Environmental competitiveness evaluation by Life Cycle Assessment for solid fuels generated from *Sida hermaphrodita* biomass

Authors:

Andreas Schonhoff[1]*, Nicolai David Jablonowski[2], Petra Zapp[1]

* corresponding author

e-mail: a.schonhoff@fz-juelich.de

postal address: Forschungszentrum Jülich GmbH
Wilhelm-Johnen-Straße
52428 Jülich
Germany

Affiliations:

[1] Forschungszentrum Jülich GmbH, Institute of Energy and Climate Research - Systems Analysis and Technology Evaluation (IEK-STE), Wilhelm-Johnen-Straße, 52428 Jülich, Germany

[2] Forschungszentrum Jülich GmbH, Institute of Bio- and Geosciences - Plant Sciences (IBG-2), Wilhelm-Johnen-Straße, 52428 Jülich, Germany

Keywords:

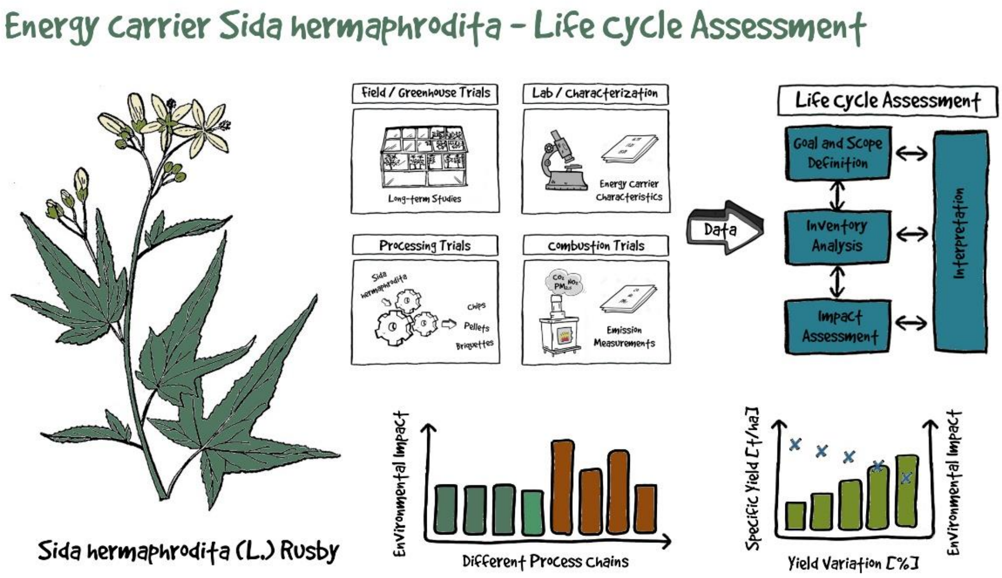
Life cycle assessment, biogenic energy source, small-scale combustion, biomass, perennial energy crop, solid biofuels

Biomass and Bioenergy, 2021, Elsevier

https://doi.org/10.1016/j.biombioe.2021.105966

Abstract

As part of a comprehensive evaluation of the use of *Sida hermaphrodita* (hereafter referred to as Sida) biomass as a solid biofuel, a life cycle assessment (LCA) according to ISO 14040/14044 was carried out by means of a suitable cradle-to-gate system design. The supply and use of chips, pellets and briquettes was studied by internal and external comparisons to show competitiveness and improvement options. The results show fewer differences within the Sida process chain designs but larger distinctions to compared alternative biofuels such as wood or *Miscanthus* pellets. A major finding is that Sida process chains cause lower environmental impacts in comparison with alternative biofuels. The study identified hot spots within the Sida process chains and starting points for further improvement. A sensitivity analysis of important parameters, such as specific yield or heating values was performed. Because there are no similar investigations on the environmental impact of Sida used as a biogenic solid fuel to date this manuscript presents first results. So far, the results indicate that Sida provides a more sustainable option for the use of biomass in combustion processes in relation to environmental impacts.



https://doi.org/10.1016/j.biombioe.2021.105966

1 Introduction

With regard to gross final energy consumption the European Union's (EU-28) share of renewable energy was 18.0 % in 2018, which was mainly (ca. 50 %) covered by biomass [1, 2]. Striving further development of decreasing greenhouse gas emissions by 40 % and increasing the renewable energies share to 32 % in 2030 compared to 1990 shows the action required [3]. At the political and societal level recent developments like "The European Green Deal", which specifically targets the decarbonization of the energy sector [4], or "Fridays For Future", which formulate even more ambitious goals [5], reinforce a continuous improvement of technologies (e.g., design of processes or improvement of combustion properties) in biomass-based energy applications. The comprehensive evaluation of new and innovative biomass supply can help to identify beneficial technologies but also describe improvement potentials. A less spread energy plant, the woody-like perennial non-food *Sida hermaphrodita* (L.) Rusby (hereafter referred to as Sida) offers improvements for energy generation [6]. As one part of a holistic approach, environmental impacts of the supply and use of Sida are assessed by life cycle assessment (LCA) [7].

Sida, also known as Virginia mallow or Virginia fanpetals, is part of the mallow family and has its origin in North America (Figure 1). In the middle of the 20th century, the plant was imported via Russia to Poland, where it is mainly used for energy purposes today. Without clear statistics on the European level Sida gains currency in a magnitude of less than 1,000 ha cultivation area [8]. One remarkable advantage of Sida is the possible high yield of up to 25 t_{DM} ha^{-1} [6]. Further good reasons to take a closer look at the use of Sida as an energy carrier can be found in its benefit for the ecosystem and the low requirements regarding soil conditions, allowing extensive cultivation [9]. Long flowering periods of Sida provide an important source for pollinators [10], heavy metals can be absorbed in terms of soil remediation [11], the nutrient need is low and the water demand is half as much as for willows in short rotation coppice (SRC) [12]. The ability to grow on marginal land allows the avoidance of the "food vs. fuel"-discussion [13]. Considering alternative fertilization using digestate as a residue from biogas production, substantial Sida biomass yields were even obtained when grown on marginal soils [14, 15]. In addition, calculations based on production cost data from Jablonowski et al. [7] show the economic competitiveness in comparison to wood pellets for example.

Figure 1: Photographical illustration of a Sida plants; A: Sida inflorescent B: young Sida plants C: Sida shoots at bottom D: Sida plants at harvest time in March 2018 at one of the test fields of the IBG-2: Plant Sciences, Forschungszentrum Jülich GmbH.

At the IBG-2: Plant Sciences, Forschungszentrum Jülich GmbH, Germany, different topics like the growth of Sida on marginal sandy soils, its symbiotic relationship with legumes such as alfalfa, or the technical and normative usability as an energy carrier have been investigated [13, 9, 6, 16]. Generated data from laboratory, greenhouse and long-lasting field studies built the basis for the inventory in our study.

In the last two decades bio-based products and biomass use came more into focus of LCA and the methods are constantly developing and being discussed (e.g., [17, 18, 19]). One focus of discussion is on different methods for the consideration of carbon storage and land use in LCA. Liptow et al. [19] emphasized limiting conditions like data availability and variability as well as differences of topic-specific methods (cf. 2.1.4). Pawelzik et al. [18] recommended the application of the ILCD method (cf. 2.1.3) for systems that use bio-based materials. In addition, Martín-Gamboa et al. [20] showed a large variety of assessment methods and system boundaries for LCAs of biomass pellet production and use. Besides the consideration of the classic biogenic energy carrier wood, other studies also include less spread or rare used biomasses like grape stalks [21] or black locust [22]. The assessment of different energy carrier forms is often limited to woody biomass (e.g., [23, 24]). The assessment of Sida, but also *Miscanthus* biomass was performed by Krzyzaniak et al. [25, 26], but with tighter system boundaries and a focus on different fertilizer applications.

The focus of the presented LCA-work is on the use of Sida as a solid energy carrier, which is processed differently in form of chips, pellets or briquettes, before it is combusted for heat production to provide district heating. Because of the fictive character of the overall process chains, the assumed processing design had to be developed for each intermediate product (e.g., pellets) of the energy carrier. Thresholds like those from the guidelines for pellets or briquettes [27, 28] and suitable equipment for the thermochemical conversion to energy were taken into consideration. To get a broad understanding of the considered applications an internal comparison (Sida process chains) to identify the most advantageous processing route were carried out. To get an idea of the environmental competitiveness of Sida an external comparison to alternative biofuels, such as different forms of wood or *Miscanthus* pellets was conducted. Furthermore, different sensitivity analyses in relation to specific yields and heating values were implemented and analyzed. According to present knowledge, this study is the first LCA that considers Sida in such a system with the scope described below. The consideration of different provision forms and the specific combination with different biomasses compared are further unique characteristics. The varied consideration of Sida energy carriers offers new perspectives for the future spreading of Sida. Moreover, a contribution to the extended knowledge about environmental impacts of biomass use is added.

