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Life cycle assessment of ethanol production from BOF gas

Production in China (NXBZ)

Client
Christina Canter, LanzaTech, 8045 Lamon Ave, Suite 400, Skokie, IL 60077

Authors
Thomas Kägi & Gavin Roberts, Carbotech AG

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Carbotech AG
P.O. Box, CH-4002 Basel
www.carbotech.ch

Office Zurich
Gasometerstrasse 9, CH-8005 Zurich
p +41 61 206 95 25, f -26

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For the confidential, complete report (incl. data inputs), please contact the client

Client
Christina Canter
LanzaTech
8045 Lamon Ave, Suite 400
Skokie, IL 60077

Contractor
Carbotech AG, Basel

Authors
Thomas Kägi & Gavin Roberts

Project Management / Contact
Thomas Kägi
+41 44 444 20 17
t.kaegi@carbotech.ch

External review of confidential, complete report
Roland Hischier, EMPA St. Gallen

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Summary

The study calculated the environmental impact of ethanol from blast oxygen furnace (BOF) gas in the ferroalloy industry on the methodological basis of a life cycle assessment. In particular, the following objectives were to be considered:

- Analysis of the environmental impacts of ethanol from BOF gas from China (NXBZ plant) including sensitivity analysis to assess the influence of the power source (country power mix and wind farm).
- Comparison of environmental impacts of ethanol from BOF gas with conventionally produced ethanol market mix.

The functional unit used in this study was one ton of ethanol >99% (purity >99%).
The environmental impacts of the European Footprint (EF 3.1) method were calculated. In this report, the five most relevant environmental impacts are presented, with relevance determined by contribution to total environmental impact.

Ethanol from BOF gas from China (NXBZ site) has lower environmental impact than the ethanol market mix in most environmental categories considered, with the notable exception of the carbon footprint, that performs similarly (within a 15 % range). This is because the BOF gas is not already used otherwise, and can therefore be considered as a waste stream. If the input electricity for the production is replaced with renewable power such as wind power, the carbon footprint becomes smaller than for the ethanol market mix.

1 Initial situation and objective

Ethanol is a raw material used in many hygiene and cleaning products or as bulk chemical in the plastics industry. Ethanol is usually produced from agriculturally grown products such as sugar cane or by-products such as sugar beet molasses. With the company LanzaTech, there is now a supplier that uses a waste gas source containing carbon monoxide from the ferroalloy industry (BOF gas) to be converted to ethanol. Since this avoids the environmental impacts associated with agricultural cultivation, such as land consumption, acidification, eutrophication, and toxic effects of pesticides, this approach seems compelling from an environmental perspective. However, LanzaTech wants to use life cycle assessment to ensure that the new approach to ethanol production performs better from an environmental perspective. For this purpose, Carbotech AG was commissioned to carry out such a life cycle assessment, taking into account all relevant processes involved.

In particular, the following objectives should be considered:
- Analysis of the environmental impacts of ethanol from BOF gas.
- Comparison of environmental impacts of ethanol from BOF gas with conventionally produced ethanol market mix.

2 Methodology and procedure

Today, there is a broad consensus that LCA is the most comprehensive and meaningful method to assess the environmental impact of products and systems. Therefore, this method is used to elicit the environmental impact of the mentioned products.

2.1 General description of life cycle assessment

Life cycle assessment (LCA) is a method for recording and assessing the effects of human activities on the environment and deriving optimization potentials from them. Due to the complexity of nature and the global economic system, it is not sufficient to consider only individual problem substances or local impacts. The requirement for a comprehensive assessment results in the following requirements for the method:

- Consideration of the various environmental impacts as comprehensively as possible
- Consideration of the entire life cycle
- Quantification of the environmental impact
- Evaluation of the various effects as a basis for decisions
- Scientifically supported to achieve a high level of reliability and acceptance

Life cycle assessment is the method which today best meets these requirements. The results of the LCA can be used:

- as decision-making aids for different variants
- to record the relevant effects
- to determine the main influencing factors
- in strategic planning to identify optimization potentials
- for the evaluation of measures
- as a basis for eco-design
- for the derivation of recommendations for action

2.2 Procedure for life cycle assessment

After the problem and the systems to be investigated have been defined, the flows of goods, materials, and energy as well as the resource requirements are recorded. Subsequently, the effects on the environment are determined with the help of selected indicators that describe these effects. With the aim of expressing the results with a key figure and thus enabling or at least facilitating the evaluation, an assessment of the various environmental impacts can be made by weighting them accordingly.

According to ISO 14'040 and 14’044 (ISO, 2006a, ISO, 2006b), a life cycle assessment includes the following steps:

- Defining the objectives and system boundaries (framework conditions)
- Recording of the relevant material and energy flows as well as the resource requirements (life cycle inventory)
- Determining the impact on the environment (impact assessment)
- Interpretation of the environmental impact based on the objectives (interpretation).
- Development of measures (optimization)

As Figure 1 shows, this is not a linear process, but an interactive cognition and optimization process.

