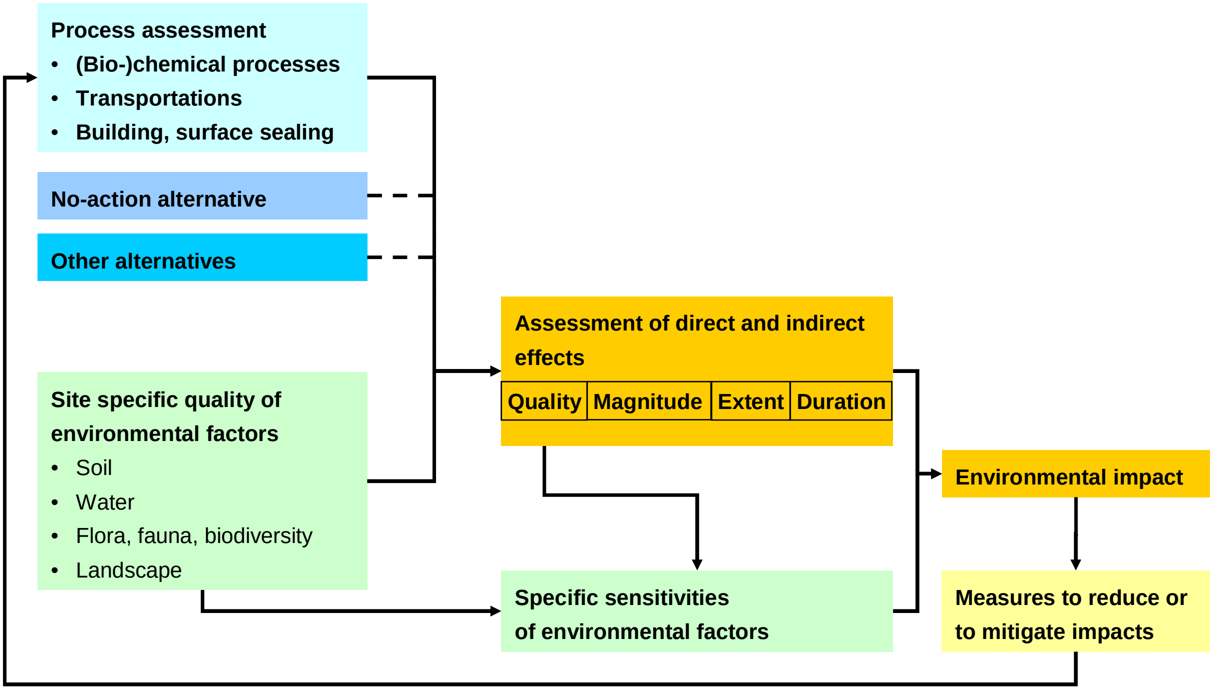

Fig. 7-1 Structure of an LC-EIA in the SWEETFUEL project.

Reference systems

Generally, an EIA compares a planned project to a so-called no-action alternative (a situation without the project being implemented) in terms of environmental impacts. This assessment is restricted to one specific project or site such as a biorefinery. Biomass production sites and / or the impacts associated with the end use of the manufactured products are usually not considered.

For SWEETFUEL, the scope, and therefore also the reference system, of the EIA was chosen to encompass all life cycle stages from biomass production through biomass conversion up to the use of the manufactured products. This corresponds to a life cycle perspective and goes beyond the regulatory frameworks for EIA.

Covering the impacts of biomass production is crucial for the environmental assessment because the land-use impact (including indirect impacts on fauna and flora, biodiversity, soil and water) of biomass production exceeds the land-use impact of biomass conversion by far. Therefore, the reference systems are divided into 1) reference systems for biomass production and 2) reference systems for biomass conversion and use.

Impact assessment

The assessment of environmental impacts of biomass production, conversion and use is carried out as a benefit and risk assessment. This is useful if no certainty exists regarding the possible future location of biomass cultivation sites and conversion facilities.

Impact assessment for biomass production

In the case of biomass production the factors that have been identified to assess the possible benefits and risks of biomass production are illustrated in Fig. 7-2.

