

## LIFE CYCLE ASSESSMENT OF LIQUID INVERTED SUGAR AND HIGH-FRUCTOSE CORN SYRUP

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### ABSTRACT

The aim of this study is to compare the environmental impact of liquid inverted sugar (77°Bx) produced with enzymatic hydrolysis of beet sugar and HFCS (75% DM) produced from corn in a wet milling process. Given the different sweetness equivalents of liquid inverted sugar (77°Bx) and HFCS (75% DM), the reference flows were defined as 900 kg of liquid inverted sugar or 1000 kg HFCS. The analysis was performed with the life cycle assessment (LCA) method focusing on the cradle-to-gate stage. The inventory data of liquid inverted sugar processing were supplied by a producer while the LCA of HFCS relies on secondary data (literature) which describes the material and energy flows associated with glucose production. Life cycle inventory of relevant inputs and outputs were available from the Ecoinvent 3.4 database. Environmental impacts were calculated with the ReCiPe 2016 (H) life cycle impact assessment (LCIA) method. LCA results have revealed that inverted liquid sugar has a lower impact in 14 out of the 18 analysed impact categories. Consumption of inverted liquid sugar (>77°Bx) instead of HFCS (75% DM) could lead to significant reduction in GHG emissions (by 38%), fossil energy (by 31%) and water (by 95%) consumption, and reduces the required land area by 67%.

Keywords: high-fructose corn syrup, inverted sugar syrup, life cycle assessment

### 1. INTRODUCTION

Sucrose obtained from sugar beet or sugar cane has been a part of the human diet for centuries. Furthermore, sucrose found in fruit or honey has been introduced to the human diet for millennia [1, 2]. In the recent decades, varieties of new sweeteners are developed in order to substitute sucrose in the standard food formulation [3]. Despite huge effort, none of these sweeteners was able to comply with numerous standards currently adopted by food industry regarding colour, aroma, texture, fermentation and shelf-life [4]. However, two liquid sweeteners, inverted sugar syrup and high-fructose corn syrup (HFCS), have found a huge market due to similar characteristics to the basic sucrose solutions.

The process of inverted sugar production includes several technological processes. Firstly, sucrose crystals are dissolved at higher temperature forming sugar syrup above 70% of DM. Afterwards, syrup is cooled and specific amount of corresponding enzyme is added. Hydrolysis of sucrose yields glucose and fructose in 1:1 ratio. After syrup filtration, the obtained inverted sugar syrup (above 70% DM) has increased sweetness level compared to sucrose syrup. Sweetness level of 1 kg of completely inverted sugar syrup (70% DM) is equal to 1 kg of sucrose crystals [5].

The production of high-fructose corn syrup involves 4 major processing steps: (a) wet milling of corn to obtain starch, (b) liquefaction - hydrolysis of the starch to obtain glucose, (c) isomerisation -conversion of a portion of the glucose to fructose, and (d) enrichment of the glucose-fructose stream to increase the fructose concentration. Typical composition of high-fructose corn syrup includes 55% of fructose and 41% of glucose with maltodextrin residues up to 4%. Therefore, 1 kg of HFCS (75% DM) corresponds to the sweetness of 1 kg of sucrose crystals [4].

The aim of this study was to compare the environmental impacts of inverted liquid sugar produced from beet sugar and high-fructose corn syrup. The analysis was performed with the life cycle assessment (LCA) method, which takes into account the potential environmental impacts associated with all the stages of the product's life cycle.

## 2. MATERIALS AND METHODS

Life cycle assessment was performed according to the principles of attributional LCA [6] and following the cut-off modelling approach as defined by Ecoinvent [7]. The life cycle impact assessment (LCIA) is based on life cycle inventory (LCI) data which includes information on environmental flows (i.e. emissions and resource use) associated with the entire life cycle of a process or product directly linked to the investigated products.

### 2.1. Functional unit and reference flows

The functional unit was defined as the sweetness equivalent of 1000 kg of sucrose. The reference flow is the amount of the product necessary to deliver the performance described by the functional unit. Given that liquid inverted sugar (77°Bx) and HFCS (75% DM) have a relative sweetness factor of 1.1 and 1, respectively, the reference flow was defined as 900 kg of liquid inverted sugar or 1000 kg HFCS (Table 1). If not explicitly stated otherwise, data in tables and charts refer to 1 functional unit and the respective quantity of reference flow.