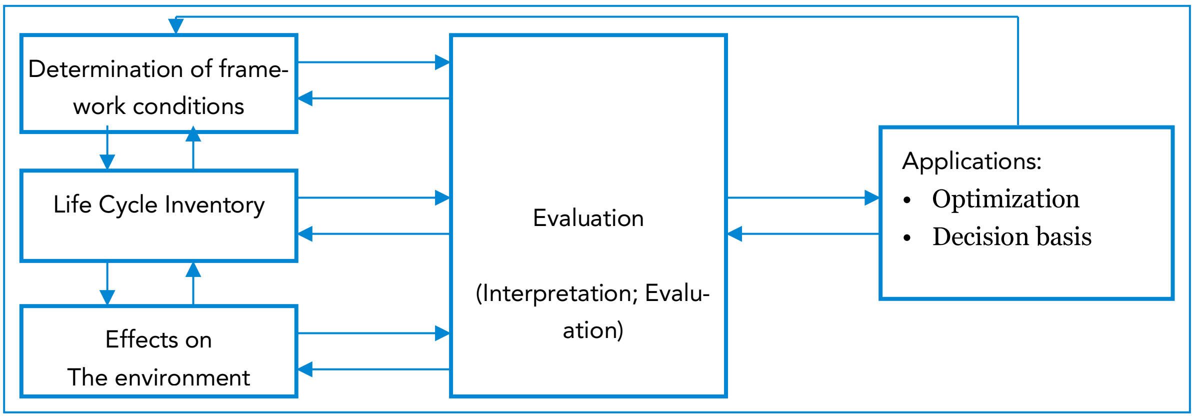

Figure 1: Steps of a life cycle assessment according to ISO 14'040

2.3 Objective and general conditions

The definition of the systems to be investigated and compared depends on the objective or question. This results in different framework conditions and system boundaries. The system boundaries define which processes and upstream processes are taken into account. For example, the time frame of the data used as well as the environmental impacts to be investigated are defined.

2.3.1 Objective

The study calculated the environmental impacts of ethanol from ferroalloy industry BOF gas on the methodological basis of a life cycle assessment. In particular, the following objectives were to be considered:

- Analysis of the environmental impacts of ethanol from BOF gas from China (NXBZ location) including sensitivity analysis to assess the influence of the power source (country power mix and renewable energy credits).
- Comparison of environmental impacts of ethanol from BOF gas with conventionally produced ethanol market mix.

2.3.2 Functional unit

If a product is compared with alternatives, these must provide the same benefit or fulfill the same function. The quantity to which the comparison refers is called the functional unit.

The functional unit used in this study is one ton of ethanol (purity >99%).

An identical further use of the ethanol is assumed, so that the further use of the ethanol has no effect on the comparison.

2.3.3 Application and target group of the study

The study is primarily aimed at the client and the interested public.

2.3.4 External review

An external review of the study was carried out by Roland Hischier of EMPA St. Gallen. The review report is included in the appendix of the confidential report. The review states that the present study complies with the international standards for life cycle assessments (ISO 14'040 and 14'044).

2.3.5 Description ethanol production

The following ethanol variants are considered:

2.3.5.1 Ethanol production from gas fermentation

Provision of gas for fermentation

LanzaTech has developed novel fermentation processes to convert carbon oxides and hydrogen-containing gases into fuels and chemical products, including ethanol, 2,3-butanediol, acetic acid, isopropanol, acetone, butanol, succinic acid, and isoprene. Process inputs can be low-value gases or waste gases from industries such as steelmaking, oil refining and chemical production, as well as gases produced from the gasification of forest and agricultural residues, municipal waste, natural gas, and coal. Ethanol from LanzaTech evaluated in this study is produced exclusively from waste gases from production. Thus, only this process route is considered in more detail in this study. For analyses of the other process routes, please refer to the paper by Handler et al. (2015). A graphical representation of the LanzaTech process is shown in figure 2. The industrial off-gas from the ferroalloy facility considered in this study is similar to a gas stream from the oxygen blast furnace (BOF) of a steel making facility. The BOF route accounts for about two-thirds of the steel produced worldwide (Handler et al., 2015). In steelmaking, carbon from coal, natural gas and/or oil is used to reduce iron ore to ferrous metal after the following reaction:

$$FeO + 3C \rightarrow Fe + 3CO$$

This reaction takes place in the blast furnace and produces molten iron or pig iron with a high carbon content (typically 3.5-4.5%). This iron is then processed in a basic oxygen furnace (BOF). The blast furnace controls the amount of carbon that remains in the final steel product by blowing pure oxygen over the pig iron. The oxygen reacts with the carbon in the pig iron and discharges it as a carbon-rich gas residue consisting of 50-60% CO, 10-20% CO_2, and 20-30% N_2. Some of these gases can be used on site for heat generation. In Europe, about 25% of all BOF ferroalloy facility gases are flared instead of being used for heat or power generation (Boston Consulting Group & Steel Institute VDeh., 2013). On a global scale, a much higher percentage is flared, and this percentage varies widely by region. LanzaTech is focusing commercial development of this technology on situations where BOF gas is underutilized (i.e., not internal to the ferroalloy facility), as these scenarios offer the greatest opportunity for value creation in ongoing ferroalloy facility operations by turning this low-value gas stream with variable composition and flow rates into a consistent source of high-value fuels and chemicals. BOF gas is thus used for ethanol production only where it is flared or not otherwise used. During flaring, all of the carbon contained in BOF gas is converted to CO_2 and released to the environment.