2 Material and methods

In line with ISO 14040/14044 standards the LCA for Sida was carried out including the mandatory steps of goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and interpretation [29, 30]. To realize the assessment, different process chains were implemented in the LCA-Software GaBi 9.2 [31]. Information for the main (foreground) processes was taken from a project [6, 16], complemented by suitable literature data. Necessary data for background processes was taken from the GaBi and ecoinvent 3.5 databases [32, 33]. Detailed data for the single processes of the *Miscanthus* process chain was taken from above mentioned project data, literature and databases. Thus, these data and further details about germination rate [34], plant density or weed control [35], ash contents [36], etc., were combined with existing datasets from ecoinvent 3.5 (e.g., chopping of *Miscanthus*) into a generic process chain. Data for the process chains of further alternative woody biomasses (see 2.1.2) was taken from the ecoinvent 3.5 database by the use of aggregated LCI datasets.

2.1 Goal and scope

Goal of this study is the comparison of environmental impacts of three different processing routes for Sida biomass used as a solid fuel. An internal comparison of impacts allows the identification of the most advantageous processing route. Additional aim of the study is the generation of information for potential stakeholders (e.g., farmer or energy carrier users) about environmental impacts (e.g., climate change), by an external comparison to alternative biomasses. Furthermore, improvement potentials are evaluated for each processing route.

Therefore, three different process chains (Figure 2) were developed representing the different pathways of Sida biomass. The following process chains describe the production and use of chips (process chain SI), pellets (process chain SII) and briquettes (process chain SIII). The environmental impacts are compared to results from established conventional biomass process chains for the use of *Miscanthus* and woody biomass.

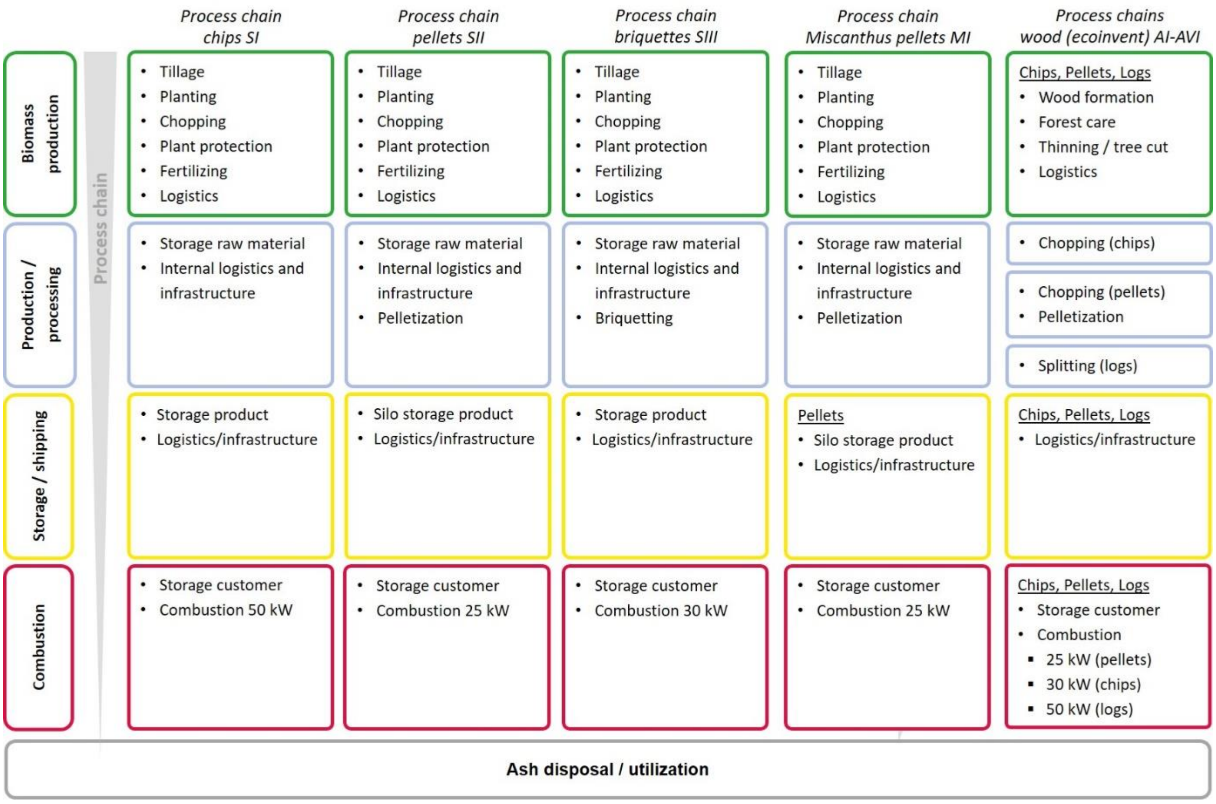


Figure 2: Simplified structure of process chains with five process stages for the supply and use of Sida as a solid fuel in process chain SI (chips), SII (pellets) and SIII (briquettes) as well as for alternative wood-based solid biofuels process chain.

2.1.1 Sida process chains

The process chains SI, SII and SIII are set as cradle-to-gate systems. All essential steps from the biomass production to the combustion stage, including ash disposal, were considered. The three developed and implemented Sida process chains consist of five process stages as shown in Figure 2.

The system starts with the process stage of biomass production containing the same process modules in all process chains but with different quantitative characteristics, depending on the considered lower heating values, biomass losses, etc. Processes include actual applications like harrowing or fertilizing, their energy demands (e.g., diesel or electricity) and manufacturing of equipment as well as the production and supply of necessary operation materials, like fertilizers or water. Thus, this stage contains the tillage of the farmland, the planting of seedlings and related preparations (plant protection) and the fertilization during growth phase. Afterwards, the chopping of the Sida biomass is realized analog to corn harvest using a conventional corn shredder. The implemented process chains also consider all related transports of machinery and biomass with a distance of 5 km in maximum.

Because of the different processing variants like chip production, pelletization or briquetting the structure of the production and processing stage differs in all process chains. The storage and natural drying in SI, SII and SIII is taken into account by specific buildings. The internal transport of raw material is performed by agricultural standard equipment (tractor). For the processing of Sida raw material (chips) to pellets or briquettes, mobile technical units are incorporated, while their mobility is considered with a distance of 50 km in maximum. Besides transport of the technical units, the specific processes are considered by their energy demands for operation and proportionate production of the machinery. The pelletization unit is assumed to have a throughput of about 350 kg h^{-1} and a related energy capacity of 15 kW. Performance data of the briquetting unit is given by a throughput of 300 kg h^{-1} and an energy capacity of 22 kW.

The intermediate products storage (e.g., silos), logistics and infrastructure are varied for the storage and shipping stage. Included activities are the production and operation of storage facilities as well as internal transports. Due to the different types of intermediate products (chips, briquettes, pellets) specific technical equipment is required. Internal logistics are realized by agricultural machinery in SI, screw conveyors in SII and fork lifter in SIII. The storage facilities are modelled by suitable buildings (chips, briquettes) or silos (pellets) as well as a proportionate electricity use.

The combustion stage includes activities like electricity supply for the operation of the users' storage facility in addition to the furnace operation and its manufacturing. The different types of Sida intermediate products (chips, pellets, briquettes) also affect the combustion stage, which is distinguished by the performance class of the used small-scale furnaces. The combustion of chips in process chain SI was modelled by a 50 kW (thermal capacity) furnace, originally designed for wood chips. Process chain SII contains a 25 kW furnace designed for wood pellets, while process chain SIII uses a 30 kW furnace, originally constructed for wood logs. The furnace's datasets (e.g., 25 kW) does not only represent the specific capacity but cover a specific range (e.g., 20-100 kW) lower than 100 kW (nominal capacity). The use of different performance levels reflects practical tests with small-scale furnaces [7].

Ash disposal is included in all process chains as the last step. "Disposal by household waste" is assumed due to the performance class of < 100 kW [37]. This stage is implemented by an ash disposal via incineration of household waste and via sanitary landfill. As a basis for the general process development, a basic process chain of a Sida cultivation area of four ha harvested at one time was assumed. This determination plays a crucial role for the design of process modules (e.g., dimensioning of pelletization or storage).

2.1.2 Process routes for alternative biomass

Just as the process chains SI, SII and SIII the process chain for *Miscanthus* was developed as a generic setup of processes. The general layout of the considered processes is oriented analogous to the mentioned Sida process chains (Figure 2). As these process chains correspond to the general structure of the data sets for woody biomass (see following explanations), comparability is given. Analogous to the process stages described in 2.1.1 the *Miscanthus* (MI) process chain includes a biomass production stage (e.g., tillage, preparation and harvest), the production and processing (e.g., pelletization), storage and shipping, the combustion stage (25 kW) and final ash disposal. An overview is given in Figure 2.