*Table 1. Description of the analysed products and reference flows*

Product name	Description	Functional unit	Reference flow
Liquid inverted sugar	Inverted liquid sugar >77°Bx from beet sugar produced from sugar beet cultivated in Germany.	Sweetness equivalent of 1000 kg of sucrose	900 kg of liquid inverted sugar
High-fructose corn syrup*	HFCS (75% DM) produced from corn in a wet milling process (global average production).		1000 kg of HFCS

\* due to unavailability of data referring to the HFCS product system, the HFCS is represented with the impact of glucose syrup (75% DM) made from corn grain (see section Limitation of the study).

### 2.2. System boundaries and life cycle inventory data

In this study, system boundary includes only processes associated with the production chain of the analysed products. Distribution, use of liquid inverted sugar and HFCS by food manufacturers or consumers, and disposal are not considered in this LCA as there is substantial variation in the potential use for these products. Furthermore, environmental flows associated with the construction, maintenance and disposal of infrastructure, buildings and equipment in the processing stage was not considered according to their minor contribution proved by previous LCA studies related to food products.

Data on the consumption of materials and energy during beet sugar processing into inverted sugar were collected from the industry (primary data), while the quantity of material and energy flows associated with HFCS processing was estimated based on literature data (secondary data). Life cycle inventory (LCI) of material and energy flows associated with inverted sugar or HFCS processing are available from the Ecoinvent 3.4 database. The Ecoinvent LCI database [8] is considered to be the most comprehensive and reliable LCI database in Europe and includes a comprehensive accounting of emissions emitted and resources consumed in the entire life cycle of many products and processes.

In the inverted liquid sugar processing module, the dataset includes the electricity and heat requirements (from natural gas combusted in average industrial boiler), as well as tap water required for sugar processing and washing of the process equipment (Table 2). Potential impacts associated with the production of enzymes and treatments of waste water generated during the process are also considered.

Data on chemicals and cleaning agents used in the processing process were not provided by the producer and they are not included in the assessment. Life cycle inventory data of inputs associated with inverted sugar production are available from the Ecoinvent database. The LCI data for beet sugar (primary raw material for liquid inverted sugar production) refer to a typical technology for the production of sugar from sugar beet in the period 1998–2005 in Europe (sweet juice is extracted from sugar beets by diffusion and purified and crystallized to sugar). The original ecoinvent process (beet sugar production | sugar, from sugar beet | Cutoff, U - Copy – RoW, Ecoinvent 3.4.) was slightly modified to include only sugar beet produced in Germany on the input side. The LCI dataset of sugar beet includes all relevant environmental flows (emissions and resource consumption) associated with the provision of seeds, mineral fertilizers, pesticides, all machine operations and corresponding machine infrastructure and sheds, transport activities, as well as the direct field emissions from the application of fertilizers and pesticides and the atmospheric CO<sub>2</sub> uptake by the sugar beet. Potential CO<sub>2</sub> emissions arising from land transformation are not included in the Ecoinvent LCI of sugar beet.

*Table 2. Material and energy flows associated with the processing of beet sugar into liquid inverted sugar and their LCI data*

	Units	Amount	LCI data (from the ecoinvent 3.4 database)
<b>INPUTS</b>			
Raw materials			
Beet sugar granulated	kg	720	beet sugar production   sugar, from sugar beet   Cutoff, U - Copy - RoW*
Tap water	m <sup>3</sup>	0.3	market for tap water   tap water   Cutoff, U - Europe without CH
Transport			
Transport of beet sugar (Distance: 300 km)	tkm	432	market for transport, freight, lorry, unspecified   transport, freight, lorry, unspecified   Cutoff, U - GLO
Processing			
Electricity	kWh	35.48	market for electricity, medium voltage   electricity, medium voltage   Cutoff, U - SL
Heat from natural gas	MJ	435	heat production, natural gas, at industrial furnace >100kW   heat, district or industrial, natural gas   Cutoff, U – Europe without CH
Tap water for washing	m <sup>3</sup>	0.66	market for tap water   tap water   Cutoff, U - Europe without CH
Enzymes	kg	0.18	market for enzymes   enzymes   Cutoff, U - GLO
<b>OUTPUTS</b>			
Liquid inverted sugar >77°Bx	kg	1000	Reference product
Wastewater	m <sup>3</sup>	0.66	market for wastewater, average   wastewater, average   Cutoff, U - Europe without CH

\*modified ecoinvent process (see above).