Gas fermentation

The LanzaTech process considered here converts carbonaceous feed gas into ethanol. The fermentation process can accommodate a range of input gas compositions and is tolerant of typical gas impurities such as sulfur, minimizing pretreatment requirements. The microbes utilize CO as both a carbon and energy source. In addition to the input carbon as a gas, a fermentation medium containing macro- and micronutrients for the microorganisms is fed into the bioreactor. The LanzaTech process is a continuous fermentation, meaning that the medium is continuously fed into the bioreactor while the fermentation broth, which contains ethanol, fermentation byproducts, and spent biomass, is removed in equal parts.

Product separation

Product separation is achieved by a distillation process. Settled solids, consisting of biomass and other organic matter from the bioreactor, are separated from the product stream and fed to an anaerobic digestion unit.

Distribution

A generic transportation distance of 200 km by lorry is assumed for the distribution of the high-purity ethanol to various producers.

Further use

The ethanol can be used in various products. Since the use of this ethanol is identical to the use of conventional ethanol from sugar beet or sugar cane, further use is omitted from this study.

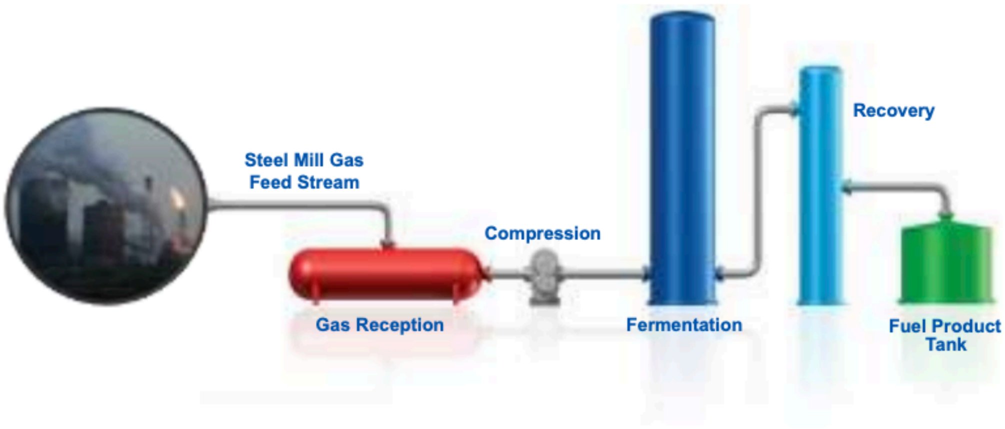

Figure 2: Production chain for the production of ethanol from BOF gas, as an example of gas fermentation (source: LanzaTech)

Ferroalloy facility

The Ningxia Binhe Silicon Carbide Products company and the Ningxia Ningyuan Alloy company ferroalloy in China produce about 200'000 tons of silicon carbide and 180'000 t of MN alloy. This generates around 400 million GJ of BOF gas, that cannot be used internally and is not used externally but flared. The ethanol production volume is around 60'000 tons. This corresponds approximately to the demand of 2.4 million GJ BOF gas.

2.3.5.2 Conventional ethanol mix used

The conventional ethanol mix used in the reference scenario is based on the ecoinvent market model for 99.7% ethanol. A share of 32% comes from Brasil (mainly sugar cane), 44% from other countries (mainly sugar cane Asia), 19% mainly from USA (mainly corn), and 15% from Europe and Eurasia (mainly sugar beet).
Ethanol is produced by fermentation from both the sugar beet and the sugar-containing juice of the sugar cane. The ethanol obtained in this way has a purity of around 95%. For use in hygiene products, the ethanol is further processed into high-purity ethanol (99%).
Subsequently, the ethanol is delivered to Europe, by truck or in combination with container ships.

2.3.6 System boundary

The present LCA considers the ecological impacts and savings "from the cradle to the intermediate storage", i.e., from the extraction of the raw materials through the individual steps of the production chain up to and including delivery of the ethanol to a client in Europe. In accordance with the LCA approach, all environmentally relevant processes within the system boundary are recorded and evaluated as far as possible.

Assuming that the further steps of the use and end-of-life phases are identical for all ethanols, the further processing and use phases were not considered.

The system boundary of the present study thus essentially comprises the following material and energy flows of the subsequent processes and services that are considered relevant (see Figure 3):

- Supply of the auxiliary materials and production ethanol
- Transportation of raw materials and auxiliary materials, transportation for the import of ethanol
- Waste from the production of ethanol and from the provision of auxiliary materials and energy
- Provision energy heat and electricity, energy sources such as petroleum, natural gas, coal, etc. for the processes involved.

For all of these processes, impacts from emissions to soil, air, and water, as well as resource requirements (e.g., energy resources or land use) are considered.

