D5.4 Simplified LCA & LCC of food waste valorisation

Description of standardised models for the valorisation spreadsheet tool for life-cycle assessment and life-cycle costing

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List of abbreviations

AD	Anaerobic Digestion
ALCA	Attributional life cycle assessment
BOD	Biological oxygen demand
CHP	Combined Heat and Power
CLCA	Consequential life cycle assessment
C-LCC	Conventional life cycle costing
CO_2e/CO_2-eq.	Carbon dioxide equivalents
COD	Chemical oxygen demand
DM	Dry Matter
DOC	Dissolved organic matter
EF4	Emission factor for N2O emissions
E-LCC	Environmental life cycle costing
FM	Fresh Matter
FSC	Food supply chain
FORKLIFT	FOod side flow Recovery LIFe cycle Tool
FU	Functional unit
GHG	Greenhouse Gases
GHG	Green House Gases
GWP	Global warming potential
ILCD	International reference life cycle data system
IPCC	Intergovernmental Panel on Climate Change
ISO	International organization for standardization
LCA	Life cycle assessment

LCC	Life cycle costing
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LHV	Lower Heating Value
MS	Member states
MSW	Municipal solid waste
N-P-K	**NPK** fertilisers refer to the content of nitrogen (N), phosphorous (P), and potassium (K)
oDM	Organic Dry Matter
RS	REFRESH situation
SB	System boundary
S-LCC	Societal life cycle costing
TOC	Total organic coal
TRL	Technology readiness level
TSP	Triple sugar phosphate
WP	Work package
WtF	Waste to energy

Executive summary

The current report provides the general methodological background documentation on the REFRESH FORKLIFT tool for life-cycle assessment and life-cycle costing. Pros and cons of the modelling approach are discussed, and in particular, how it may complement the REFRESH food-use hierarchy. Details about the methodological considerations, general principals and assumptions are found in this report.

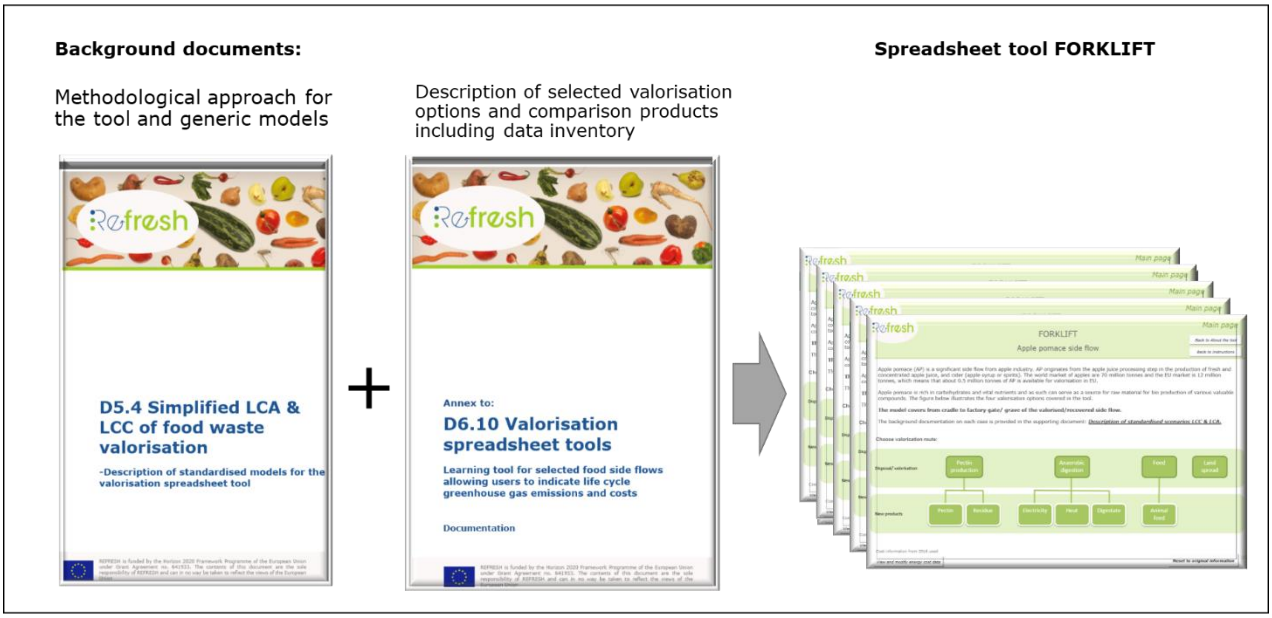
Urged by the importance of resource efficiency and the circular economy agenda of EU and national policy makers, many stakeholders are seeking alternatives for current surplus food or side flows within the food supply chain. Any new valorisation route for side flows (i.e. not the driving products) will be associated with monetary and environmental impacts. Robust, consistent and science-based approaches could allow informed decision making at all levels, from individual stakeholder to policy level. The EU H2020 funded project REFRESH (Resource Efficient Food and dRink for the Entire Supply cHain) aims to contribute to food waste reduction throughout the food supply chain and evaluate the environmental impacts and life cycle costs.

Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) are well-documented and common approaches for assessing the environmental impacts and costs of a system. Both LCA and LCC are characterised by allowing for a large flexibility in system scoping. Consistent approaches are required for reliable comparisons between different options. Furthermore, assessors might have a deep knowledge of the systems they are assessing but not an in-depth understanding of LCA or LCC. Thus, highlighting challenging methodological aspects and encouraging the practitioner to identify the most relevant questions contributes to a better scoping practice of LCA and LCC. Based on the guidelines provided in the REFRESH report *"Generic strategy LCA and LCC"* (Davis et al. 2017) [1], we developed FORKLIFT(FOod side flow Recovery LIFe cycle Tool) a simplified learning tool in a spreadsheet format, which provides a basic footprint analysis of greenhouse gas emissions and costs.

The FORKLIFT toolbox (Figure i). was developed to help stakeholders gain a general understanding and to highlight the environmental impacts and costs for selected valorisation routes of a given side-flow. Being a learning tool, it is not intended for full footprint analysis to be communicated. It can be considered as a first step in understanding the dynamics of selected parameters usually controlled by the generator or the user of the side-flow. The model can be used by policy makers, researchers, professionals, businesses, and other interested stakeholders

[1] https://eu-refresh.org/generic-strategy-lca-and-lcc

Figure i: The FORKLIFT toolbox: Methodological approach, description of the valorisation routes and data sources and modelling assumptions, the web-based spreadsheets tools for evaluation of GHG gases and costs



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How can users apply the FORKLIFT spreadsheet tools

By using FORKLIFT the user can gain an understanding of a system from an environmental and cost view. The user of the tools has the possibility to compare static systems which are reasonable to consider and change default values according to his/her contexts' specific situation (e.g. country, means of transport, heat source). Effects of the change are immediately shown in the result figure which enables the user to try different parameters and watch the effects. Emissions and costs of the valorisation option are shown in relation to a range of comparison products. Which kind of product on the market will really be supplemented is up to the user. The tool covers different food side-flows, which are different in terms of nutrients, fats, proteins, carbohydrates and fibres. The spreadsheet tool can point towards areas of high impact (hotspots) and can support decisions for interventions.

Specifically, FORKLIFT has a cradle-to-factory gate perspective, starting from the point of generation of the side flow up to its valorisation. GHG emissions from the upstream processes, before the side flow was generated, are allocated between the main product and side flow, based on their actual or estimated economic value for the generator of the side flow (economic allocation). Side flow price, however, directly represents the costs of upstream processes. The tool does not consider future market developments and the impact of potential large-scale changes on infrastructures. For capturing such changes, the user is recommended to apply a full consequential LCA-LCC assessment following the guidelines provided in the REFRESH report *"Generic strategy LCA and LCC"*[2]. Selected valorisation routes for

[2] https://eu-refresh.org/generic-strategy-lca-and-lcc

apple pomace, brewers spent grain, tomatoes, slaughtering by products (blood), and whey permeate, are further explored in the in the REFRESH report *D6.10 Valorisation spreadsheet tools.*

What can we learn from the FORKLIFT tool

FORKLIFT spreadsheets are easy to use which enable the user to change different parameters and to try out how these changes affect the life cycle costs and emissions. It is therefore a suitable learning tool with the additional effect of making it possible to compare the results with alternative systems available on the market. A stakeholder that generates or utilises a side flow can interpret the results regarding the effects of interventions themselves, as they are also often the ones who know the market conditions best.

The tool clearly shows that many parameters influence the outcomes and that it is not easy to make universal conclusions regarding the best environmental or economic options. This is highly dependent on the context (country, energy sources, substituted products at the markets). Thus, it may serve as an important complement to a food use hierarchy.

In FORKLIFT quantitative data has been gathered and streamlined for selected important side flows to make LCA and LCC approaches accessible to users, thus the model, to some extent, fills the gap between qualitative models (e.g. the food use hierarchy) and quantitative models.

Finally, and most importantly, the tool may enhance stakeholders' possibilities to pinpoint environmental and cost related hotspots in a given context. As such it can support the stakeholder in the early phase of development taking informed decisions of a valorisation process/waste management option without having a full inventory at hand and thus contribute to the development of economic and environmentally sustainable handling of food side flows.

The framework developed and the specific spreadsheet models, which are thoroughly described, can be extended with other side flows in the future. From this perspective the current work should be seen as a starting point.

1 Introduction

The REFRESH project aims at contributing towards the EU Sustainable Development Goal 12.3 of halving per capita food waste at the retail and consumer level and reducing food losses along production and supply chains, reducing waste management costs, and maximising the value from un-avoidable food waste and packaging materials.

This goal can only be achieved if food is produced using the available resources efficiently and effectively, from both an economical and environmental perspective. This includes the prevention of unwanted side flows from the food supply chain, as well as utilising any value from such side flows to the best effect. Such an increase in resource efficiency will have an economic effect, while reducing the pressures on climate, water, and land use.