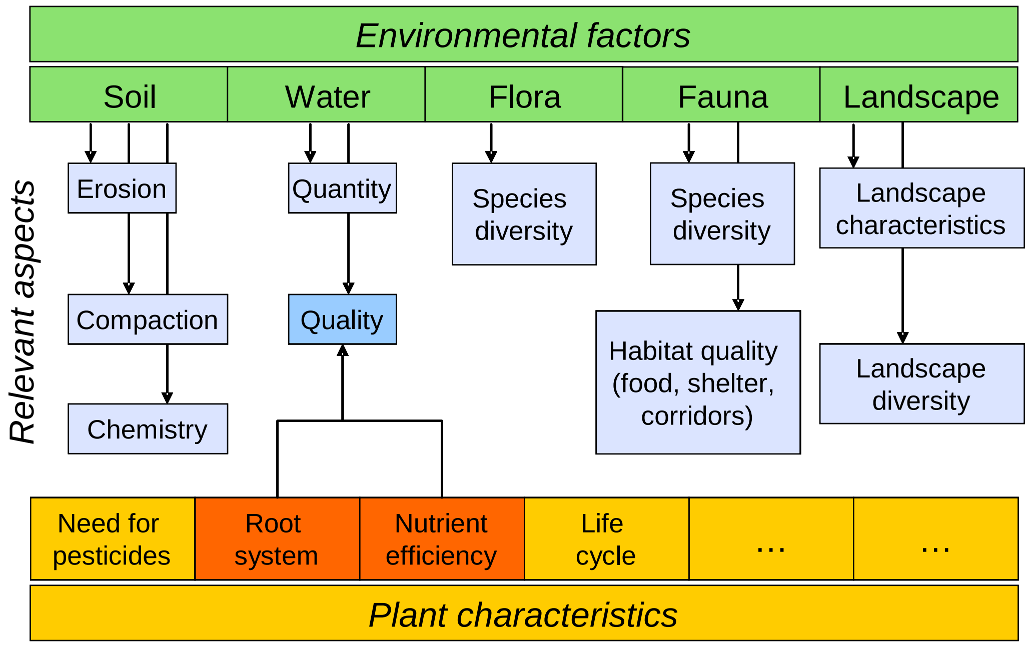

Fig. 7-2 Identification of factors for the LC-EIA of biomass production.

Based on these factors, a biomass-specific assessment of the environmental impact is conducted. After that, an evaluation of different biomass feedstock relative to the respective reference systems is done by qualitative-descriptive classification in different classes. Moreover, geographic differences are evaluated.

Impact assessment for biomass conversion and use

A separate benefit and risk assessment is performed for biomass conversion and use. This assessment covers the impacts caused by a conversion plant, by the use of bio-based energy carriers and products as well as by transportation of biomass feedstock and intermediates. The benefits and risks assessment for conversion, use and transportation investigates potential effects of conversion and use units on the local environment. The aspects human health, soil, flora, fauna and landscape are studied. Effects beyond the local environment (e.g. greenhouse effect) are derived from results of LCA.

The potential environmental benefits and risks of the different conversion technologies as well as the environmental issues potentially affected by these factors are shown in Table 7-4.

Table 7-4 Technology-related factors, environmental issues and potential environmental impacts of biomass conversion and use.

Technology-related factor	Environmental issue	Potential environmental impact
Emission of noise and odours	Human health	Annoyance by an increase of environmental noise or gaseous emissions
Waste water and waste water treatment	Water	Depletion of water resources Nutrient input into water bodies causing eutrophication
Amount of traffic (noise and gaseous emissions)	Human health	Annoyance by an increase of environmental noise or gaseous emissions
Size and height of conversion plants	Soil Flora Fauna Landscape	Soil compaction or soil sealing Loss of vegetation Loss of habitat Landscape disturbance

Development of conflict matrices

Aggregated conflict matrices are created based on the biomass-specific benefits and risks, which summarize the impacts of biomass production, conversion and use on the selected environmental factors.