The inventory data of corn grain processing into high-fructose corn syrup was derived from literature [9] referring to glucose production using wet milling. The dataset includes aggregated data on electricity and heat consumption, raw materials, chemicals and water usage, as well as information on emissions to air and effluents (Table 3). The potential environmental impact of the corn grain (primary raw material for glucose production) was modelled based on life cycle inventory dataset from the Ecoinvent 3.4 (market for maize grain | maize grain | Cutoff, U – GLO). The inventory data refer to the average inputs/outputs of global corn production in mid 2000s.

Table 3. Material and energy flows associated with the processing of corn grain into glucose syrup (75% DM) and their LCI data

	Units	Amount	LCI data (from the ecoinvent 3.4 database)
<b>INPUTS</b>			
Raw materials			
Corn grain	kg	1125	market for maize grain   maize grain   Cutoff, U - GLO
Processing			
Electricity	MJ	700.5	market group for electricity, medium voltage   electricity, medium voltage   Cutoff, U - UCTE
Heat from natural gas	MJ	1635.75	heat production, natural gas, at industrial furnace >100kW   heat, district or industrial, natural gas   Cutoff, U - RoW
Lime (CaO)	kg	0.225	quicklime production, milled, loose   quicklime, milled, loose   Cutoff, S - CA-QC
Sulphuric acid (100%)	kg	0.3375	market for sulfuric acid   sulfuric acid   Cutoff, U - GLO
Sulphur dioxide	kg	2.295	market for sulfur dioxide, liquid   sulfur dioxide, liquid   Cutoff, U - RoW
Urea	g	156	market for urea, as N   urea, as N   Cutoff, U - GLO
Sodium hydroxide (50%)	g	211.5	market for sodium hydroxide, without water, in 50% solution state   sodium hydroxide, without water, in 50% solution state   Cutoff, U - GLO
Sodium chloride	g	48.75	Sodium chloride, powder, at plant, processing - FR
Cyclohexane	g	41.25	market for cyclohexane   cyclohexane   Cutoff, U - GLO
Chlorine	g	9	market for chlorine, liquid   chlorine, liquid   Cutoff, U - GLO
Water	m <sup>3</sup>	0.495	market for tap water   tap water   Cutoff, U - RoW
<b>OUTPUTS</b>			
Products and by-products			
Glucose syrup (75% DM)	kg	1000	Reference product
Corn gluten feed	kg	201	By-product
Corn gluten meal	kg	60	By-product
Corn oil	kg	20.25	By-product
Emissions to air			
Particulate (PM10)	g	0.525	Emission to air/unspecified
Emissions to water			
BOD5	g	0.15	Emission to water/unspecified
Chlorides	g	89.1	Emission to water/unspecified
Sulphate	g	0.15	Emission to water/unspecified
Suspended matter	g	0.525	Emission to water/unspecified

As seen from the table, glucose production is a multifunctional process, which apart from the main product, glucose, has three by-products (gluten feed, gluten meal and oil). According to ISO 14040:2006 and the principles of attributional LCA the overall impact of a multifunctional process should be portioned

between its co-products following an allocation procedure. In this study the overall impacts of the processing process is allocated between its co-products following economic allocation. Based on the economic allocation approach, Setzer [10] estimated that 84% of the overall impacts should be attributed to the main product, i.e. glucose.

### 2.3. Geographical and temporal relevance of the results

Data on material and energy flows associated with beet sugar processing into inverted liquid sugar was collected from a modern industrial-scale facility and describes average consumption of raw materials and utilities in 2018. When relevant, country-specific data were used to calculate the environmental impacts of products and processes associated with the production of inverted liquid sugar. Otherwise, global or European average data were used from the Ecoinvent database. Data on material and energy flows associated with sugar beet production refer to the typical inputs and yields of sugar beet in Germany in the period 2009–2012. Other inputs are mainly represented with Ecoinvent processes describing the flows associated with average technology in 1995–2005.

Data for corn wet milling came from a detailed production inventory of a modern corn wet mill in the USA, as described by Renouf et al. [9]. Although not explicitly stated by the authors, given the year of the publication it is reasonable to assume that the data refer to a typical technology for corn wet milling in early 2000s in the USA. The corn analysis was based on data from the Ecoinvent 3.4 database describing the average input and output flows associated with corn cultivation in the world in the period of 2004–2006. Other inputs of HFCS processing are modelled with Ecoinvent data which usually describe the average production technology in the period from 1995 to 2005. As far as possible the environmental burdens associated with inputs and outputs of HFCS processing are calculated with global data. This means, that the LCA results refer to the average impact of HFCS on global level. If global average data was not available, than regional or country-specific data were used which is clearly indicated in the name of the Ecoinvent LCI dataset (last letters in the name of the Ecoinvent process; see Tables 2 and 3).