Generally, a new valorisation route for side flows from the food supply chain will be associated with impacts (monetary and environmental), for example for capital investments or developing new technologies. In the long term, however, this might lead to better resource utilisation, which will result in lower running costs and reduced environmental impact. Thus, informed decision making at all levels, from individual stakeholder to policy level, requires robust, science-based approaches to analyse such scenarios.

Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) are well-documented and common approaches for assessing the environmental impacts and costs of a system. Both LCA and LCC are characterised by allowing for a large flexibility in system scoping. Consistent approaches are required for reliable comparisons between different options. Furthermore, assessors might have a deep knowledge of the systems they are assessing but not an in-depth understanding of LCA or LCC.

While the REFRESH report "D5.3 Generic strategy LCA and LCC" provides guidelines on how to assess side flows combining LCA and LCC, FORKLIFT (FOod side flow Recovery LIFe cycle Tool) aims at providing stakeholders with a hands-on tool helping to gain a general understanding and highlight the environmental impacts and costs for selected valorisation routes, focusing on selected parameters.

By highlighting challenging methodological aspects and encouraging practitioners to identify the most relevant questions, the learning spreadsheet tool is destined to policy makers, researchers, professionals, businesses, and other interested stakeholders and addresses the following REFRESH objectives:

- Supply consistent LCA and LCC data for selected cases of valorisation routes to be used for the identification of the most sustainable and economically viable solution.
- Contribute to the development of the REFRESH decision support system and develop an accessible web-based tool providing consistent LCA and LCC data.

2 Goal and scope of this report

2.1 Specific objectives

The specific objective of this report is to provide the background documentation on the REFRESH FORKLIFT tool from a methodological perspective. The report outlines the methodological choices and assumption related to the goal and scope, the limitations of the model, and the intended audience. Furthermore, this report presents generic models on valorisation and disposal options, which are available across all side flows (e.g. anaerobic digestion, end-of-life treatment) and general considerations on the assessment of animal feeding and fertilising. All side flow specific valorisation options and corresponding data inventory, as well as the specific data inventory for the generic valorisation and disposal options, are described in "*Valorisation spreadsheet tools – Learning tool for selected food side flows allowing users to indicate life cycle greenhouse gas emissions and costs".* Worked out examples are used to illustrate important aspects for the development of new valorisation routes, the benefits of the tool, as well as its limitations.

The FORKLIFT tool (FOod side flow Recovery LIFe cycle Tool) is intended to be disclosed to public.

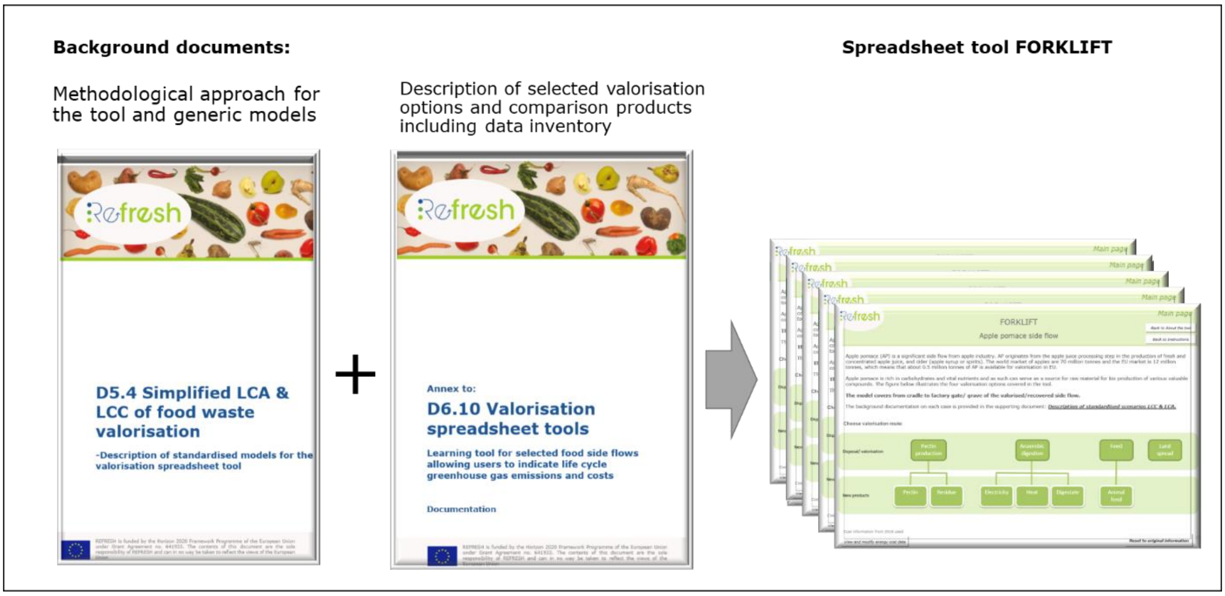

Figure 1: The FORKLIFT toolbox: Methodological approach, description of the valorisation routes, data sources and modelling assumptions for web-based spreadsheet tools evaluating GHG gases and costs

2.2 Selected products and routes

2.2.1 Food side flows

Side flows of the food supply chain (FSC) are defined as a material flow of food and inedible parts of food from the food supply chain of a driving product. The stakeholder in the FSC producing this flow tries to have as little as possible of it. The principle 'the less, the better' applies to these flows (Davis et al. 2017).