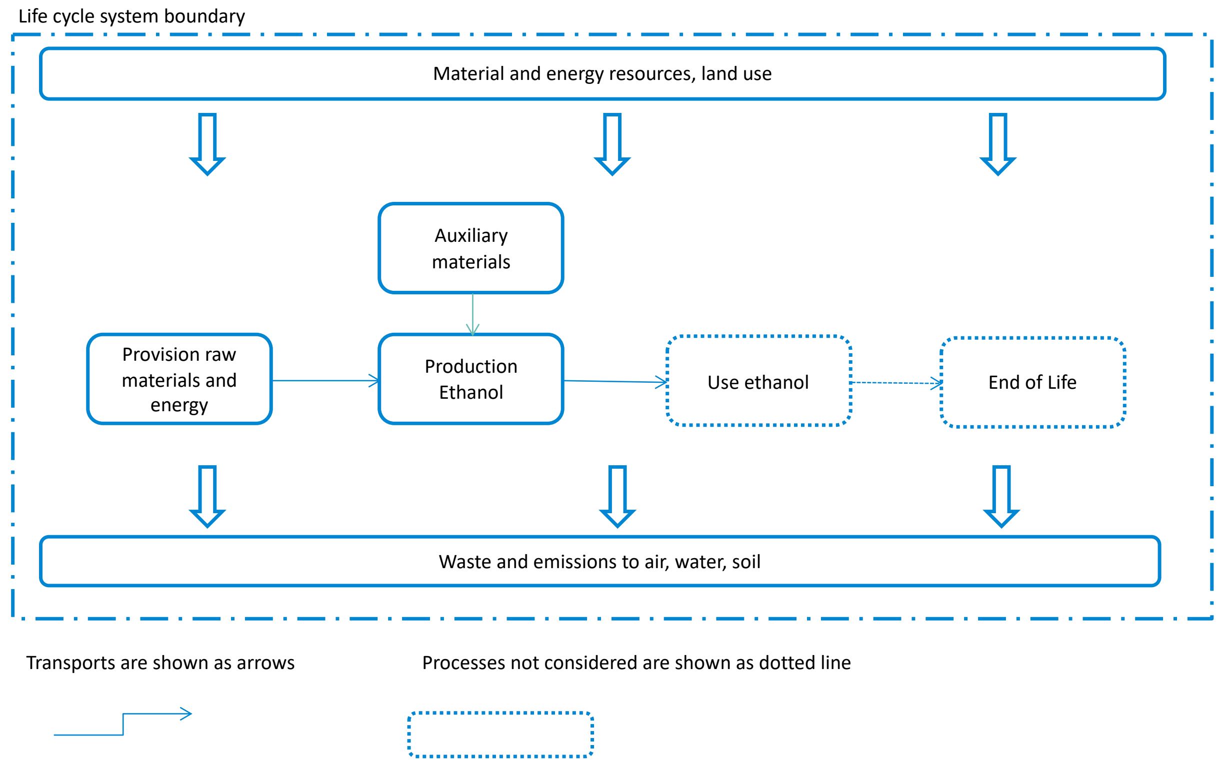

Figure 3: Schematic representation of the processes considered

2.4 Life cycle inventory

2.4.1 Modelling the product system

In the life cycle inventory, a model is designed for the system to be balanced and the energy and material flows of the associated processes are recorded. These include:

- The relationships of a process with other processes in the technosphere, such as the quantity of raw materials required, auxiliary materials, energy requirements, transports or recycling or disposal systems.
- The relationships of a process with its natural environment of the ecosphere, such as demand for resources (fossil fuels, land resources, etc.) and emissions, such as CO_2, VOCs, methane, nitrogen oxides, and others.

The life cycle inventory was calculated with the life cycle inventory software SimaPro version 9 (PRé Consultants, 2023) and used as a basis for the impact assessment.

2.4.2 Foreground data

The input and output data used for ethanol from BOF gas production cannot be shown for reasons of confidentiality.

Since the electricity mix used has a decisive influence on the result, this was updated for China to reflect a more recent situation. This is because the consumption mix in China has changed significantly in recent years, so that the corresponding ecoinvent inventories no longer correspond to reality. In China, the share of coal is decreasing every year and is now just over 60 %

Table 1: Composition of China's electricity mix. Adjusted with (IEA, 2022).

Input	Unit	China electricity mix
Coal	%	63.5%
Oil	%	0.2%
Natural Gas	%	3.0%
Hydro	%	17.4%
Solar PV	%	3.4%
Wind	%	6.0%
Nuclear	%	4.7%
Biofuels	%	1.7%
Other	%	0.1%

2.4.3 Background data

Foreground data were linked to background data from the ecoinvent V3.9.1 database (ecoinvent, 2022). The use of ecoinvent background data has a high acceptance rate. The use of a uniform basis increases the consistency of the background data and thus enables better comparability of the results.