The following qualitative indicators are used in the conflict matrices to compare the environmental impacts of biomass production, conversion and use to the respective reference systems (relative evaluation):

- "Positive": compared to the reference systems, biomass production, conversion and use is more favourable
- "Neutral": biomass production, conversion and use show approximately the same impacts as the reference system
- "Negative": compared to the reference systems, biomass production, conversion and use is less favourable.

7.4 Methodology economic assessment

This subchapter contains a summary of the methodology used for the economic assessment. For the complete methodology please refer to /Basavaraj, Parthasarathy Rao et al. 2014/.

7.4.1 Conceptual framework for economic assessment

The conceptual framework of economic assessment is based on the life cycle discerning production, processing, use and maintenance costs. A steady state cost model (meaning all technologies remain constant in time) is employed and thus it cannot be used to model the dynamic effect in the real markets. The cost model assumed is linear homogeneous or homogeneous to degree 1 implying that as inputs are doubled the output is also doubled. The present study concerns the comparison of production of the end products (as described in sweet and biomass sorghum scenarios) on one hectare of land.

7.4.2 Cost categories

Four levels of cost categories are distinguished in the current study for all the sweet and biomass sorghum scenarios to conduct economic assessment. These include;

- Production costs of sweet sorghum and biomass sorghum which include all production activities starting with land preparation till harvest.
- Transport cost which includes cost of transporting sweet sorghum and biomass sorghum to the centralized ethanol processing units.
- Processing costs which include cost of converting sweet and biomass sorghum to different use pathways
- Cost of acquisition, operations and maintenance

A detailed overview of the above mentioned cost categories along with units are described in Table 7-5. The costs include all the generic sweet and biomass sorghum scenarios and do not distinguish between different use pathways.

7.4.3 Cost and revenue estimation

Cost estimation implies an assessment of the value or price something has. A parametric type of cost estimation (cost per unit) is used. The costs per complete process (either production or processing) of the reference flows (sweet and biomass sorghum scenarios) have been calculated by multiplying the costs per reference unit with the absolute amount of inputs required for the process output.

In case of capital costs on machinery / equipment, interest cost on investment and working capital, depreciation and personnel costs (wages and salary), the information is gathered from available literature wherever relevant for cost estimation. These costs are then scaled to

match the production output required for each standardised processing plant. The revenues derived from the co-products for each of the sweet and biomass sorghum scenarios described are subtracted in the total cost of producing the process outputs.

For cost estimation, the world average price of inputs used to generate outputs of sweet and biomass sorghum are obtained from "pink sheets" from World Bank and FAO statistics and relevant websites (www.alibaba.com, www.amazon.com). In case of non-availability information, prices for inputs are obtained from literature.

Table 7-5 Overview of cost categories

Cost category	Cost type with units
Production cost	Seed cost (kg / ha / yr) Fertilizer cost (kg / ha / yr) Pesticide cost (kg / ha / yr) Diesel cost for field preparation, sowing, fertilizing, spraying and harvesting (litres / ha / yr)
Transport cost	Diesel cost (litres / ha / yr)
Processing cost	Yeast (gram / litre of ethanol) CaO (kg / ha / yr) H_2SO_4 (kg / ha / yr) NH_3 (kg / ha / yr) Enzymes (gram / litre of ethanol) NH_3 (kg / ha / yr) Chemicals for water treatment (kg / ha / yr) Power (kWh / ha / yr)
Acquisition, operation and maintenance	Capital costs of machinery (euros) Rent (euros) Personnel costs (euros / day) Interest cost on investment (loan) and working capital (%) Depreciation costs (euros)

7.4.4 Geographical differences and Exchange Rates

The inputs used to generate outputs of sweet and biomass sorghum, differ depending on the geographical reference that is considered. For example, inputs for production and processing of sweet sorghum to ethanol in the cane fallow scenario are obtained under Brazilian conditions as geographical reference. Due to these geographical differences, world average prices (in dollars) obtained from "pink sheets" of World Bank, FAO statistics and relevant websites (www.alibaba.com, www.amazon.com) for the inputs are converted to euros at 2012 exchange rates. The data on absolute quantities of input used were compiled for the year 2012 by WP5. Hence, 2012 is used as reference year for exchange rate conversion from dollars to euros and cost estimation.