The choice of side flows implemented in FORKLIFT are based on recommendations by experts/stakeholders within REFRESH provided in "Top 20 Food Waste Streams" (Moates et al, 2016) and "Valorisation appropriate waste streams" (Sweet at al. 2016) based on the following criteria:

- Difficult to prevent;
- Large volumes and/or significant environmental impacts;
- High valorisation potential;

Selected side flows for the assessment are: apple pomace, blood from slaughtering, brewers' spent grain, tomato pomace, whey permeate and rapeseed press cake.

2.2.2 Valorisation options

Valorisation options representing REFRESH Situations 2-4 (see section 4 and 5 for more details) were identified through an in-depth literature survey and experts/stakeholder's knowledge within REFRESH (Moates et al, 2016). Only mature technologies were considered. Valorisation options are described in detail in the Annex to D6:10 "*Valorisation spreadsheet tools – Learning tool for selected food side flows allowing users to indicate life cycle greenhouse gas emissions and costs".*

To maintain accuracy, each side flow was modelled separately considering the specific circumstances and constraints related to the side flow, such as valorisation potential, constraints relating to processing and handling (water content, perishability, legal requirements), its value and environmental upstream impact, etc.

Figure 2 and Figure 3 provide an overview of the selected side flow and valorisations options included in the model.