Additional aggregated LCI datasets for alternative biomasses (AI - AVI) were taken from the ecoinvent database. Due to limited availability, considered datasets were referred to wood-related energy carriers only. The compared alternative process chains represent energy carriers like wood chips, wood pellets and wood logs. The considered data include all process stages from biomass production to the energy carrier combustion and ash disposal. The performance classes are in the same magnitude as the Sida process chains SI, SII, SIII and MI. Considered process stages are “the infrastructure, the wood requirements, the emissions to air, the electricity needed for operation, and the disposal of the ashes” [38]. To ensure comparability in relation to the technical key data, only selected datasets (performance reference < 100 kW) were utilized. The performance of the considered furnaces ranges between 25 and 50 kW. In most cases, available state-of-the-art processes (SOTA, 2014) with relation to Switzerland (CH) or the rest of the world (RoW) are considered, because these datasets represent principally processes with lower impacts.

2.1.3 Functional unit and relation

The functional unit (FU) is the supply of 100 GJ thermal energy from combustion of the energy carriers (chips, pellets, briquettes), representing the heating demand for approx. 550 m² living space of a newly constructed apartment building (7 flats) according to German energy saving regulations [39]. The geographical system boundaries in relation to the used data are at European or German level and all data are not older than 2015, if possible.

To realize the valuation of environmental impacts the LCIA-method of the International Reference Life Cycle Data System (ILCD), which includes 16 impact categories, was used [40]. Additionally, a normalization was performed with the method of Product Environmental Footprint (PEF Pilot 1.09), which refers to the EU-27 and includes biogenic and non-fossil carbon emissions [41]. The unit of the output is presented in European person equivalents (PE) [42].

2.1.4 Life cycle inventory

It is necessary to record all inventory data related to the process chains. Selected data for Sida (SI, SII, SIII) and *Miscanthus* (MI) are shown in the following Table 1 with regard to the functional unit of 100 GJ_{th} (see 2.1.3). While Sida data are taken from own trials and research at lab and field scale [6, 16], data for *Miscanthus* are taken from different literature and own calculation (e.g., [35, 7]).

The main inputs (mass related) of SI, SII and SIII are biomass (up to 8,153 kg FU^{-1}) and water (up to 6,232 m³ FU^{-1}). Further inputs are fertilizer (92.8 - 99.8 kg FU^{-1}), direct electricity use (1,041 – 2,728 MJ FU^{-1}) and further energy resources such as material inputs for electricity supply or equipment manufacturing (21.6 – 23.8 GJ FU^{-1}). The intermediate products of each process chain were 6,200 kg chips in SI, 5,811 kg pellets in SII, and 5,999 kg briquettes in SIII, which correspond to the main output of 100 GJ thermal energy in all cases. As a related output, the biomass loss (dry matter) can be numbered with 645 kg_{DM} FU^{-1}, 651 kg_{DM} FU^{-1} and 897 kg_{DM} FU^{-1}, respectively, which equals an input related loss of 8.5 to 11 %. Combining the dry matter loss with the water loss during processing the share of losses increases to 20 to 25 %. The ash content ranges from 2.1 to 3.6 % of the energy carrier mass (127.1 - 225.2 kg FU^{-1}).

The used values for *Miscanthus* are in similar magnitudes (Table 1). As it can be seen, the most advantageous key data of *Miscanthus* is the heating value and low ash content, which was taken from [36]. The fertilizer use is significantly lower (75-80 %) than in SI-III. According to Lask [35] the plant density was assumed as 15,000 plants ha^{-1} for *Miscanthus*, though there are also suggestions for plant densities of 10,000 plants ha^{-1} (e.g., [43, 44]).

For the used datasets of woody biomass processes, the amounts of input material and electricity use are in the same magnitude (Table 1). The ash content of the datasets is significantly lower, with values less than 50 % of Sida (0.4-1.0 %). Due to different moisture contents and processing, the heating value varies between 14 MJ kg^{-1} and 20 MJ kg^{-1}. The presented data for process chains AI-AVI in Table 1 represents the direct input data of the datasets' documentary [33].

Table 1: Life cycle inventory (LCI) for Sida hermaphrodita process chains SI, SII, and SIII, miscanthus chain MI and six selected compared alternative process chains (SOTA = state-of-the-art)

Flow	Unit	SI chips	SII pellets	SIII briquettes	MI pellets	AI logs[1]	AII logs[2]	AIII pellets[3]	AIV chips[4]	AV chips[5]	AVI chips[6]
Inputs											
Harvested biomass	[kg FU^{-1}]	8,152	7,582	7,661	7,239	7,190	7,700	6,670	7,050	7,480	7,290
Water	[m³ FU^{-1}]	6,160	6,131	6,232	4,954						
Electricity*	[MJ FU^{-1}]	1,041	2,396	2,728	2,418	1,336	1,429	1,876	2,002	2,146	2,002
Energy resources**	[MJ FU^{-1}]	21,642	22,770	23,794	19,661						
Fertilizer	[kg FU^{-1}]	99.8	92.8	93.8	76.0						
Intermediate products											
energy carrier eq. (pellets, chips, briquettes)	[kg FU^{-1}]	6,200	5,811	5,999	5,821						
Outputs											
Thermal energy	[MJ FU^{-1}]	100,000	100,000	100,000	100,000						
Biomass loss***	[kg FU^{-1}]	897	645	651	615						
Ash	[kg FU^{-1}]	127	209	215	175	74.7	80	29.8	66.7	68	66.7
parameter											
Heating value	[MJ kg^{-1}]	16.13	17.21	16.67	17.18	depending on moisture ranging between 14 and 20 MJ kg^{-1}					
Moisture (harvesting)	[%]	24.1	24.1	24.1							
Moisture (product)	[%]	9.9	15.0	15.0							

[1] AI - mixed logs | 30 kW | RoW | SOTA; [2] AII - mixed logs | 30 kW | RoW; [3] AIII - wood pellets | 25 kW | CH | SOTA; [4] AIV - wood chips - industrial | 50 kW | CH | SOTA; [5] AV - softwood chips - from forest | 50 kW | CH; [6] AVI - hardwood chips - from forest | 50 kW | RoW | SOTA

With regard to currently discussed LCA-topics it has to be noted that the effect of Sida converting into soil organic carbon and the consequent CO_2-sequestration, which depend on factors as location, soil type or cultivation methods, are not included in the present work due to missing data and ongoing discussions [45, 46, 47]. For identical reasons of not available data, the inclusion of a multiple cycle cultivation (e.g., 20 years of cultivation) was not taken into account (e.g., changes in harvest yield or amounts of fertilizer). It can be expected that a distribution of specific parameters (e.g., fertilization) would reduce specific environmental burdens over a variety of cycles.

3 Results and discussion

3.1 Internal comparison

To identify the most advantageous processing route for Sida the results of the LCIA can be ranked for specific categories. In Figure 3 it is shown that the results of categories like “Climate change incl or excl” or “Ozone depletion” are very similar. They differ by less than 15 % while other impact categories like “Acidification” or “Eutrophication, terrestrial” vary widely, with differences of 100 % or more, which have their origin in the combustion stage. The factors between the largest and lowest value per impact category range from 1.1 to 4.3.

To be able to compare the process chains summarizing all 16 impact categories, the LCIA results were transformed into normalized values (unit: person equivalents, PE) by the mentioned method (see section 2.1.3). The normalized values of the implemented process chains SI, SII, and SIII demonstrated that the impacts differ by less than 2 %, making it impossible to see a clear winner of the process chains.