7.4.5 Cost aggregation

To aggregate costs over the different phases of the life cycle of sweet and biomass sorghum for different use pathways, the steps involved were:

- Identification of the subsystems that could result in different cost and revenues
- Assignment of costs or prices to the respective subsystems identified in step 1
- Calculation of costs per unit of subsystem by multiplying the cost per reference unit with the absolute quantities of the process outputs
- Aggregation of all the costs and prices of all the subsystems over the complete life cycle.

This stepwise calculation allows one to provide costs for certain cost categories (production, processing, co-products) and costs over a certain period of time.

7.4.6 Discounting

Discounting in the present study is applied for two reasons. To understand whether profit can be made from the technology choice of sweet and biomass sorghum for different use pathways and the other to deal with cost of borrowings. Typically, the discount rate for private investments is between 5 % and 20 %, to be decided by the private decision maker. For long-term projects in the public sector, the discount rates can be as low as 2 %.

In the study, discounting wherever relevant is integrated into the calculations. The discount rates for different installations vary based on how they depreciate. For example, much of the major equipment installation has a useful life of 15 years and would be depreciated at 10 % per annum. Hence, instead of computing separately for each of the investment processes (example capital equipment, plant, building) estimates available from Asia Pacific Economic Cooperation (APEC) Energy Working Group reports 2010 which have similar product outflows were used for analysis wherever relevant.

7.4.7 Uncertainty in cost data and sensitivity analysis

As already specified in the general settings, sweet sorghum is cultivated in various regions covering multiple climatic conditions and cultivation practices (e.g. the amount of fertiliser as well as harvesting expenditures) which can result in strong variations in yield. The influence of those yield differences are assessed via sensitivity analyses. Thus, low, typical and high case values were defined to cover the bandwidths of such parameters.

Furthermore, due to various process technologies used in multiple regions different conversion efficiencies may occur. Thus, also for this parameter, low, typical and high datasets were defined to cover a bandwidth of the parameter.

Additionally, inconsistencies in the costs used in the economic assessment can relate to the definition of the cost, collection methods, costing method and type, cost considerations, geographical differences, exchange rates, among others. To overcome such uncertainties, data on absolute quantities used in the process were defined for low, typical and high cases. Ac-

cordingly, the results are presented for low, typical and high cases for each of the use pathways of sweet and biomass sorghum.

7.4.8 Capital and Operational cost and assumptions for economic assessment

The cost model used for economic assessment takes into account indicators of commercial viability i.e. Net variable cost, NPV (net present value) & IRR (internal rate of return). Most of the assumptions on financing (site development costs, procurement & construction costs, equity and debt capital and crushing capacity) for this study are directly taken from APEC report, 2010 and investment costs for use of biomass sorghum to biogas and biomethane (typical for European conditions) were provided by KWS (a plant breeding company in Germany named after Kleinwanzlebener Saatzucht), partner in the SWEETFUEL project (Table 7-6). Operational expenditure (OPEX) is arrived at taking all cost on per litre basis and scaling it up using plant capacity (Table 7-6). The financial analysis further assumes an amortisation period of 15 years. It is generally found that both processing and labour costs have greater impact on scale economies of the plant. Hence, sensitivity analysis is carried out by assuming 10 % and 15 % decline in processing and labour cost for typical and high scenarios, respectively. Further, the interest costs, rent, other payments on working capital are assumed to remain constant as the scale increases. A nominal interest rate of 10 % is assumed for financial analysis in all the scenarios.

7.4.9 Systematic exclusions in the study for economic assessment

Though a life cycle framework is used in the present study for economic assessment, it does not take into consideration certain of the costs in life cycle phase due to: in some cases non availability of data and in other complexities involved in their calculations and linearity assumption of cost model as in the present study.

The costs not considered in the assessment include:

- Research and development costs
- Transfer payments (subsidies)
- External costs (Taxes and tariffs)
- Externality costs
- End of life costs/disposal costs
- Profit margin

Table 7-6 Value of capital and operational expenditures for the economic assessment for different scenarios /APEC 2010/.