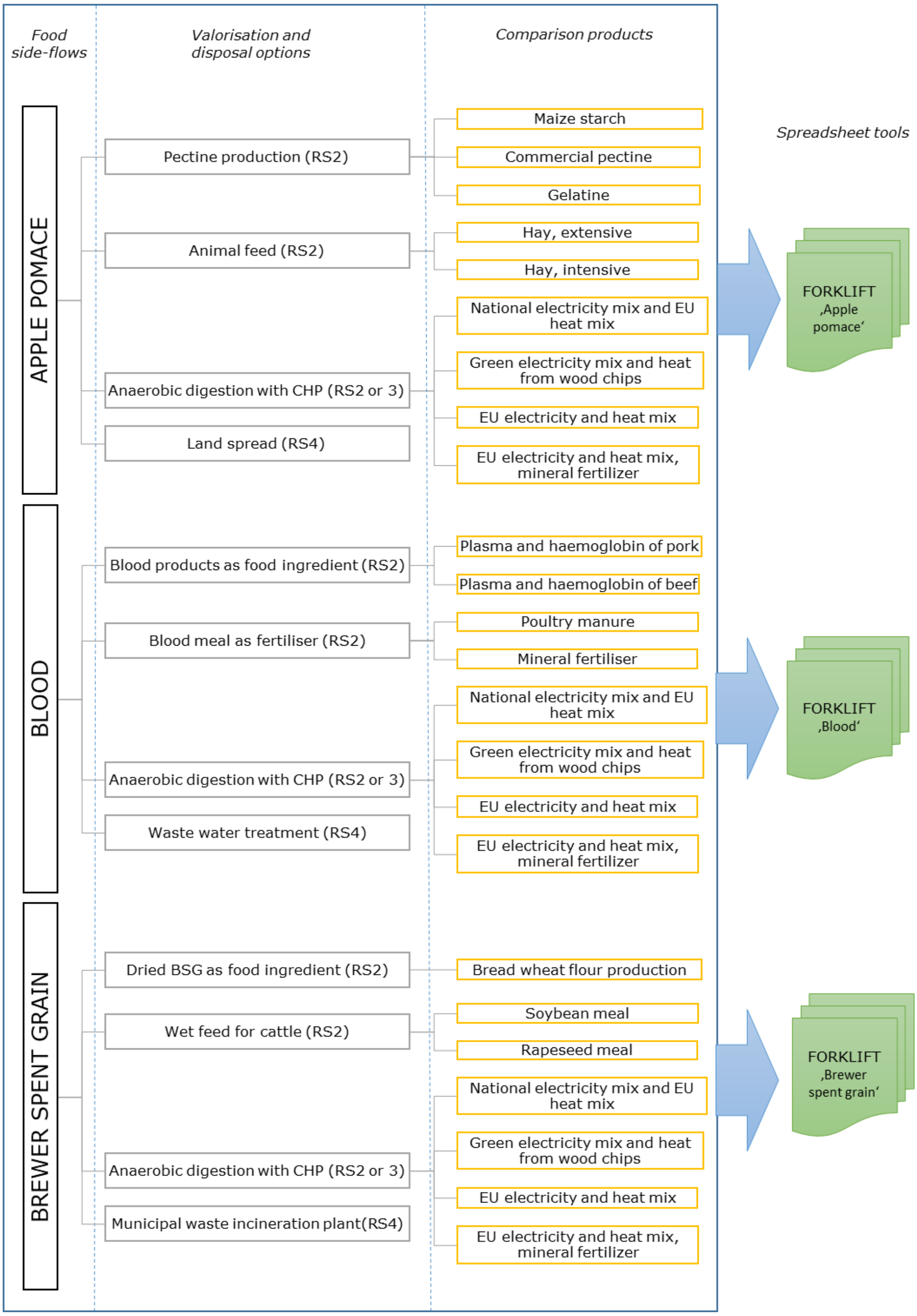

Figure 2: Valorisation and disposal options included in the spreadsheet tool 'FORKLIFT' – part I

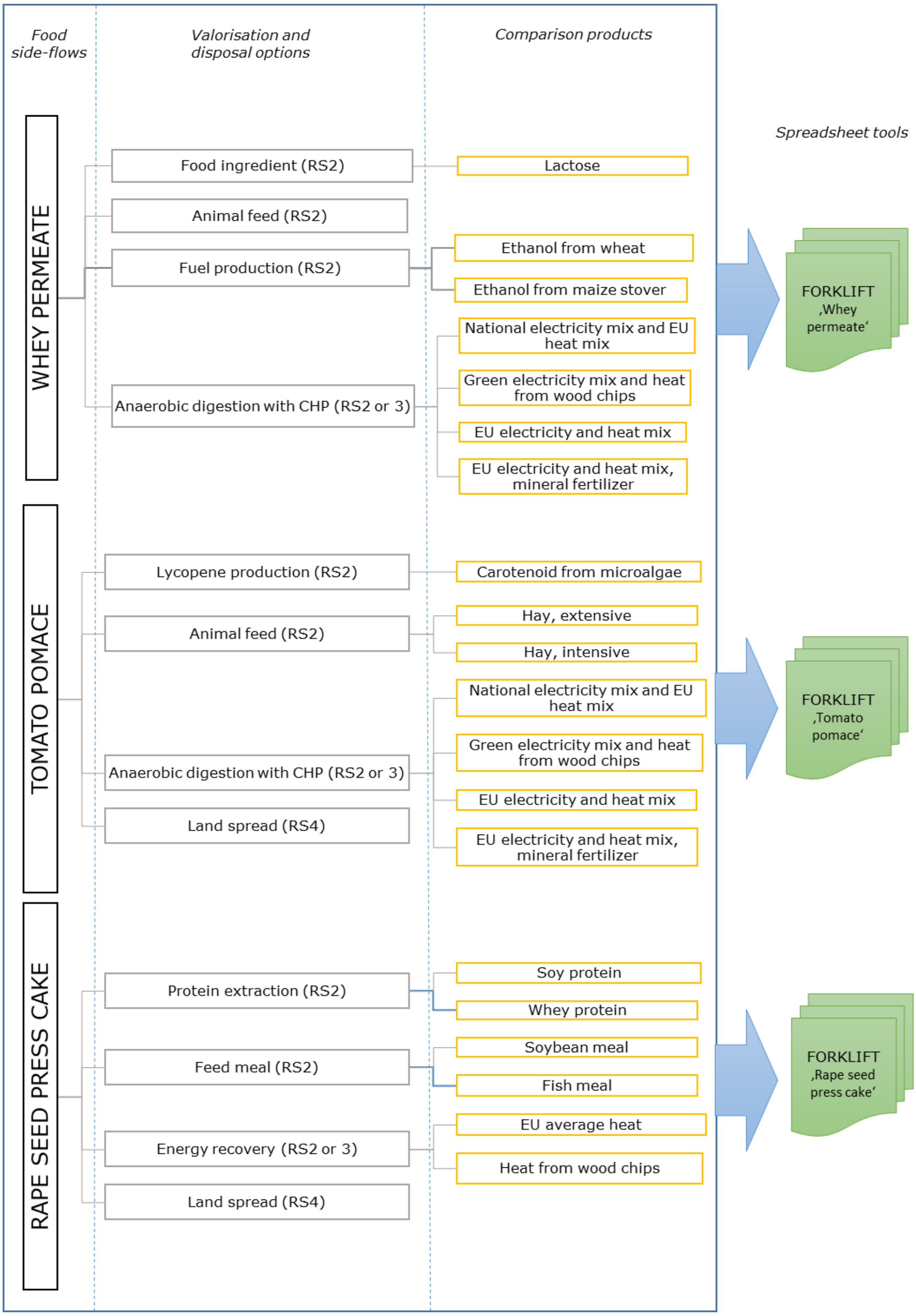

Figure 3: Valorisation and disposal options included in the spreadsheet tool 'FORKLIFT' – part II

2.3 Validation

A qualitative validation of the developed models was carried out, making use of experienced LCA and LCC and process experts in the team, considering uncertainty and the impact of the parameters in the spreadsheet model (see Figure 4). Previous LCA studies of food production and processing systems show that the magnitude and type of energy used, resource utilisation, as well as emissions of methane and nitrous oxide are important parameters for indicating global warming impact. When setting up the models, the focus has been on capturing these parameters.