2.4.4 Allocations

The following allocations are applied in the systems:

- BOF gas is generated during ferroalloy production and its “disposal”. The corresponding CO_2 emissions during further treatment are therefore credited in full to ferroalloy production. This corresponds to the usual handling of BOF gas, both with regard to the steel inventories in the databases and with regard to the exemption of CO_2 emissions in the case of further utilization of the BOF gas (for example, for electricity).
- The fermentation process from BOF gas produces by-products (protein feed, heat) at the Chinese site, which are further used. Economic allocation is used to allocate the environmental impact between the main product (ethanol) and the by-products.
- The inventories used for the production of ethanol from sugar beet molasses and sugar cane are also based on an economic allocation for the division between the products and by-products.

2.4.5 Sensitivities

- A sensitivity analysis will show how the results change if renewable energy (wind power) is used as electricity source instead of the Chinese grid mix.

2.5 Impact assessment

In this step, the life cycle inventory is evaluated with regards to the impact on the environment. The calculation of the impact balance includes the following sub-steps:

- Classification (classification of substances from the life cycle inventory with regard to their effects).
- Characterization (calculation of impact on the environment).
- The individual substances are weighted against each other according to their damage potential with respect to a lead substance. This results in the damage potential with regard to a specific environmental impact. In the case of global warming potential, CO_2 is used as the lead substance and contributions from other greenhouse gases such as methane and nitrous oxide are converted into CO_2 equivalents.

The environmental impacts of the EF3.1 method(European Commission. Joint Research Centre., 2023) were calculated. The five most relevant environmental impacts are presented in this report, with relevance determined by contribution to total environmental impact (see next chapter).

2.6 Evaluation of environmental impacts

The result of the impact assessment is a compilation of various indicators, each of which describes one aspect of the environmental impact. In order to obtain a well-founded basis for decision-making, the various impacts can be weighted and combined into a single indicator. The weighting of different environmental impacts is a process in which values are incorporated and which is therefore supported as widely as possible to ensure a high level of acceptance.

In the context of this study, the EF 3.1 method (aggregated ecopoints) was used. Regarding the use of the overall aggregating methods, the present study deviates from the ISO standard 14040.[1].

[1] Since the evaluation of the various environmental impacts depends on value measures, these overall aggregating methods (single score methods) are partly rejected. It should be noted that even a selection of environmental impacts is subjective. If only a part of the impacts is considered, e.g., only the carbon footprint, this is equivalent to weighting the other impacts with zero. The consideration of the individual impact categories can be quite helpful, e.g., for the determination of the causes of specific impacts and the elaboration of possible optimization potentials. However, individual environmental aspects must not be excluded as a basis for decision-making or for considering the overall environmental impact. For this purpose, overall aggregating assessment methods are not only helpful but also necessary ((Kägi et al., 2016)) and to ensure the validity of the results.

3 Results

3.1 Comparison of ethanol from BOF gas at the Chinese (NXBZ) site with ethanol market mix

Figure 4 provides an overview of how ethanol from BOF gas performs at the Chinese site compared to the current ethanol market mix used. Table 2 presents the results in absolute terms and normalized to the ethanol market mix. In addition, the results of the sensitivity analyses performed are shown in the table. The results of all EF midpoint categories are shown in the appendix.

3.1.1 Environmental impacts (midpoints)

Ethanol produced from BOF gas at the Chinese site performs significantly better than ethanol from the regular market for most relevant environmental impacts: particulate matter (-34 %), acidification (-52%), human toxicity carcinogenic (-92 %) and land use (-93 %).

In the ethanol market mix, most of the environmental impacts are dominated by agricultural cultivation (especially the direct field emissions and land consumption generated there), followed by further processing to ethanol and distribution. However, distribution is not relevant in terms of land use and human toxicity carcinogens.

In the case of ethanol from BOF gas from the Chinese NXBZ site, most of the environmental impacts are dominated by process energy. In particular, the electricity demand is decisive, or rather the resource consumption and emissions associated with the production of the Chinese electricity mix.

3.1.2 Total environmental impact

In terms of the environmental footprint, it can be seen that ethanol from BOF gas produced at the Chinese site performs better EF 3.1: -65%).

For the ethanol market mix, the environmental footprint under the under the EF method is dominated by agricultural cultivation (in particular the direct field emissions and land consumption there), followed by distribution to Europe and further processing.

In the case of ethanol from BOF gas from China, process energy (Chinese electricity mix) is most relevant. Distribution and material requirements for processing are less relevant.