### 2.4. Life cycle impact assessment (LCIA) method

The environmental impact assessment is performed with the ReCiPe 2016 LCIA method [11]. ReCiPe 2016 is the most recent and harmonized indicator approach available for LCIAs. The potential environmental impacts are analysed and measured within 18 midpoint impact categories. As often encountered in scientific models, the assessment follows the hierarchist cultural perspective.

## 3. RESULTS AND DISCUSSION

### 3.1. Life cycle impact assessment results

Table 4 summarizes the results of environmental impact assessment within the ReCiPe 2016 midpoint impact categories. Inverted liquid sugar has a lower impact in 14 out of the 18 analysed impact categories. Consumption of inverted liquid sugar (>77°Bx) instead of HFCS (75% DM) could lead to significant reduction in GHG emissions (by 38%), fossil energy (by 31%) and water (by 95%) consumptions, and reduces the land area (by 67%) required to produce the raw materials. HFCS had lower impacts in 4 impact categories (fine particulate matter formation, human non-carcinogenic toxicity, terrestrial acidification and ecotoxicity).

Table 4. Life cycle environmental impact of liquid inverted sugar and HFCS

Impact category	Unit	Liquid inverted sugar	High-fructose corn syrup*
Fine particulate matter formation (PM)	kg PM <sub>2.5 eq</sub>	3.07E+00	1.52E+00
Fossil resource scarcity (FD)	kg oil <sub>eq</sub>	1.17E+02	1.69E+02
Freshwater ecotoxicity (WE)	kg 1,4-DCB	8.71E+00	1.73E+01
Freshwater eutrophication (WEU)	kg P <sub>eq</sub>	1.32E-01	3.33E-01
Global warming (GW)	kg CO <sub>2eq</sub>	4.93E+02	7.90E+02
Human carcinogenic toxicity (HTc)	kg 1,4-DCB	1.23E+01	2.41E+01
Human non-carcinogenic toxicity (HTnc)	kg 1,4-DCB	6.34E+02	2.12E+02
Ionizing radiation (IR)	kBq Co-60 <sub>eq</sub>	2.75E+01	5.53E+01
Land use (LU)	m <sup>2</sup> a crop <sub>eq</sub>	2.30E+02	7.04E+02
Marine ecotoxicity (ME)	kg 1,4-DCB	1.20E+01	1.95E+01
Marine eutrophication (MEU)	kg N <sub>eq</sub>	5.94E-01	8.76E-01
Mineral resource scarcity (MD)	kg Cu <sub>eq</sub>	1.13E+00	2.07E+00
Ozone formation, Human health (Oh)	kg NO <sub>x eq</sub>	1.62E+00	1.75E+00
Ozone formation, Terrestrial ecosystems (Oe)	kg NO <sub>x eq</sub>	1.65E+00	1.79E+00
Stratospheric ozone depletion (OD)	kg CFC11 <sub>eq</sub>	4.40E-03	5.64E-03
Terrestrial acidification (TA)	kg SO <sub>2eq</sub>	2.08E+01	5.40E+00
Terrestrial ecotoxicity (TE)	kg 1,4-DCB	1.54E+03	1.21E+03
Water consumption (WD)	m <sup>3</sup>	1.17E+01	2.37E+02

The following chart (Fig. 1) shows the relative results within the analysed midpoint impact categories. For each indicator, the product with the higher environmental impact is set to 100% and the results of the other product are displayed in relation to this result.