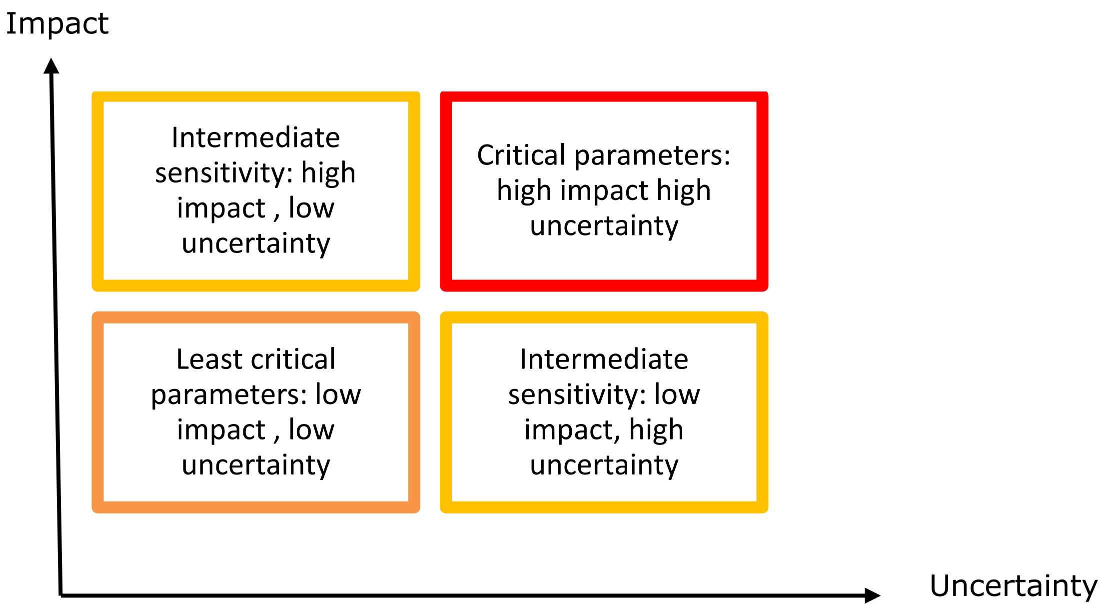

Figure 4 Validation matrix used for the spreadsheet models

3 Methodological considerations

3.1 Detailing the approach based on the REFRESH guidance

Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) are well documented and generic approaches for assessing the environmental and cost dimensions of a system. LCA summarises all environmental impacts associated with the life cycle of a product and an E-LCC (environmental-LCC), being the method applied in REFRESH and the FORKLIFT tool, is an LCC approach that summarises all costs associated with the life cycle of a product including those involved at the end of life. In an E-LCC the costs must relate to *real* money flows. Externalities that are expected to be internalised must also be included. An E-LCC is a costing method that can be integrated with LCA (i.e. having same functional unit and system boundaries)

The core approach in the FORKLIFT tool is based on the framework presented in the REFRESH report "Generic strategy LCA and LCC-Guidance for LCA and LCC focused on prevention, valorisation and treatment of side flows from the food supply chain" (Davies et al., 2017). The framework recommends the following stepwise procedure:

1. Phrase the question of your study; what is the purpose of the study?
2. Establish if the flow being investigated in the study is a side flow (if not, then this is outside the scope of this report), and which REFRESH situation is applicable, by using the decision tree in Figure 3. In the case of several situations (scenarios) run through the decision tree for each situation.
3. Establish whether your study is a footprint or intervention study, by using the decision tree provided.
4. If cost is assessed, establish if E-LCC is suitable for the study
5. Utilise provided tables for recommendations on methodological choices in the LCA/LCC study.

The stepwise procedure was applied for FORKLIFT according to:

Step 1: Phrase the question of the study, identify the audience for the result
FORKLIFT is developed to **help business** and **stakeholders** in identifying food-side flows/waste streams, as defined in "Generic strategy LCA and LCC" (Davis, et al. 2017), that are appropriate to be valorised, and provides a *first indication* of potential hotspots for a given *valorisation* route.
FORSKLIFT responds to the following question: *What are the potential environmental and cost implications of a valorisation route of a side flow as defined in Davis et al. (2017).*

Step2: Establish which REFRESH situation (RS)

FORKLIFT is developed for comparisons between RS2 - Side flow valorisation, RS3 - Valorisation as a part of waste management and RS4 - End of life treatment. A decision tree for determining RS is provided in Figure 5. RS1- Prevention of a side flow is not within the scope of the model.