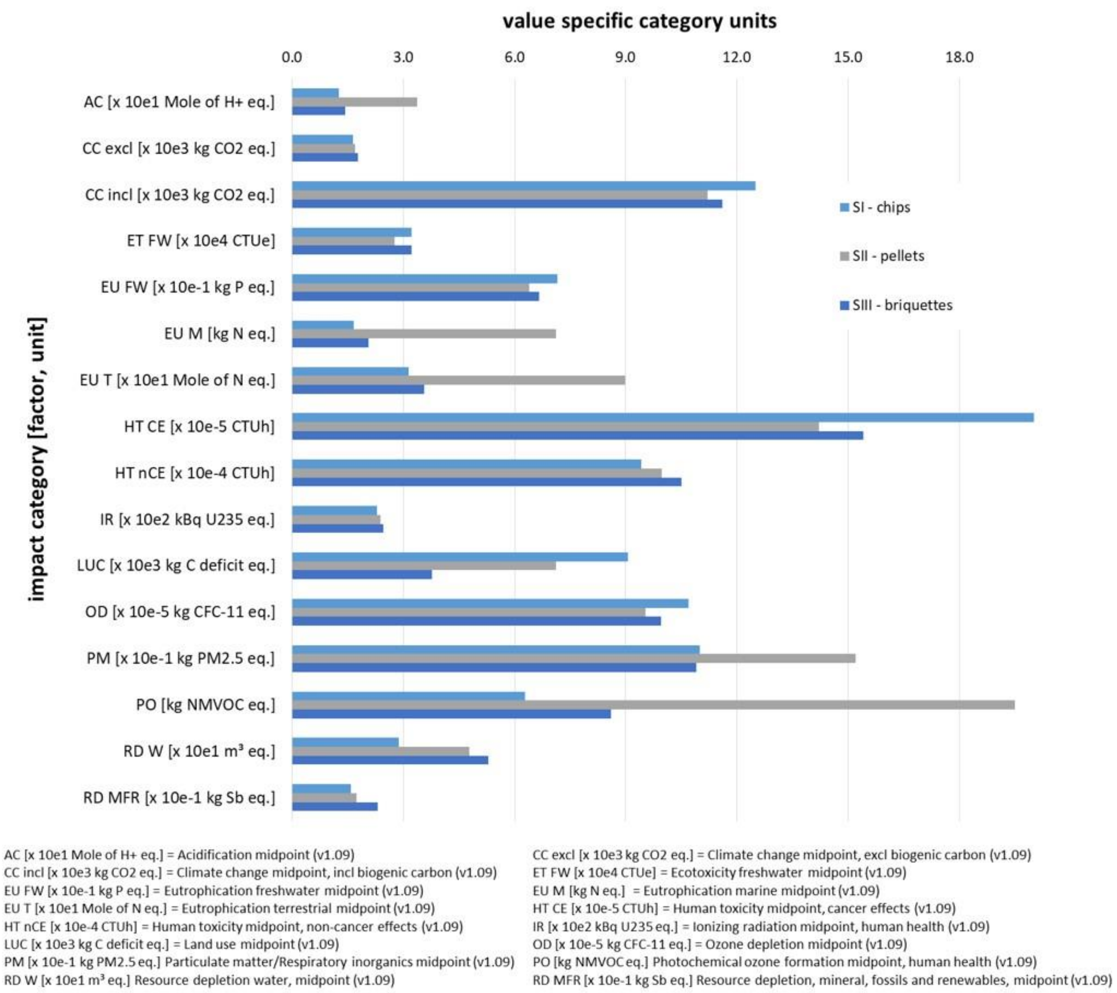


Figure 3: Results of the LCIA for process chains SI, SII and SIII. Results per impact category according to ILCD in specific unit equivalents (comparability only given within the specific category) per 100 GJth.

Figure 4 shows the relative shares of the impact categories. The five impact categories with the largest impact (PE value) are mostly the same in all process chains and can be ranked by decreasing impact:

- Human toxicity midpoint, cancer effects (HT CE)
- Ecotoxicity freshwater (ET FW)
- Human toxicity midpoint, non-cancer effects (HT nCE)
- Resource depletion, mineral, fossils and renewables (RD MFR)
- Climate change midpoint, incl. biogenic carbon (CC incl)

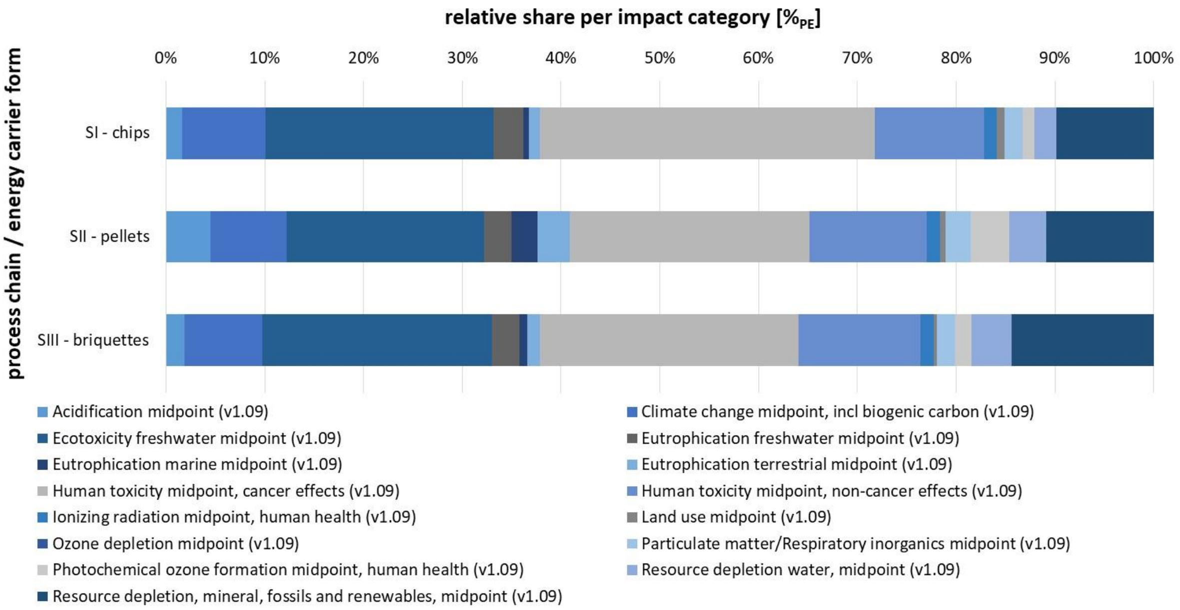


Figure 4: Relative shares of person equivalents per impact categories for process chains SI, SII and SIII per 100 GJth.

These largest impact categories range in a magnitude between 8 % (CC incl in SII) and 34 % (HT CE in SI) share per process chain. Main cause for the impacts can be named exemplarily by the furnace production in the categories “ET FW” and “HT CE” or by the fertilizer production in the impact categories “HT nCE” and “RD mfr”. The main cause for the large impact of the category “CC” is the combustion. It has to be remarked that this large impact is mainly associated with biogenic CO_2, so that an LCIA method excluding biogenic carbon dioxide (CC excl, Figure 3) lowers the impact substantially to a remaining impact of 11 to 14 %. The remaining amount is mainly caused by external processes like seedling, furnace or fertilizer production.

It can be stated that the basic distribution of the category shares is very similar for all Sida process chains. Significant differences can be identified for the “HT CE” category in process chain SI and the “RD MFR” category in process chain SIII. These distinctions can be traced back to the impact of single process modules. While the “HT

CE" category is mainly influenced by different furnaces' manufacturing, the "RD MFR" category differs due to storage facilities and equipment.

The differences between the considered process chains are also reflected for selected categories (Figure 5, A) as well as the sum of all 16 impact categories per process stage (Figure 5, B). The five graphs for single impact categories show the separate process stages. For example, the ash disposal stage has nearly no influence on the "HT CE" category but on the "ET FW" category. In principle, the process stages "biomass production" and "combustion" represent the largest impact originators. Anomalies within Figure 5, B can be identified by the small shares of the production and processing as well as the ash disposal stage in process chain SI. The first discrepancy can be explained by minimized technical efforts for chips processing, while the ash disposal is lower due to less ash content of Sida chips.

As mentioned before, the large impact of the combustion stage is caused by biogenic CO_2, which has to be credited in an LCIA excluding biogenic CO_2.

The presented process chains show no significant differences between SI, SII, and SIII. However, the closer look into impact category and process stage specific results reveals focal points of impacts' origins. These can be used as starting points for technology or biomass related process improvement. It is noteworthy that not all processes can be influenced. On the one hand, it is possible to reduce the influence of fertilizer production by minimizing its application but on the other hand, furnace production cannot be influenced. Moreover, based on the discussed results an impact category depending optimization (e.g., CO_2 reduction) can be initiated, but only if this does not contribute to the worsening of other categories. In relation to the assessment of single process stages, similarities with other alternative process chains can be stated. Other studies like Ruiz et al. [48] or Fantozzi et al. [49] have also shown largest impacts in the process stage "biomass production" but also in pelletization or briquetting. To get a clearer separation between the environmental impact results of Sida process chains the change of goal and scope characteristics (e.g., adjustment of functional unit and overall setting) can be used, since such modifications could lead to a stronger expression of distinctiveness. One basic possibility is the relocation of the system boundaries to intensify and identify significant differences. Another option would be the consideration of temporal developments for activities in the biomass production stage (e.g., taking into account cultivation circles) as described in Fantozzi et al. [49] in relation to SRC for example. Furthermore, the effects of a change in the "general setup" (framework; e.g., larger cultivation area than four ha as design base) should be analyzed.