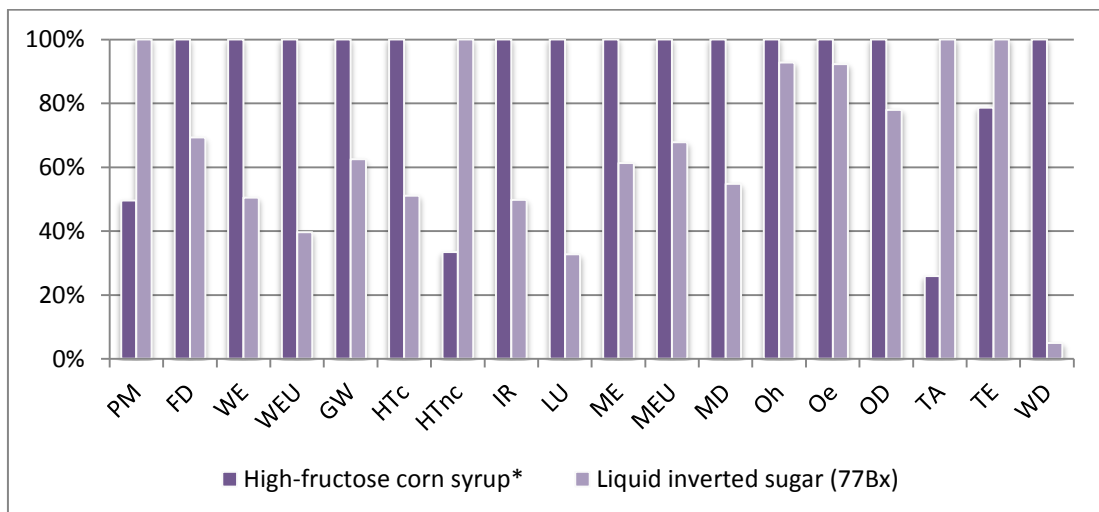


Figure 1. Relative difference between LCIA results for liquid inverted sugar and HFCS (the product with the higher impact category result is set to 100%)

### 3.2. Contribution of individual processes to impact category results

Fig. 2 shows the contribution of processes associated with liquid inverted sugar processing to the overall results within the selected life cycle impact category. The figure shows that the overall environmental impact of inverted liquid sugar is dominated by beet sugar production. The beet sugar processing into inverted liquid sugar has relatively minor influence on overall results (in general less than 20%) except in global warming, fossil energy depletion, terrestrial ecotoxicity and human toxicity impact categories. In the later four impact categories the processing related impacts are dominated by impacts associated with transport activities. The relatively high share of transport related impacts in total environmental impact can be explained with large transport distances (300 km in one direction) and the chosen transport mode (road transport) which is characterized by high environmental impact per tkm. Nevertheless, the highest impacts appear in the background system (provision of raw materials) which consists of processes on which the liquid inverted sugar producer has no, or very limited, influence.

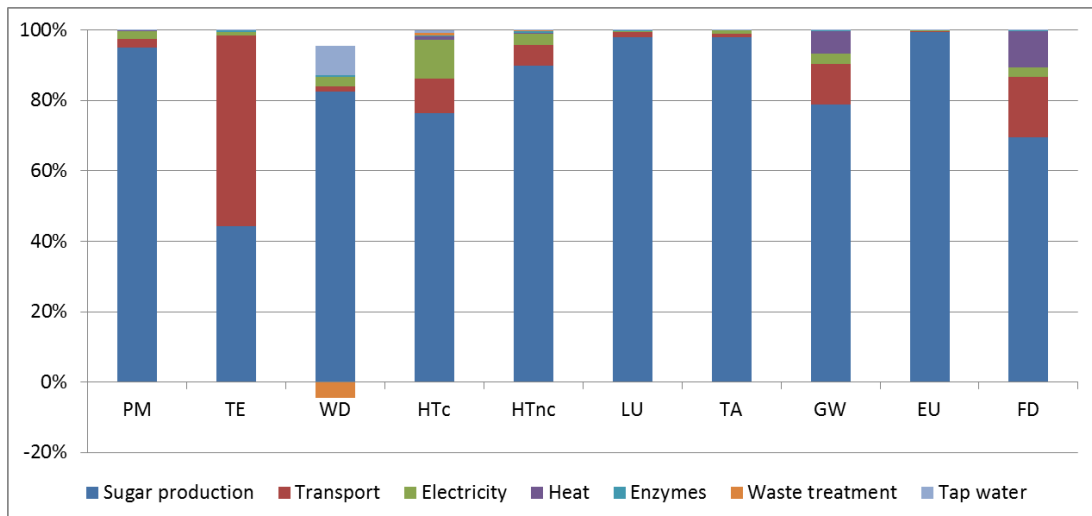


Figure 2. Contribution of individual processes associated with liquid inverted sugar production to impact category results