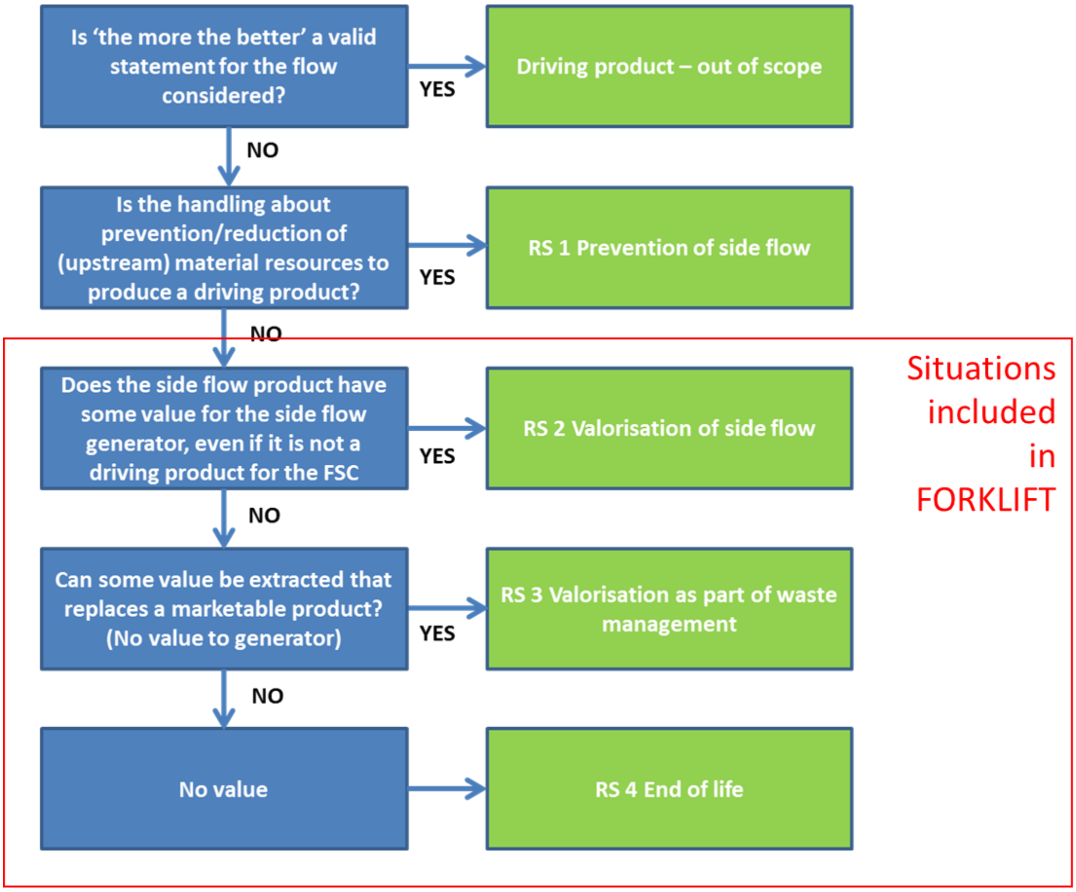

Figure 5: Scope of the spreadsheet tool developed (Davis et al., 2017)

Step 3: Footprint or intervention study

The results obtained from FORKLIFT should provide an indication of environmental effects and costs, but not serve as a decision support tool for interventions as such. Considering the question of the study (Step 1) "*What are the potential environmental implications and cost implications of a valorisation route of a side flow as defined by Davis et al (2017)"?* The tool should give a principal understanding of the impacts associated with a valorisation route.

Thus, when using FORKLIFT, the study has the character of a footprint study and an attributional approach (ALCA) of a static system is to be preferred. It is worth noting that, in the next step of the assessment, the calculated footprint can be used for comparison with different static systems *not* interfering with each other (which would have been the case if taking a consequential approach). The iterative journey of finding an appropriate framework for a generic and simplified spreadsheet tool was documented in a conference article (Unger et al, 2018). The applicability of different modelling frameworks (attributional, consequential small-scale, consequential large-scale) were discussed in order to develop a suitable spreadsheet tool. Aspects such as theoretical robustness, data availability and communicative capacity from the view of the users of the tool were the determining factors for agreeing the final modelling framework.

Step 4: Is E-LCC appropriate?
FORKLIFT should provide an integrated assessment of GHG emissions and costs using the same system boundaries. In addition, stakeholders indirectly affected through externalities are not considered.

Therefore, FORKLIFT follows an E-LCC approach because the aim of the assessment includes both environmental and costing impacts. Conventional LCC is out of the scope of this tool. And the assessment does not aim at including external costs for all stakeholders (e.g. society, government, etc.), thus also societal LCC is out of the scope of this tool.

Step 5: FU, SB, cut-off and handling multi-functionality

Functional Unit (FU)

The functional unit for LCA and E-LCC is the "quantified performance of a product system for use as a reference unit" (ISO 14044). The goal in this study is to quantify environmental impacts and costs for disposing or valorising a given quantity of side flow to a given co-product.

The corresponding Functional Unit (FU) is *one tonne of side flow being valorised/disposed to XX.* Where *XX* is/are the end-product(s) of the selected valorisation route.

In the case of several co-products of one valorisation option, the impact of these are quantified and added together.