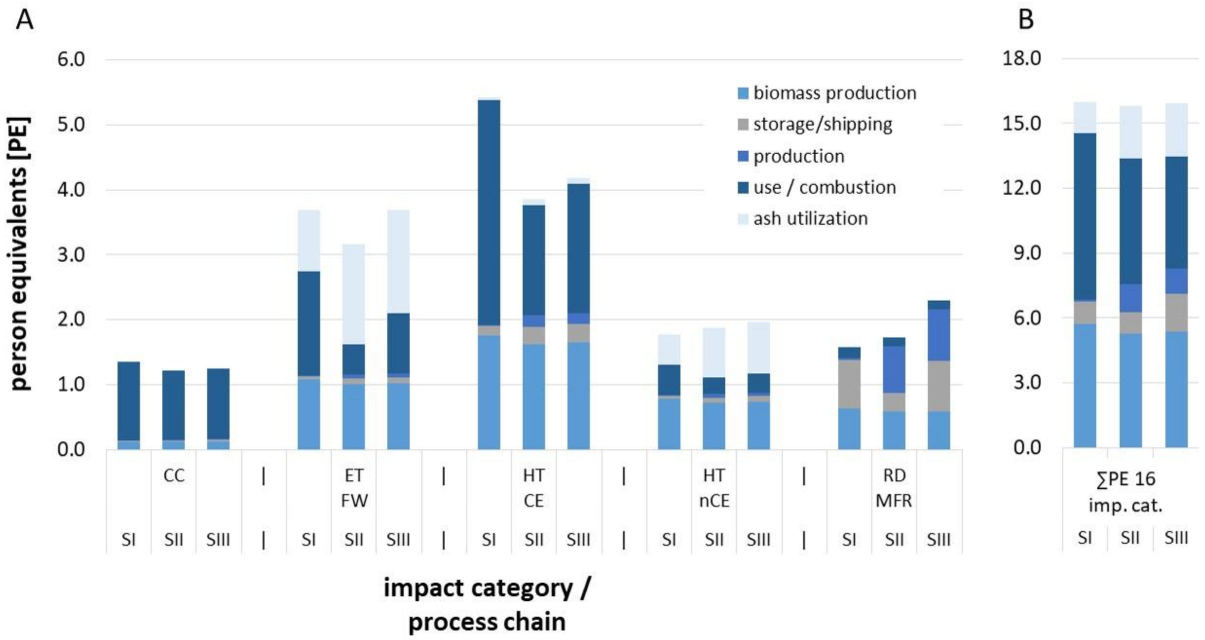


Figure 5: Shares of PE per process stage for process chains SI, SII and SIII; for largest impact categories (A) and for the sum of all impact categories (B) per 100 GJth.

3.2 External comparison

The comparison with alternative biomasses (e.g., wood pellets) shows that the summarized PE values of most alternatives compared are larger than those of Sida

(Sida pellets = 100%). The compared impacts in Figure 6 range from 85 % for *Miscanthus* (13.4 PE) to 147 % for wood chips (23.28 PE) against the best-case value of SII (100%). Five of the seven compared process chains indicate a larger overall impact than the Sida process chains. The alternative process chains with lower impacts are MI (*Miscanthus* pellets) with a 15 % lower impact than SI-III and AI (mixed wood logs) with ca. 2 % lower impacts. A comparison with wood chips from wood processing industries shows the largest impact difference (+47.3 %). The influence of the technology level can be seen for mixed logs representing state-of-the-art (AI) and average (AII). It leads to a significant change of impacts. Since no explicit state-of-the-art technology was assumed for the process chains SI, SII, and SIII the impacts would probably be lower with such assumptions and implementations. Reasons for differences in woody biomass (process chains AI-AVI) impact results can be found in different lower heating values (range from 14 to 19 MJ kg^{-1}) or differences of ash contents. Further compared datasets are shown in the Supplementary Table I and support the above-described advantageousness of Sida (70 to 80 % of the examined cases of alternative biomass result in larger environmental impacts).

It can be stated that there is a large variety in the overall results but some of the presented biomasses (e.g., mixed logs, 30 kW, RoW, SOTA) are close to Sida. In most cases, however, Sida is advantageous. How these relations alter if parameters like the heating value of *Miscanthus* or the yield of Sida are changing, is presented in a sensitivity analysis in section 3.3. These analyses provide information on how changes in the framework conditions affect the environmental impact of Sida and *Miscanthus*.

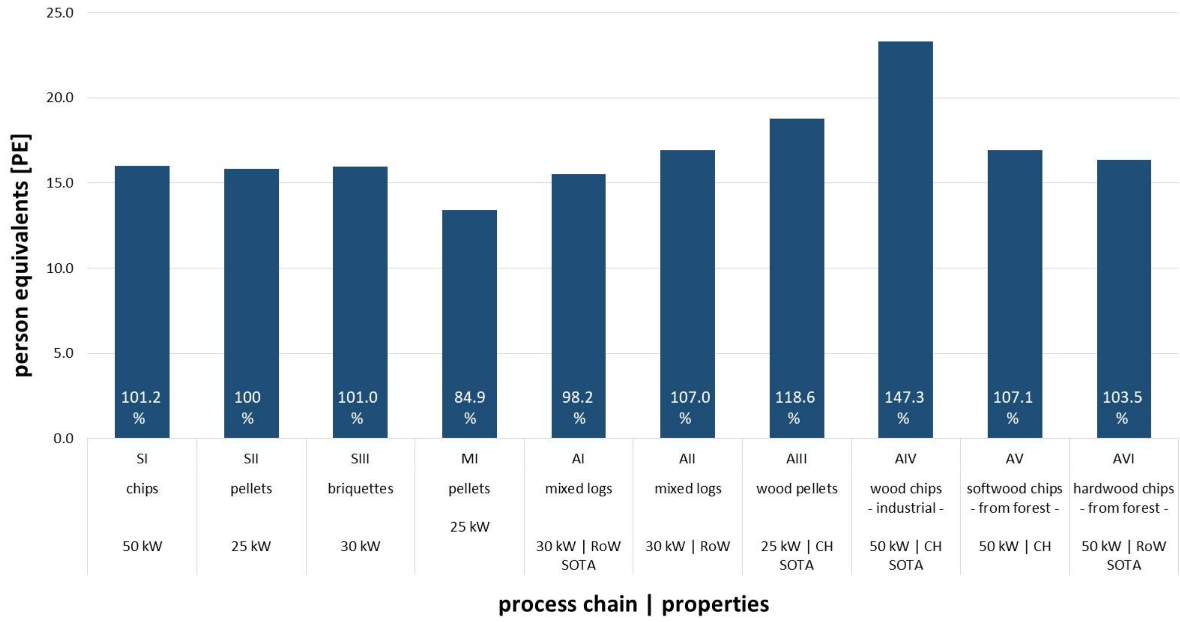


Figure 6: Comparison of relative total PE values for Sida process chains SI, SII, and SIII, Miscanthus process chain MI as well as 6 different wood process chains AI-AVI; percentages reflect the process chain specific impact in relation to SII per 100 GJth.

3.3 Sensitivity analysis of influencing parameters

The influencing parameters along the Sida process chains were studied in different respects. The following described results focus on the comparison with *Miscanthus* (factor of interest: heating value) and the presented advantage of Sida (factor of interest: specific yield).

3.3.1 Lower heating value Miscanthus

In relation to the results, it is of particular interest, which parameters lead to a reduction of the gap between Sida and *Miscanthus*. This is worth a closer look, because the used data for *Miscanthus* is based on literature. Therefore, the first investigated factor is the lower heating value (LHV) of *Miscanthus*. A lowering of the LHV by 2.5, 5.0 and 10.0 % leads to an increase of the overall impacts expressed in PE by 8.4 % in maximum. Figure 7 shows the changes from the initial value of 13.42 PE up to the maximum value of 14.55 PE. It has to be mentioned that the LHV used is an average value of randomly selected values from the database mentioned [36]. According to different literature like [50] or [51] the LHV of *Miscanthus* is lower than the used value employed in this study (15.66 MJ kg^{-1} with 10 % moisture).