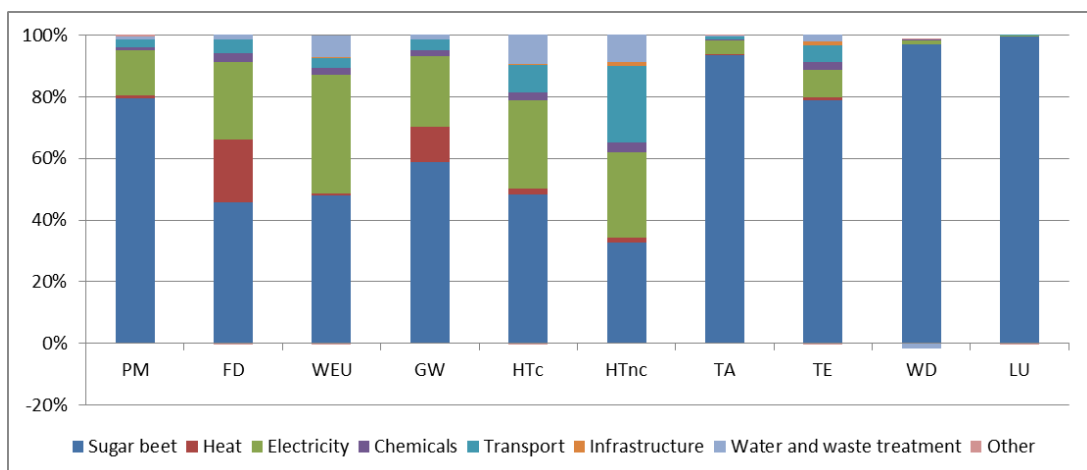
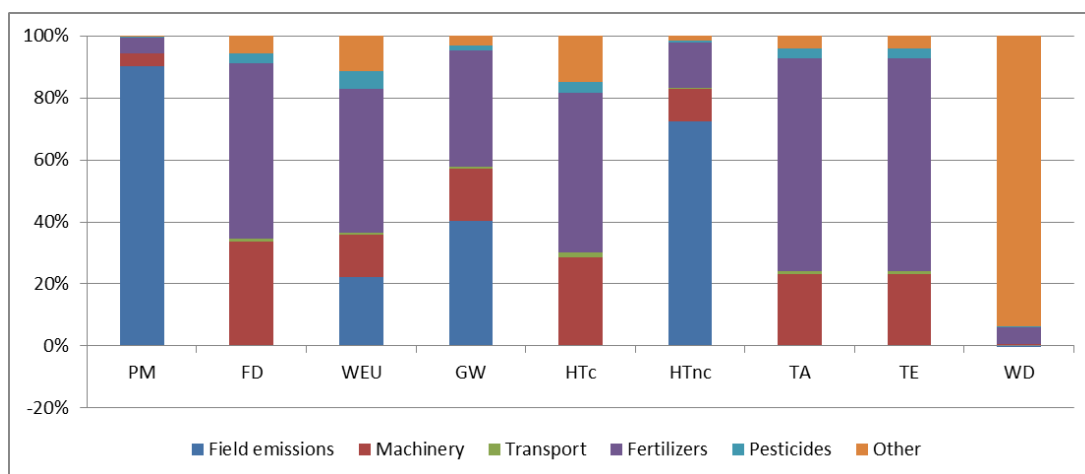


Figure 3. Contribution of processes and flows to the environmental impact of sugar produced from sugar beet

The figures below show the results of the contribution analysis of the two most important upstream processes (in terms of their contribution to the overall results), that is beet sugar production and sugar beet production. As anticipated, the overall environmental impact of sugar is dominated by impacts associated with sugar beet cultivation. Impacts associated with the production of fertilizers, field emissions (from the application of fertilizers and pesticides) along with machinery (diesel fuel) are the main impacts related to sugar beet production.



*Figure 4. Contribution of processes and flows to the environmental impact of beet sugar produced in Germany*

Contribution of individual process to the overall environmental impact of HFCS within the selected impact categories is depicted in Fig. 5. Environmental flows (emissions and resource use) associated with corn production cause most of the impacts within the selected impact categories.

The process of corn processing into HFCS has relatively minor influence on overall results within most of the impact categories. Exceptions are the global warming, fossil energy depletion, freshwater eutrophication and human toxicity impact categories in which heat and electricity consumption during the processing stage have significant contribution to the overall impacts.