Scenario	CAPEX (Capital expenditure, million euros)	OPEX (Operational expenditure; million euros) Low scenario	Crushing Capacity (million tonne per annum)
Sweet sorghum: juice to ethanol	57.53	82.10	1 million tonne stalks
Sweet sorghum: juice+ grain to ethanol	57.53	89.43	1 million tonne stalks+ 0.1 million tonne grains
Grain to food scenario	57.53	83.79	1 million tonne stalks
Sweet sorghum: syrup to ethanol	57.53	88.17	1 million tonne stalks
Biomass sorghum to biogas	2.0	0.75	11 500 tonne biomass
Biomass sorghum 2nd gen. ethanol	112.22	1413.14	0.5 million tonne
Biomass sorghum FT diesel	56.19	210.77	1 million tonne

7.4.10 Data origin and data quality

Since sweet sorghum is cultivated in many different regions, for the SWEETFUEL project a multitude of data and information with respect to agricultural production and reference systems are needed. There was no generic data format concerning economic assessment. Data requirement are strongly dependent on the goal and scope of the study, and the cost differences are the main concern rather than absolute figures. Concerning the cultivation of sweet sorghum across geographical reference systems, data on production of sweet and biomass sorghum for the study is obtained from WP 5 compiled across geographical settings and is used for the economic assessment.

7.5 Methodology SWOT analysis

This subchapter contains a summary of the methodology used for the SWOT analysis. For the complete methodology please refer to /Rutz & Janssen 2012c/.

7.5.1 The SWOT analysis

A SWOT analysis is a strategic planning tool used to evaluate the Strengths, Weaknesses, Opportunities, and Threats involved in a project or business venture. It involves ***specifying the objective*** of the business venture or project and identifying the ***internal and external factors that are favourable and unfavourable to achieving that objective***.

In this report the SWOT analysis is applied to different value chain systems of sweet sorghum as an energy crop. Factors which are internal to the sweet sorghum pathways (characteristics of cultivation and conversion) are classified as Strengths (S) or Weaknesses (W), and those external to the sweet sorghum pathways (regarding markets, policies and sustainability certification) are classified as Opportunities (O) or Threats (T). The SWOT matrix is shown in Fig. 7-3.

	Favourable to achieve the objective	Unfavourable to achieve the objective
Internal	**Strengths**	**Weaknesses**
External	**Opportunities**	**Threats**

Fig. 7-3 General scheme of the SWOT tables

7.5.2 Objective of the analysis

The objective of the SWEETFUEL sustainability analysis is **to identify the best pathways to produce and use sweet sorghum as energy crop from an ecological, economic and social point of view**.

The SWOT analysis is a tool to contribute to this objective. Results of the SWOT analysis shall help in decision making processes for improved sweet sorghum value chains in different climates and framework conditions in order to:

- ensure competitiveness/complementary with other energy (bioethanol) crops
- ensure competitiveness with fossil based energy/products
- guarantee environmental, social and economic sustainability

The SWOT analysis describes the state-of-the-art of sweet sorghum chains in order to formulate optimisation strategies for sweet sorghum production and use pathways. Also poten-

tial future developments are considered and integrated in the SWOT analysis. Thereby, the timeframe includes the years 2014 (the real situation at the end of the SWEETFUEL project) and 2020 (expected future based on conservative assumptions).

7.5.3 Stakeholder involvement

In order to complete the SWOT tables, an extended stakeholder review was included in the analysis. A “Workshop on SWEETFUEL SWOT Analysis” was organised on 17 April 2012 in Bologna, Italy. Furthermore, the draft SWOT analysis report and a dedicated questionnaire were sent to stakeholders for input. Many stakeholders provided very useful comments which were included in the final report. The stakeholders are listed in the Acknowledgements of this report.

7.5.4 Structure of the SWOT analysis

Sweet sorghum is a promising energy crop adaptable for different climatic conditions and providing a large variety of products and by-products, such as energy, food, fodder, and fibre. This is the result of the large genetic variability of the *Sorghum* genus leading to a wealth of different genotypic and phenotypic traits of sweet sorghum varieties. Therefore, strengths, weaknesses, opportunities and threats are also very diverse among sweet sorghum varieties and different value chains in productions systems.