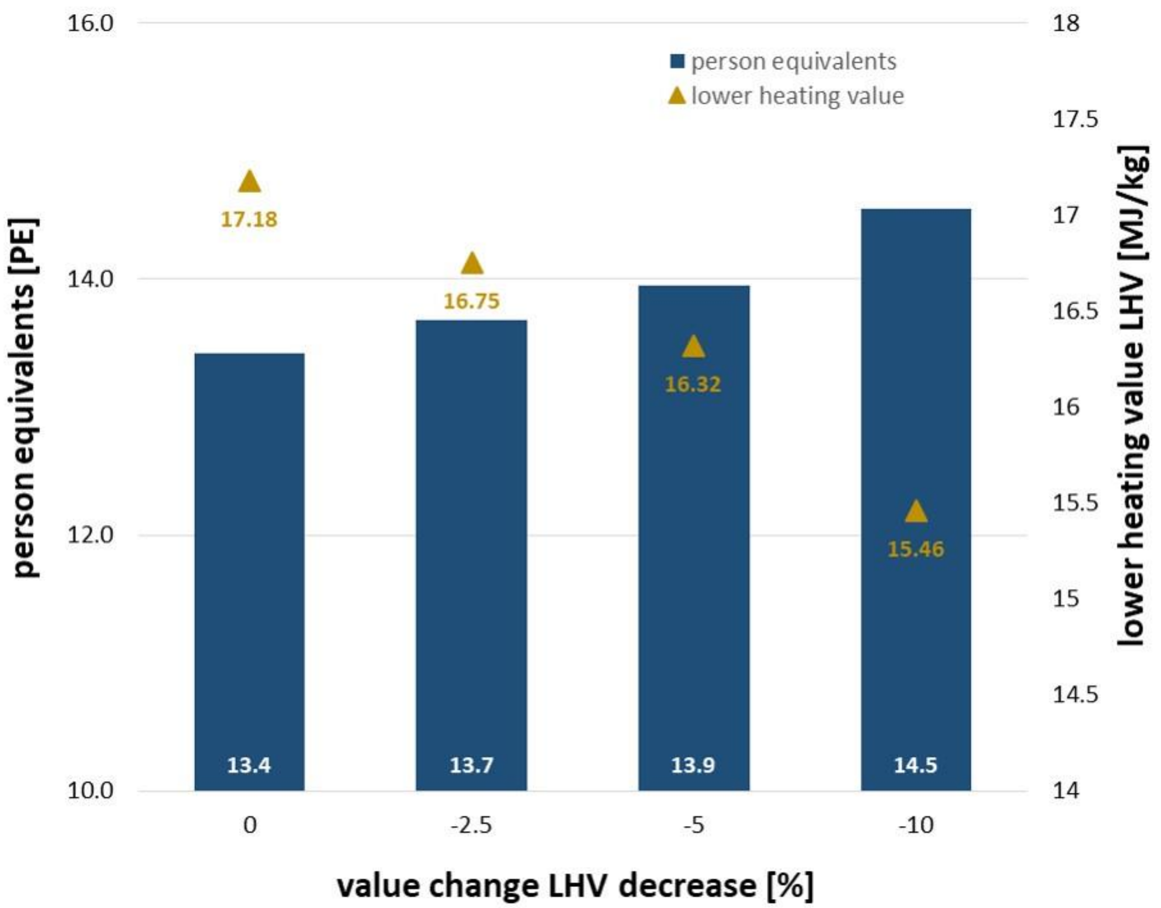


Figure 7: Change of PE values per 100 GJth for Miscanthus (pellets) in dependence of varying lower heating values.

3.3.2 Yield of Sida

Furthermore, the variation of yields of Sida can show the scope of the advantages in comparison to alternative biomasses. By variation of Sidas' yield in the underlying calculation, parameters, influencing the results, are changing (e.g., area demand per FU). The exemplary variation is done for process chain SII (pellets) by increasing and decreasing the yield.

As Figure 8 illustrates the increase in yield by 2.5, 5.0 and 10.0 % culminates in lower environmental impacts. By a decrease from 15.8 PE for the initial yield setting to 15.4 PE for a yield enhancement of 10 % the relative difference is 3 %. While the initial area demand is 2,898 m², a 10 % increase of yield minimizes the demand to 2,634 m². It can be stated that the rate of the PE change is more influenced by a change of the LHV (-8.4 %) than by the increase of the yield (+3%). Even if both energy carriers are principally different, it can be assumed that a transferability of the results is given, but must be proven.

Decreasing the yield by -30 % leads to an impact growth to 18.2 PE, which equals a relative change of 14.6 % (Figure 8). Thus, a significantly lower yield of process chain SII leads to an impact still competitive to four of the six compared alternative biomasses (AI-AVI in Figure 6). However, this also indicates that the cultivation site should be selected carefully, with regard to essential yield-enhancing factors, such as soil quality and fertility, sufficient water supply, etc.

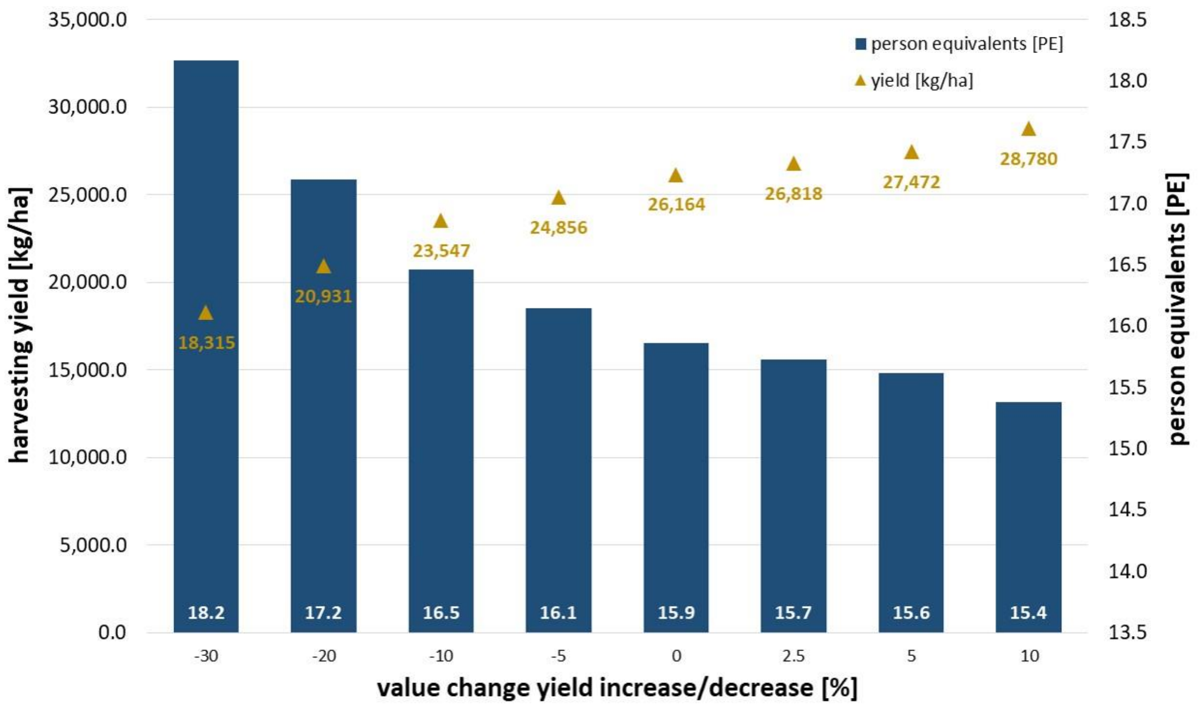


Figure 8: Change of PE value per 100 GJth for SII process chain (pellets) in dependence of varying yields (kg ha-1); increasing yield up to 10 % and decreasing yield down to -30 %.

The resulting effects of the sensitivity analysis suggest that environmental-impact-related competitiveness with *Miscanthus* is possible. In the case of worse parameter for *Miscanthus* (e.g., increasing moisture or ash content) and simultaneous improvement of parameters for Sida (e.g., lower ash content), the environmental impact could be equivalent or even better for Sida. These transition boundaries should be determined in further works.

These results demonstrate the wide range of competiveness related to the environmental impact. Since the Sida data represents one set of (real) average parameters, it could be useful to determine also transition boundaries for parameters like ash content or moisture. Furthermore, the consideration of other intermediate forms (briquettes and chips) should be explored.

Further studies on influencing parameters can be realized by the change of specific processes within the different process stages (e.g., production of processing machinery) or the variation of machinery throughputs. As possible and maybe desirable effects of these alterations, the reduction of background process' (e.g., furnace production) influences could be minimized.

4 Conclusions

An internal comparison of different production and processing pathways for Sida biomass did not show considerable differences in their overall environmental impacts. Differences can be found in the characteristics of single impact categories and their trigger, such as specific process modules (e.g., electricity supply) or related elementary flows (e.g., CO_2). External comparisons with alternative biomasses like wood or *Miscanthus* have shown, in most cases (except *Miscanthus* and mixed logs (SOTA)), beneficial properties of Sida. Only the process chains of mixed wood logs and *Miscanthus* showed slightly better performances. Measured against the compared data sets of alternative biomasses, a relative ecological competitiveness is still given with significantly lower yields of Sida biomass. Moreover, future work could be identified as follows. Operations like the precise determination of competition boundaries (minimum yield or heating values) or the comparison with further energy carriers inside and outside the field of biomass can be derived from the present results. Further research on the comparison with conventional energy carriers (e.g., gas) would be possible by the choice of suitable system boundaries and relations. This could also lead to an extension to a cradle-to-gate-system, for example. To provide information on the most charged emission paths (air, soil, water) the analysis of these shares could be realized and compared with further biomasses. Unaffected by the choice of biomass, it can be derived that a careful selection of impact-intensive (e.g., furnaces, fertilizer), but also less influential (e.g., electricity supply) components, may decrease environmental impacts. Technical and process-related findings cannot be generally transferred to other biomasses, due to specific design requirements. In order to sharpen the robustness of the results, additionally, a stronger specification of the furnaces would be conceivable. In the case of scale ups or scenarios the accompanying frameworks (e.g., cultivation area, mobile densification units) should also be purpose-oriented and in adequate dimensions. Summarizing, our results suggest Sida biomass as a useful alternative to established solid biofuels, such as wood-based energy carriers.