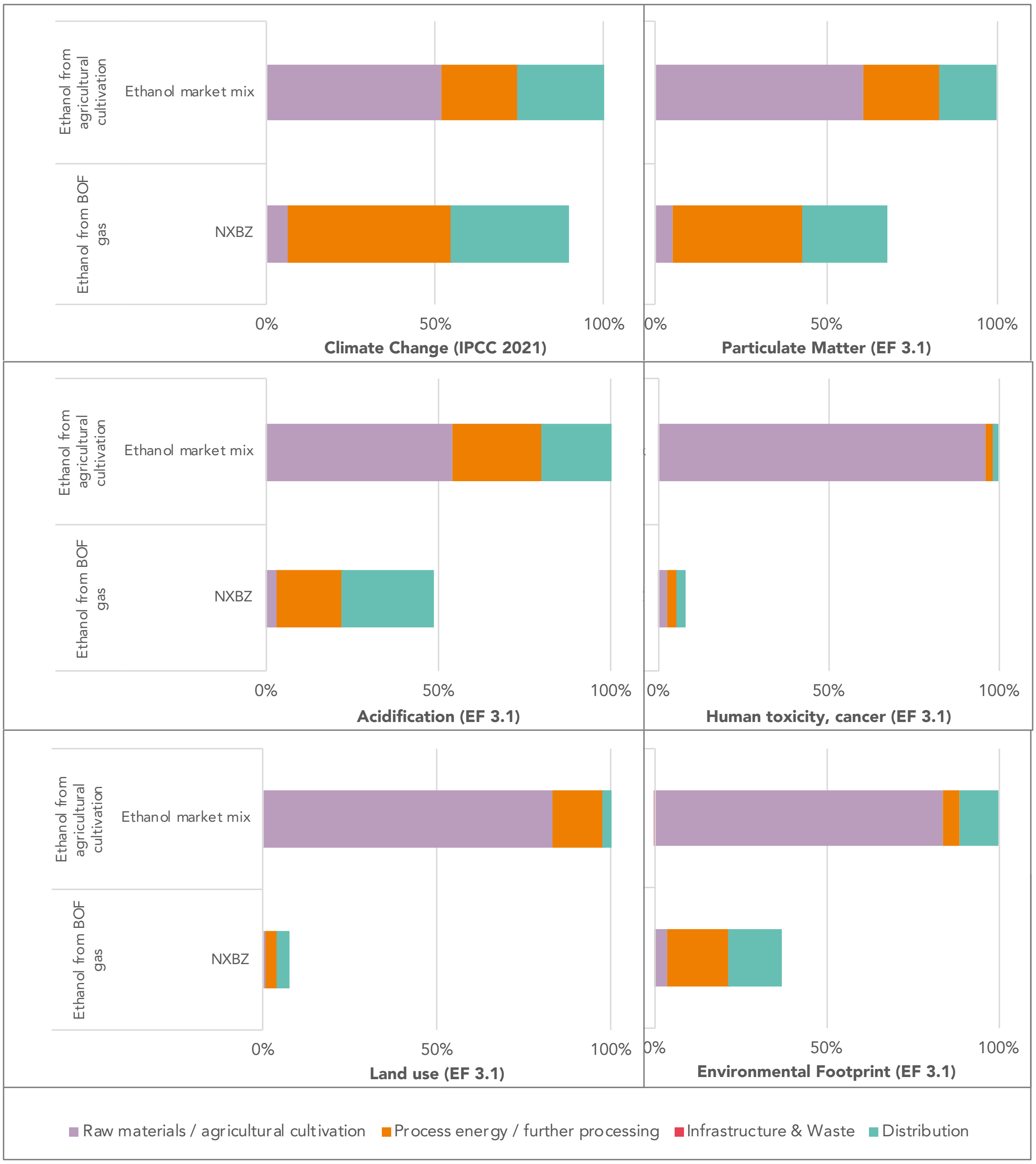

Figure 4: Relevant environmental impacts of ethanol from BOF gas production compared to the conventional ethanol market mix. The results are normalized per environmental impact to the result of the conventional ethanol market mix.

3.2 Sensitivity analysis

The sensitivity analysis (Figure 5) shows how the results change if pure wind power is used for the production of ethanol.

Table 2 presents the results in absolute terms and normalized to the ethanol market mix. The results for all EF midpoint categories are shown in the Appendix.

3.2.1 Environmental impacts (midpoints)

Ethanol from BOF gas produced at the GZJZ site with wind power performs significantly better than with Chinese power mix or than the ethanol market mix in terms of all environmental impacts considered.

The main reason for the reduction in environmental impacts is that the renewable power production shows much lower impacts than the coal based Chinese electricity mix.

3.2.2 Total environmental impact

With regard to the environmental footprint, similar findings can be noted:
If wind power is directly used as electricity source instead of the Chinese grid mix, the total environmental impact is reduced.