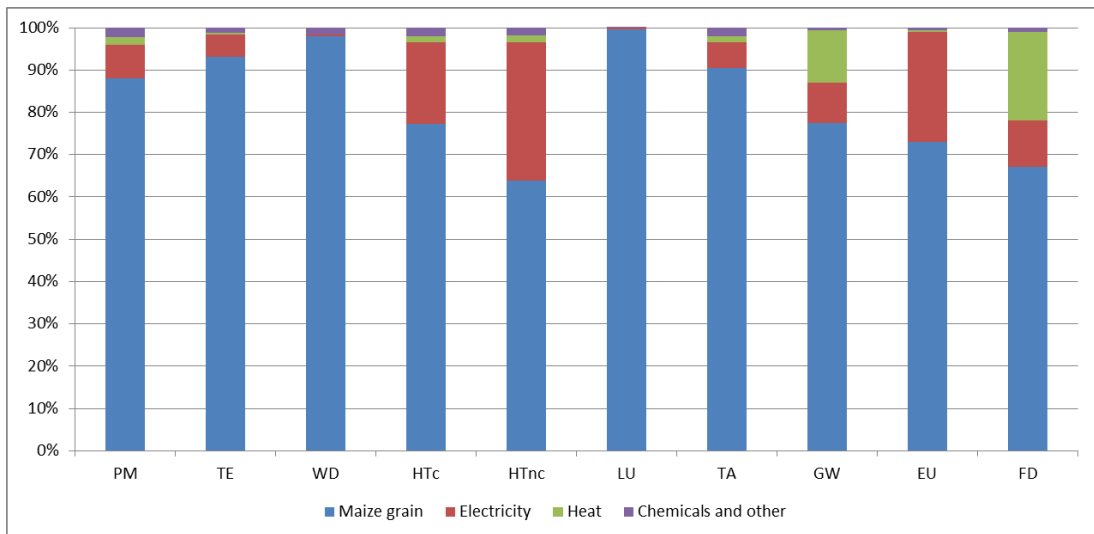


Figure 5. Contribution of individual processes associated with HCFS production to impact category results

The global corn production is dominated by the USA which is responsible for around 38% of the corn produced globally. The figure below shows the contribution of processes to the overall environmental impact of corn production in USA („maize grain production | maize grain | Cutoff, U – US”; Ecoinvent 3.4). Field emissions associated with the application of fertilizers and pesticides have a dominant impact in most of the impact categories, however flows associated with drying and production of fertilizers have also significant share in some impact categories. It is interesting to see, that corn production has a positive impact on human toxicity (negative value on the charts). This means that corn removes more heavy metals from the soil (uptake) than it is incorporated into the soil via fertilizers and pesticides.

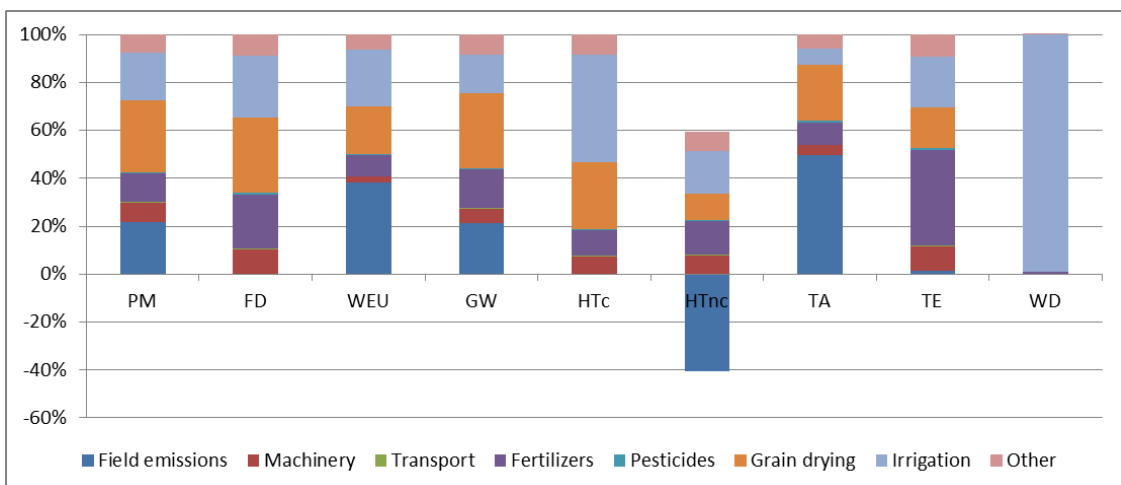


Fig. 6. Contribution of processes and flows to the life cycle environmental impact of the corn produced in USA

### 3.3. Limitations of the study

Modelling of inverted liquid sugar relies on primary data supplied by a producer and reliable and comprehensive LCI data (Ecoinvent 3.4 database). Some process inputs (see system boundaries) were not accounted for, but given their relatively small share in the total mass flow, it is not likely that their inclusion would significantly change the results.