5 Acknowledgements

The implementation of the LCA was possible with kind provision of data from Dr. Michael Müller and Matthias Dohrn, Institute of Energy and Climate Research IEK-2 (Microstructure and Properties of Materials) at Forschungszentrum Jülich GmbH, and Martin Meiller, Fraunhofer-Institut für Umwelt-, Sicherheits- und Energietechnik UMSICHT. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

[1] Eurostat
Renewable energy statistics
2020
Available from: https://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics [accessed 30.11.2020]

[2] Eurostat
Energy from renewable sources
2017
Available from: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_from_renewable_sources [accessed 30.11.2020]

[3] European Commission
EU climate action
2018
Available from: https://ec.europa.eu/clima/policies/strategies/2030_en [accessed 30.11.2020]

[4] European Commission
Communication from the Commission (...) - The European Green Deal - COM(2019) 640 final
2019

[5] Rankin, J.
Greta Thunberg tells EU: your climate targets need doubling
The Guardian. 2019, Guardian News & Media Limited London.

[6] Jablonowski, N. D., Kollmann, T., Nabel, M., Damm, T., Klose, H., Müller, M., Bläsing, M., Seebold, S., Krafft, S., Kuperjans, I., Dahmen, M., Schurr, U.

Valorization of Sida (Sida hermaphrodita) biomass for multiple energy purposes
Global Change Biology Bioenergy, 2017. 9 (1): p. 202-214.

[7] Jablonowski, N. D., Kollmann, T., Meiller, M., Dohrn, M., Müller, M., Nabel, M., Zapp, P., Schonhoff, A., Schrey, S.
Full assessment of Sida (Sida hermaphrodita) biomass as a solid fuel
Global Change Biology Bioenergy, 2020. 12 (8): p. 618-635.

[8] Nahm, M., Morhart, C.
Virginia mallow (Sida hermaphrodita (L.) Rusby) as perennial multipurpose crop: biomass yields, energetic valorization, utilization potentials, and management perspectives
Global Change Biology Bioenergy, 2018. 10 (6): p. 393-404

[9] Nabel, M., Temperton, V. M., Poorter, H., Lücke, A., Jablonowski, N. D.
Energizing marginal soils – The establishment of the energy crop Sida hermaphrodita as dependent on digestate fertilization, NPK, and legume intercropping
Biomass and Bioenergy, 2016. 87: p. 9-16

[10] Borkowska, H., Styk, B., Molas, R.
Energiepflanze mit hohem Potenzial
Erneuerbare Energien, 2006(7): p. 76-77

[11] Borkowska, H., Wardzinska, K.
Some Effects of Sida hermaphrodita R. Cultivation on Sewage Sludge
Polish Journal of Environmental Studies, 2003. 12(1): p. 119-122

[12] Borkowska, H., Molas, R.
Two extremely different crops, Salix and Sida, as sources of renewable bioenergy

Biomass and Bioenergy, 2012. 36: p. 234-240

[13] Nabel, M., Schrey, S. D., Temperton, Harrison, L., Jablonowski, N. D. **Legume Intercropping With the Bioenergy Crop Sida hermaphrodita on Marginal Soil** Frontiers in Plant Science, 2018. 9 (905)

[14] Nabel, M., Schrey, S. D., Poorter, H., Koller,R., Jablonowski, N. D. **Effects of digestate fertilization on Sida hermaphrodita: Boosting biomass yields on marginal soils by increasing soil fertility** Biomass and Bioenergy, 2017. 107: p. 207-213

[15] Nabel, M., Schrey, S. D., Poorter, H., Koller,R., Nagel, K. A., Temperton, V. M., Dietrich, C. C., Briese,C., Jablonowski, N. D. **Coming Late for Dinner: Localized Digestate Depot Fertilization for Extensive Cultivation of Marginal Soil With Sida hermaphrodita** Frontiers in Plant Science, 2018. 9 (1095)

[16] Kollmann, T. **Energetische Nutzung von Biomasse aus Sida hermaphrodita** Master Thesis, 2015, FH Aachen Campus Jülich Fachbereich 10: Energietechnik: Jülich. p. 62 p.

[17] Bjørn, A., Owsianiak, M., Molin, C., Hauschild, M. **LCA History** Hauschild M., Rosenbaum R., Olsen S. (editors). Life Cycle Assessment, 2018. Springer International Publishing. Cham.

[18] Pawelzik, P., Carus, M., Hotchkiss, J., Narayan, R., Selke, S., Wellisch, M., Weiss, M., Wicke, B., Patel, M. K. **Critical aspects in the life cycle assessment (LCA) of bio-based materials - Reviewing methodologies and deriving recommendations**

Resources, Conservation and Recycling, 2013. 73: 211-228.

[19] Liptow, C., Janssen, M., Tillman, A.-M.
Accounting for effects of carbon flows in LCA of biomass-based products- exploration and evaluation of a selection of existing methods
The International Journal of Life Cycle Assessment, 2018. 23 (11): 2110-2125.

[20] Martín-Gamboa, M., Marques, P., Freire, F., Arroja, L., Dias, A. C.
Life cycle assessment of biomass pellets: A review of methodological choices and results
Renewable and Sustainable Energy Reviews, 2020. 133: 110278.

[21] Ferreira, J., Esteves, B., Cruz-Lopes, L., Evtuguin, D. V., Domingos, I.
Environmental advantages through producing energy from grape stalk pellets instead of wood pellets and other sources
International Journal of Environmental Studies, 2018. 75 (5): 812-826.

[22] Żelazna, A., Kraszkiewicz, A., Przywara, A., Łagód, G., Suchorab, Z., Werle, S., Ballester, J., Nosek, R.
Life cycle assessment of production of black locust logs and straw pellets for energy purposes
Environmental Progress and Sustainable Energy, 2019. 38: 163-170.

[23] Pereira, M. F., Nicolau, V. P., Bazzo, E.
Exergoenvironmental analysis concerning the wood chips and wood pellets production chains
Biomass and Bioenergy, 2018. 119: p. 253-262.

[24] Bauer, C. (2007)
ecoinvent report No. 6-IX - Holzenergie.
Dones, R. (editor) Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von

Energiesystemen in Ökobilanzen für die Schweiz, 2007. Swiss Centre for Life Cycle Inventories. Dübendorf.

[25] Krzyżaniak, M., Stolarski, M. J., Warmiński, K.
Life cycle assessment of Virginia mallow production with different fertilisation options
Journal of Cleaner Production, 2018. 177: p. 824-836.

[26] Krzyzaniak, M., Stolarski, M. J., Warminski, K.
Life Cycle Assessment of Giant Miscanthus: Production on Marginal Soil with Various Fertilisation Treatments
Energies, 2020. 13 (8)

[27] ISO17225-6
ISO 17225-6:2014-05 - Solid biofuels - Fuel specifications and classes - Part 6: Graded non-woody pellets
2014

[28] ISO17225-7
ISO 17225-7:2014-05 - Solid biofuels - Fuel specifications and classes - Part 7: Graded non-woody briquettes
2014

[29] ISO14040
ISO 14040:2006 - Environmental management - Life cycle assessment - Principles and framework
2006

[30] ISO14044
ISO 14044:2006 - Environmental management - Life cycle assessment - Requirements and guidelines
2006

[31] GaBi-S
GaBi Software Suite - LCA Software
2020, thinkstep GmbH: Leinfelden-Echterdingen
Information: https://www.thinkstep.com/software/gabi-software

[32] GaBi-DB
GaBi professional databases
2020, thinkstep GmbH: Leinfelden-Echterdingen
Infromation: https://www.thinkstep.com/software/gabi-software

[33] ecoinvent-DB
The ecoinvent Database
2020, ecoinvent Association: Zurich
Information: https://www.ecoinvent.org/

[34] Xue, S., Kalinina, O., Lewandowski, I.
Present and future options for Miscanthus propagation and establishment
Renewable & Sustainable Energy Reviews, 2015. 49: p. 1233-1246

[35] Lask, J., Wagner, M., Trindade, L. M., Lewandowski, I.
Life cycle assessment of ethanol production from miscanthus: A comparison of production pathways at two European sites
Global Change Biology Bioenergy, 2019. 11(1): p. 269-288

[36] ECN.TNO
Phyllis2, database for biomass and waste
2020, ECN.TNO Biomass & Energy Efficiency: Petten
Available from: https://phyllis.nl

[37] DEPI
DEPI-Informationsblatt: Ascheentsorgung.
2016, Deutsches Pelletinstitut GmbH: Berlin

[38] Bauer, C.
Dataset information "heat production, mixed logs, at furnace 30kW, CH"
2017, P.S. Institut

[39] EnEV
Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagentechnik bei Gebäuden (Energieeinsparverordnung - EnEV) (engl.: Federal Government regulation on energy-efficient insulation and energy-saving systems engineering for buildings)
2015

[40] European Commission JRC
International Reference Life Cycle Data System (ILCD) Handbook: Framework and Requirements for Life Cycle Impact Assessment Models and Indicators
2010, European Commission - Joint Research Centre - Institute for Environment and Sustainability

[41] European Commission
Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations (2013/179/EU)
2013, European Commission

[42] Hauschild, M.Z., Wenzel, H.
The European Person Equivalent: Measuring the personal environmental space, in Annual report NATO/CCMS Pilot Study, Clean Products and Processes (Phase I). Report no. 242 U.S. En
2001, U.S.E.P. Agency: Cincinnati, OH

[43] Fritz, M., Formowitz, B.