However, several characteristics are common to sweet sorghum as an energy crop and thus, in a first step, the SWEETFUEL SWOT analysis describes general strengths, weaknesses, opportunities and threats of sweet sorghum.

In a second step, SWOT analyses are elaborated for different production systems in subtropical/tropical and temperate climate zones. These production systems include centralized ethanol, decentralized syrup and decentralized ethanol systems in subtropical/tropical climate as well as biogas, lignocellulose-ethanol, direct combustion and gasification systems in temperate climate. For several of these systems two SWOT tables are shown: one for the sweet sorghum cultivation and one for sweet sorghum conversion to end products. Thereby, end products may include energy carriers (e.g. biogas), energy (e.g. electricity), fertilizer (e.g. digestate), food (e.g. grains), fodder (e.g. leaves, bagasse) and other co-products. The use of energy carriers for different purposes is included in the SWOT table.

In summary, the following analyses are made and described in dedicated subchapters:

- General SWOT for sweet sorghum
- Subtropical and tropical climate
  - Centralised production system (cultivation and conversion)
  - Decentralised syrup production system (cultivation and conversion)
  - Decentralised ethanol production system (cultivation and conversion)

- Temperate climate
  - Biogas production system (cultivation and conversion)
  - Lignocellulose-ethanol production system (cultivation and conversion)
  - Direct combustion system (cultivation and conversion)
  - Gasification system (cultivation and conversion)

The SWOT tables are providing brief statements (in bullet form) on the strengths, weaknesses, opportunities and threats of the production systems. These tables shall allow a quick overview about advantages and disadvantages of each production system.

The SWOT statements address a large variety of environmental, social and economic sustainability aspects. Depending on the value chain, these statements may include the following sustainability aspects.

- Land use
  - Land use and land use change
  - Competitive land use
  - Land use conflicts
- Social aspects
  - Benefits for smallholders
  - Income opportunities
  - Employment opportunities
  - Change in traditional use and knowledge
  - Supply with modern energy as substitute for traditional bioenergy
  - Energy security
  - Gender aspects
  - Working conditions
  - Health
  - Food security
  - Food and feed prices
- Environment
  - GHG emissions
  - Human- and ecotoxicity
  - Biodiversity
  - Soil conservation and soil quality
  - Water availability, use and efficiency

  - Water quality
  - Resource depletion
  - Eutrophication (terrestrial and aquatic)
  - Acidification
- Economics
  - Productivity and processing efficiency
  - Competitiveness and comparative advantage of the feedstock
  - Net energy balance
  - National revenues, gross value added
  - Energy security (security of supply)
  - Infrastructure and logistics
  - Pricing of the end products
  - State of commercialization / competitiveness with reference products

Finally, a core focus is placed on the competition between the biomass uses for food, feed, fibres, and biofuels and on different scales of sweet sorghum production and use. Furthermore, **policy aspects** such as different policy framework conditions in target countries as well as issues of **social acceptance and public perception** are taken into account.