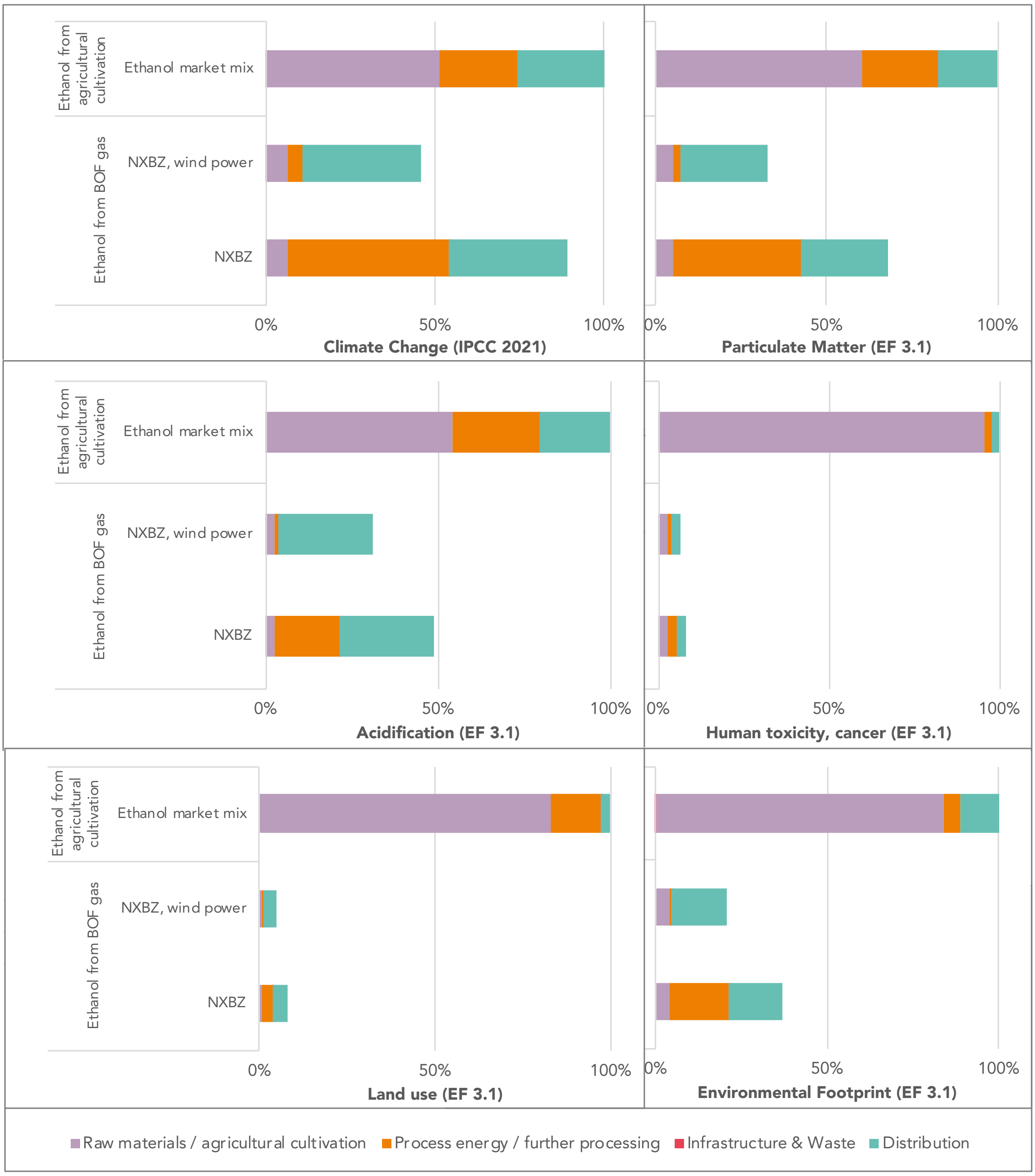

Figure 5: Total environmental impact of all variants considered. The results are normalized to the result of the conventional ethanol market mix.

Table 2: Results presented in absolute values and normalized to ethanol market mix.

Environmental impact	Unit	NXBZ site	NXBZ site with wind power as input	Ethanol market mix
Climate change (carbon footprint)	kg CO2eq / kg ethanol	1.33E+00	6.85E-01	1.49E+00
	%	89%	46%	100%
Particulate matter	desease inc./ kg ethanol	9.33E-08	4.48E-08	1.37E-07
	%	68%	33%	100%
Acidification	mol H+ eq / kg ethanol	9.47E-03	6.03E-03	1.94E-02
	%	49%	31%	100%
Cancer human health effects	CTUh / kg ethanol	6.31E-10	5.32E-10	7.92E-09
	%	8%	7%	100%
Land Use	LU points / kg ethanol	6.71E+00	4.24E+00	8.68E+01
	%	8%	5%	100%
Environmental footprint according to EF	eco points / kg ethanol	1.19E-04	6.72E-05	3.17E-04
	%	37%	21%	100%

3.3 Uncertainty analysis

Monte Carlo analysis was used for selected comparisons to consider the extent to which differences in results are truly significant.

The uncertainty analysis shows that ethanol from BOF gas at the NXBZ site performs better in all the impact categories considered. It is virtually certain, that ethanol from BOF gas at the NXBZ site performs better in terms of land use and acidification, with the other categories showing a high certainty. Even the most ambiguous of categories, climate change, shows a 64 % chance that ethanol from BOF gas has a lower carbon footprint than the ethanol market mix. If wind power is used as input energy for the carbon smart process, ethanol from BOF gas at the Chinese site scores significantly better in all the considered impact categories.