The ecoinvent process used to calculate the environmental impact of enzymes refer to enzymes derived from potato starch unlike the one used by the data provider. However, given the small impact of enzymes on overall results (<0.5%), this simplification will not significantly change the results or conclusions.

Modelling of the HFCS product system relies on secondary data from literature sources. Although published in peer-reviewed scientific journal the authors did not provide information on data source, thus it was not possible to check and verify the reliability of the original data source. Furthermore, the data refer to the production of glucose from corn grain. Glucose is the intermediate product of the HFCS production (lacking only the final step of glucose isomerization) but it is not per se the product with the lower environmental impact due to different sweetness level of glucose and HFCS.

The production process described by Renouf et al. [9] refer to sugar production which is intended for fermentation, not for human consumption. In this regard our results likely underestimate the energy requirements for HFCS production. In this study we assigned 16% of the overall impacts to by-products based on economic allocation. Others have assigned larger co-product credits to corn glucose than in this study by undertaking a system expansion to include the potential benefits from avoided production of other processes displaced by corn meal and oil. However, the system expansion approach is not commonly used in the attributional LCA approach, and it is more suitable for consequential LCAs.

### 3.4. Comparison of the results with other studies

Even after an extensive literature review we were not able to find any LCA study of liquid inverted sugars. Several reports on the life cycle environmental impacts of glucose or HFCS are publicly available and their main findings are listed in the table below (Table 5).

As it can be seen from the table, previous researches have in general focused on intermediate products along the HFCS processing chain and not on HFCS itself. These reports considered only a few environmental aspects (usually only the global warming impact) and provide a very limited description of the analysed processing technology and data source. Despite the severe limitations of the previous LCA studies of HFCS it seems that our results, at least in terms of global warming impact of HFCS (790 kg CO<sub>2</sub>eq/1000 kg HFCS 75% DM, i.e. 1053 kg CO<sub>2</sub>eq/1000 kg HFCS 100% DM), are in good agreement with other LCAs of glucose and fructose syrups.

Table 5. Overview of LCA results of glucose and fructose syrups

Product	Reference flow	LCIA results	Comment	Source
Liquid glucose (including glucose and fructose syrups)	1000 kg of final product (100% DM)	949 kg CO <sub>2eq</sub> for global warming; 40 m <sup>3</sup> water depletion; 1414 m <sup>2</sup> a agricultural land occupation	No details on the processing step at all (no reference to the LCI data or description of the production process or data source).	An et al., 2012. [12]
Isoglucose from US corn	1000 kg isoglucose	1100 kg CO <sub>2eq</sub> for global warming	Wet milling process in the USA (using economic allocation 84% of emissions to glucose). No details on data source or the amount of flows associated with processing.	Citation in Klenk et al., 2012. [13]
Isoglucose from US corn	1000 kg isoglucose	640 kg CO <sub>2eq</sub> for global warming	Dry milling process in the USA. No details on data source or the amount of flows associated with processing.	Citation in Klenk et al., 2012. [13]
High fructose corn syrup	1000 kg of HFCS	1000 kg CO <sub>2eq</sub> for global warming	Based on the study of Renouf et al. (2008).	Kendalla et al., 2010. [14]
Dextrose from corn	1000 kg of glucose (100% DM)	ca. 6000 MJ energy input; 1000 kg CO <sub>2eq</sub> for global warming; 8.5 kg SO <sub>4eq</sub> for acidification; 2.8 kg PO <sub>4eq</sub> for eutrophication potential.	A detailed description of the LCI inventory. Inventory data are derived from non-specified secondary sources.	Renouf et al., 2008. [9]

## 4. CONCLUSIONS

The comparative cradle-to-gate assessment of inverted liquid sugar and HFCS has revealed that the later has higher impact (i.e. causes more damage) in 14 out of the 18 analysed impact categories. Inverted liquid sugar has lower carbon and water footprint (by 38% and 95%, respectively) and its production requires less fossil energy (by 31%) and agricultural land (by 67%). The processing stage has relatively low contribution to the overall impact of inverted sugars and HFCS (in general less than 20% in most of the impact categories); therefore, further improvements in the process energy efficiency would have just minor impact on the overall results. Most of the life cycle impacts are attributable to the raw material production (i.e. beet sugar and corn grain) on which the inverted liquid sugar or HFCS producer has no, or very limited, influence.

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