8 Glossary and abbreviations

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
2G ethanol	see 2nd generation biofuels
APEC	Asia Pacific Economic Cooperation
ARC	Agricultural Research Council, Potchefstroom, South Africa; http://www.arc.agric.za/
Bagasse	Fibrous matter that remains after stalks are crushed to extract the juice
Biomass sorghum / BS	Sorghum cultivars with high lignocellulosic biomass yield, potentially used as energy crop
BtL	Biomass-to-Liquid; synthetic biofuels produced via biomass gasification
C4 plant	Plants using a 4-carbon molecule as a first product in the carbon fixation pathway (in contrary to a 3-carbon molecule of C3 plants), which leads amongst others to higher water use efficiencies.
CAPEX	Capital expenditure
CFC	Chlorofluorocarbons; Class of chemical compounds often used as refrigerants
CH_4	Methane
CHP	Combined heat and power; co-generation of electricity and heat
CIRAD	Centre de Coopération Internationale en Recherche Agronomique pour le Développement, Paris, France; http://www.cirad.fr
CO_2	Carbon dioxide
Cultivar	Plant or group of plants selected for some desirable characteristics. Cultivar is a general word that includes lines, varieties and hybrids.
DDGS	Dried distillers grains with solubles, a protein-rich co-product of bioethanol production from cereals
EIA	Environmental impact assessment; a standardised methodology for analysing proposed projects regarding their potential to affect the local environment
EMBRAPA	Empresa Brasileira de Pesquisa Agropecuária, Brasília, Brazil; http://www.embrapa.br
Energy sorghum	Sweet and biomass sorghum cultivars used in this project
Eq. / Equiv.	Equivalent
FAO	Food and Agriculture Organization
Fibre sorghum	Biomass sorghum cultivars with a high content of fibre; potentially used as fibre or energy crop
FP7	European Commission’s Seventh Framework Programme
FT diesel	Fischer-Tropsch diesel; the FT process converts carbon monoxide and hydrogen into liquid hydrocarbons, which can be further processed into synthetic diesel
GHG	Greenhouse gases
GJ	Gigajoule
GMO	Genetically modified organism
Grain sorghum	Sorghum cultivars with high grain yield established as food or feed crop

Ha	Hectare
Hybrid	Offspring resulting from the cross between two genetically dissimilar parental lines. Usually, seeds from hybrids don't consistently provide the desired characteristics, so hybrid seed should be repurchased by growers for each planting season.
ICRISAT-IN	International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India; http://www.icrisat.org
Idle land	Reference systems such as degraded soils or land that becomes free due to different reasons e.g. the intensification of existing land use (see also subchapter 2.1, "Alternative land use options")
IFEU	Institute for Energy and Environmental Research Heidelberg, Germany; http://www.ifeu.de
IE	Inhabitant equivalent
ILUC	Indirect land use change
IP	Intellectual property
IRR	Internal rate of return
ISCC	International sustainability and carbon certification
kWh	Kilowatt hour
KWS	KWS Saat AG, Einbeck, Germany; http://www.kws.de
L.	Linné
LCA	Life cycle assessment
LC-EIA	Life cycle environmental impact assessment (assessment of local environmental impacts taking into account the stages during the whole life cycle of a product from cradle to grave)
LCIA	Life cycle impact assessment
Line	Breeding material which tends to be genetically identical
LUC	Land use change
N	Nitrogen
N/A	Not applicable
N/D	No data / not determined
NH_3	Ammonia
NIMBY	Not in my back yard
N_2O	Nitrous oxide, commonly known as laughing gas
NO_3^-	Nitrate
NO_X	Nitrogen oxide
NPV	Net present value
ODP	Ozone depletion potential
OPEX	Operational expenditure
Pesticide	Pesticides (insecticides, fungicides, herbicides, etc.) are substances meant for preventing, destroying or mitigating any pest
PM_{10}	Particulate matter smaller than about 10 micrometres
PO_4^{3-}	Phosphate
R 11	Trichlorofluoromethane, also: chlorofluorocarbon
RED	European Renewable Energy Directive; directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009
RSB	Roundtable on sustainable biofuels

SEA	Strategic environmental assessment
SO_2	Sulfur dioxide
SWEETFUEL	Project "Sweet Sorghum: an alternative energy crop"; supported by the European Commission in the 7th Framework Programme to exploit the advantages of sweet sorghum as potential energy crop for bio-ethanol production
Sweet sorghum / SS	Sorghum cultivars with juicy stems and high juice sugar content in their stalks, potentially used as an energy and food crop
SWOT	Strengths, Weaknesses, Opportunities, Threats
UANL	Universidad Autónoma de Nuevo León, México; http://www.uanl.mx
UCSC	Università Cattolica del Sacro Cuore, Piacenza, Italy; http://www.unicatt.it
UNIBO	Università di Bologna, Italy; http://www.unibo.it
Variant	Term used here to summarise sweet, grain, biomass, energy and fibre sorghum
Vinasse	By-product of the fermentation of certain process residues to e.g. ethanol
WIP	WIP Renewable Energies, Germany; http: //www.wip-munich.de
WP	Work package
Yr	Year