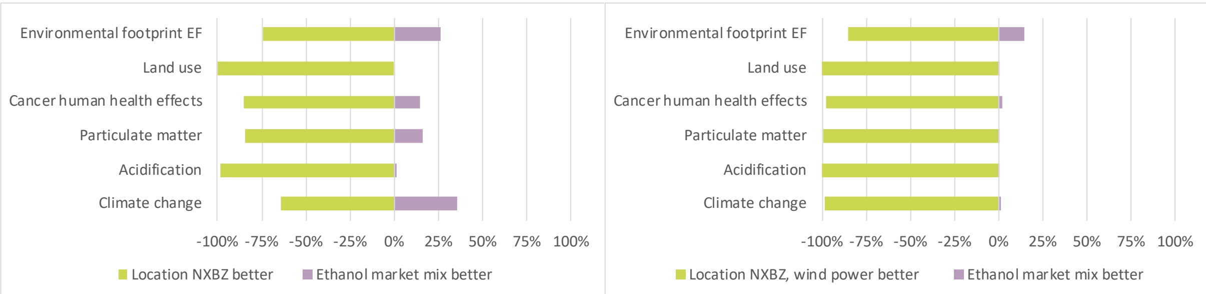

Figure 6: Uncertainty analysis with Monte Carlo simulation with 1000 runs. The green bar shows the probability that the corresponding variant ethanol from BOF gas is better. The purple bar shows the probability that the ethanol market mix is better.
Assumptions:
Significantly better: A outperforms B by >85%
Tendentially better: A outperforms B by 70%-85%
No significant difference: A outperforms B by <70%

4 Discussion

4.1 Ethanol from BOF gas from China

The LCA was drawn up here based on process design values. At the Chinese NXBZ site the BOF gas is normally flared and not used otherwise. This showed that in most categories considered, ethanol from BOF gas from China has a lower environmental impact than the ethanol market mix. Only the impact on climate change is slightly better for ethanol from BOF gas. If renewable power such as wind power is also used as direct electricity input instead of the Chinese grid mix, the ethanol from BOF gas performs better in all of the considered impact categories.

It is expected that in the future the electricity mix to be replaced will be greener i.e. more renewable. The results are likely to shift more and more towards the renewable power replacement option. Thus, ethanol from BOF gas will also perform much better from the point of view of climate change (carbon footprint). This is to the advantage of ethanol from BOF gas production. Moreover, ethanol from the BOF gas process line is still a relatively young technology that still has potential in terms of economies of scale and increased efficiency.

4.2 Limitations of the study

The life cycle assessment carried out and, in particular, the results obtained are only valid for the site considered and their conditions. The results are not easily transferable to other regions, especially because the electricity mix used in the production of ethanol from BOF gas has a relevant share in the results for most environmental impacts.

Only BOF gas was considered as a carbon source for the bacteria. The results cannot be readily applied to other carbon sources, for example, from oil refining, chemical production, and gasification of forest and agricultural residues, municipal waste, natural gas, and coal.

The ethanol market mix is an average composed of ethanol from sugar cane and sugar beet molasses. The results calculated here cannot be transferred to ethanol from other agricultural raw materials or to an individual farm or producer.

The study considered only the environmental impacts and says nothing about social or economic impacts. In particular, the impact on a possible reduction of land pressure or food competition, as less agricultural land is needed for the use of ethanol from BOF gas, was not considered further.

5 Conclusion and recommendations

Ethanol from BOF gas is recommendable and an alternative to conventional ethanol from an ecological point of view if the BOF gas is not used elsewhere, as is the case at the Chinese site. Due to the large quantities of BOF gas produced in the steel industry, the potential of BOF gas not yet used is enormous. In principle, the more environmentally friendly the electricity mix used, the more profitable it will be in the future. From an LCA point of view, it is recommended to use ethanol from BOF gas from China (NXBZ). The environmental performance is even further improved if renewable power such as wind power is used directly in the production of ethanol.

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7 Results in tabular form

Environmental impact	Unit per kg ethanol	NXBZ site	NXBZ site with wind power as input	Ethanol market mix
Acidification	mol H+ eq	9.47E-03	6.03E-03	1.94E-02
Climate change	kg CO2 eq	1.33E+00	6.86E-01	1.49E+00
Ecotoxicity, freshwater	CTUe	9.68E+00	7.67E+00	2.06E+02
Particulate matter	disease inc.	9.33E-08	4.48E-08	1.37E-07
Eutrophication, marine	kg N eq	2.26E-03	1.51E-03	1.01E-02
Eutrophication, freshwater	kg P eq	2.38E-04	1.06E-04	3.75E-04
Eutrophication, terrestrial	mol N eq	2.40E-02	1.59E-02	7.33E-02
Human toxicity, cancer	CTUh	6.31E-10	5.33E-10	7.92E-09
Human toxicity, non-cancer	CTUh	1.61E-08	7.17E-09	1.28E-07
Ionising radiation	kBq U-235 eq	5.51E-02	1.47E-02	4.75E-02
Land use	Pt	6.71E+00	4.23E+00	8.68E+01
Ozone depletion	kg CFC11 eq	3.90E-08	3.76E-08	5.87E-08
Photochemical ozone formation	kg NMVOC eq	7.07E-03	5.01E-03	9.18E-03
Resource use, fossils	MJ	1.54E+01	9.00E+00	1.56E+01
Resource use, minerals and metals	kg Sb eq	6.60E-06	3.30E-06	7.41E-06
Water use	m3 depriv.	2.05E-01	1.32E-01	6.67E+00
Environmental Footprint according to EF 3.1	eco points	1.19E-04	6.72E-05	3.17E-04