Miscanthus: Anbau und Nutzung - Informationen für die Praxis
Berichte aus dem TFZ, 2009 (19): p. 1-37

[44] Caslin, B., Finnan, J., Easson, L.
Miscanthus best practice guidelines
2010, Agriculture and Food Development Authority, Teagasc, and Agri-Food and Bioscience Institute: Oak Park, Carlow

[45] Albers, A., Avadí, A., Benoist, A., Collet, P., Hélias, A.
Modelling dynamic soil organic carbon flows of annual and perennial energy crops to inform energy-transport policy scenarios in France
Science of The Total Environment, 2019. 135278.

[46] Bessou, C., Tailleur, A., Godard, C., Gac, A., de la Cour, J. L., Boissy, J., Mischler, P., Caldeira-Pires, A., Benoist, A.
Accounting for soil organic carbon role in land use contribution to climate change in agricultural LCA: which methods? Which impacts?
The International Journal of Life Cycle Assessment, 2019

[47] Qin, Z., Dunn, J., Kwon, H., Mueller, S., & Wander, M.
Soil carbon sequestration and land use change associated with biofuel production: Empirical evidence
Global Change Biology Bioenergy, 2014. 8 (1): p. 66-80.

[48] Ruiz, D., San Miguel, G., Corona, B., López, F.R
LCA of a multifunctional bioenergy chain based on pellet production
Fuel, 2018. 215: p. 601-611

[49] Fantozzi, F., Buratti, C.
Life cycle assessment of biomass chains: Wood pellet from short rotation coppice using data measured on a real plant
Biomass and Bioenergy, 2010. 34 (12): p. 1796-1804

[50] TFZ-BY
Heizwerttabellen für verschiedene Halmgutbrennstoffe
2013, Technologie-und Förderzentrum im Kompetenzzentrum für Nachwachsende Rohstoffe: Straubing

[51] FNR
Energiegehalt fester Bioenergieträger
2014, Fachagentur Nachwachsende Rohstoffe: Gülzow

731

Supplementary Table I: Life Cycle Impact Assessment (LCIA) results per category in person equivalents [PE] for Sida process chains SI, SII and SIII compared with 18 different alternative process chains; compared process chains differ by energy carrier, geographic system boundaries and technical status (SOTA = state-of-the-art)

impact category (ILCD)	SI chips 50 kW	SII pellets 25 kW	SIII briquettes 30 kW	MI Misc. pellets 25 kW	wood pellet 25 kW | RoW	wood pellet 25 kW | RoW SOTA	wood pellet 25 kW | CH	wood pellet 25 kW | CH SOTA	mixed logs 30 kW | RoW	mixed logs 30 kW | RoW SOTA	mixed logs 30 kW | CH	mixed logs 30 kW | CH SOTA
Acidification midpoint (v1.09)	0.27	0.72	0.30	0.37	0.35	0.32	0.39	0.37	0.32	0.30	0.25	0.24
Climate change midpoint, incl biogenic carbon (v1.09)	1.35	1.22	1.26	1.23	1.09	1.03	1.32	1.24	0.13	0.12	0.07	0.06
Ecotoxicity freshwater midpoint (v1.09)	3.68	3.16	3.70	2.67	2.37	2.22	2.61	2.45	2.01	1.91	1.65	1.63
Eutrophication freshwater midpoint (v1.09)	0.48	0.43	0.45	0.40	0.61	0.58	0.69	0.64	0.40	0.38	0.28	0.27
Eutrophication marine midpoint (v1.09)	0.10	0.42	0.12	0.26	0.33	0.31	0.38	0.36	0.35	0.33	0.30	0.28
Eutrophication terrestrial midpoint (v1.09)	0.18	0.51	0.20	0.32	0.34	0.32	0.43	0.40	0.39	0.36	0.34	0.32
Human toxicity midpoint, cancer effects (v1.09)	5.42	3.84	4.18	3.54	4.08	3.83	4.32	4.05	2.73	2.63	2.20	2.17
Human toxicity midpoint, non-cancer effects (v1.09)	1.77	1.87	1.97	1.66	4.19	3.93	5.83	5.47	6.52	6.10	5.81	5.71
Ionizing radiation midpoint, human health (v1.09)	0.20	0.21	0.22	0.16	0.17	0.16	0.49	0.46	0.08	0.07	0.15	0.14
Land use midpoint (v1.09)	0.12	0.10	0.05	0.10	0.32	0.30	0.40	0.38	0.63	0.59	0.07	0.07
Ozone depletion midpoint (v1.09)	0.0049	0.0044	0.0046	0.0036	0.0046	0.0043	0.0070	0.0065	0.0044	0.0041	0.0031	0.0029
Particulate matter/Respiratory inorganics midpoint (v1.09)	0.29	0.40	0.29	0.25	2.22	1.49	2.23	1.50	1.97	1.52	1.80	1.36
Photochemical ozone formation midpoint, human health (v1.09)	0.20	0.62	0.27	0.37	0.53	0.48	0.61	0.56	1.02	0.87	0.98	0.83
Resource depletion water, midpoint (v1.09)	0.36	0.59	0.65	0.55	0.20	0.19	0.26	0.25	0.07	0.06	0.05	0.04
Resource depletion, mineral, fossils and renewables, midpoint (v1.09)	1.57	1.72	2.29	1.71	0.51	0.48	0.66	0.62	0.29	0.28	0.19	0.18
sum [PE]	15.99	15.81	15.96	13.6	17.3	15.6	20.6	18.8	16.9	15.5	14.1	13.3
[‰]	101.2	100	101.0	86.0	109.5	98.9	130.6	118.6	107.0	98.2	89.4	84.1

impact category (ILCD)	wood chips - industrial - 50 kW | RoW	wood chips - industrial - 50 kW | CH	wood chips - industrial - 50 kW | CH SOTA	softwood chips - from forest - 50 kW | RoW	softwood chips - from forest - 50 kW | CH	hardwood chips - from forest - 50 kW | RoW	hardwood chips - from forest - 50 kW | RoW SOTA	hardwood chips - from forest - 50 kW | CH	hardwood chips - from forest - 50 kW | CH SOTA
Acidification midpoint (v1.09)	0.72	0.64	0.60	0.34	0.30	0.41	0.38	0.37	0.34
Climate change midpoint, incl biogenic carbon (v1.09)	1.26	1.31	1.22	0.25	0.35	0.27	0.25	0.37	0.35
Ecotoxicity freshwater midpoint (v1.09)	3.18	2.61	2.48	1.94	1.60	1.97	1.87	1.63	1.57
Eutrophication freshwater midpoint (v1.09)	0.74	0.64	0.60	0.40	0.32	0.41	0.39	0.34	0.32
Eutrophication marine midpoint (v1.09)	0.78	0.72	0.67	0.39	0.36	0.49	0.46	0.46	0.43
Eutrophication terrestrial midpoint (v1.09)	0.87	0.82	0.77	0.43	0.41	0.54	0.50	0.52	0.48
Human toxicity midpoint, cancer effects (v1.09)	4.47	3.67	3.49	2.47	2.05	2.50	2.40	2.09	2.01
Human toxicity midpoint, non-cancer effects (v1.09)	7.30	8.14	7.61	5.76	6.69	5.96	5.57	6.94	6.49
Ionizing radiation midpoint, human health (v1.09)	0.17	0.37	0.35	0.08	0.22	0.08	0.08	0.22	0.20
Land use midpoint (v1.09)	0.42	0.30	0.28	0.59	0.08	0.62	0.58	0.08	0.07
Ozone depletion midpoint (v1.09)	0.0080	0.0078	0.0073	0.0033	0.0035	0.0034	0.0032	0.0036	0.0034
Particulate matter/Respiratory inorganics midpoint (v1.09)	4.63	4.07	3.16	3.67	3.49	3.68	2.80	3.50	2.63
Photochemical ozone formation midpoint, human health (v1.09)	1.45	1.30	1.17	0.79	0.80	0.93	0.83	0.94	0.83
Resource depletion water, midpoint (v1.09)	0.33	0.29	0.27	0.08	0.06	0.08	0.08	0.06	0.06
Resource depletion, mineral, fossils and renewables, midpoint (v1.09)	0.68	0.66	0.62	0.17	0.20	0.18	0.17	0.20	0.19
sum [PE]	27.0	25.5	23.3	17.4	16.9	18.1	16.4	17.7	16.0
[‰]	170.9	161.6	147.3	110.0	107.1	114.7	103.5	112.1	101.1