System Boundaries (SB)

The process diagram (Figure 6) gives a generic overview of life cycle stages included in the FORKLIFT tool. Note that in the tool comparison products are provided but are not formally included in the system boundaries (see Step 3 above). The SB is common for LCA and E-LCC. The recovery and disposal options included in figure 5 are assessed in detail. The environmental and economic impact from up-stream processes are estimated based on the production step, excluding transport and processing. A description of the representativeness of the chosen product is given in section 6.

Time frame and geographic consideration

The calculations provide a footprint of a current valorisation disposal option considering current knowledge, infrastructures, and market conditions year 2017. The data collected refer to EU (average) or selected single EU-countries.

For greenhouse gases, GWP100 is assumed (see *Impact assessment* p18). For costs, the most recent data available was used for all the items considered (see section 5.3).

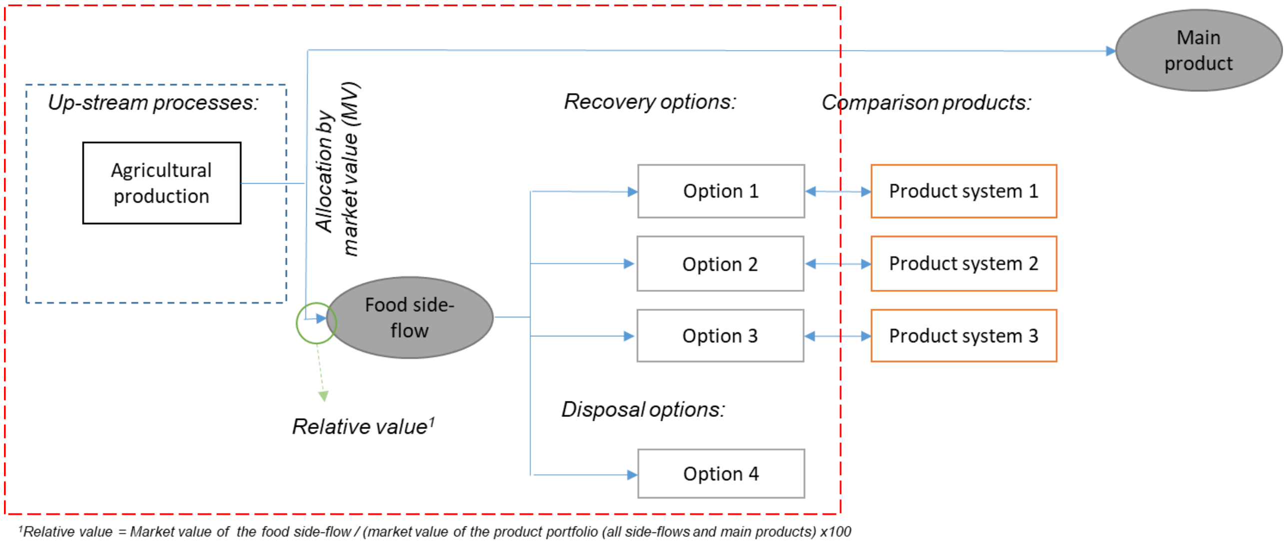

Figure 6: REFRESH generic system boundaries for the FORKLIFT tool

Allocation

Multi-output allocation generally follows the requirements of ISO 14044 (ISO, 2006a, b). As side flows are per definition co-products of multi-output processes, allocation is required at the processing stage as shown in Figure 6. Economic allocation was chosen as the appropriate method, allowing the user to include the relative value of side flow with respect to the product portfolio of the given product being processed (e.g. apples) at the point of sell. For example, if the side flow is apple pomace the value of the apple pomace at factory gate (point of sell for the side flow) is divided by the value of the apple pomace and apple juice (the product portfolio with reference to apples).

The impact of the main product(s) at farm gate (Figure 6) was used as a proxy for the total GHG and economic impact from up-stream processes before allocation. As far as E-LCC is regarded, the user can include the value/price of the side flow as a proxy of the economic impact if the value at factory gate is not known.

The modelling approach does not apply any allocation at end of life (RS4). As the goal of the study is to assess valorisation, only the total impact associated with valorisation is quantified. Additional functions are specified, but not allocated.

Cut-off Criteria

LCA: No cut-off criteria are defined for this study. Only processes contributing significantly to the GWP is considered. The assumptions made, and the accuracy of the estimates made in the inventories are described for each scenario. In the case where no matching life cycle inventories are available to represent a flow, proxy data have been applied based on conservative assumptions regarding environmental impacts.

E-LCC: With the aim of simplifying and providing reliable resources, this tool only includes, in its default version, costs directly related to LCA inventory items (e.g. raw materials, energy, etc.). Thus, it follows option A of the modelling framework stating that only costs directly related to LCA inventory items are considered for further details see "Generic strategy LCA and LCC" (Davis et al., 2017). The user can add further costs related to labour and machineries/investments, if the purpose is to further analyse financial information/analysis.

Cost modelling

Cost categorisation: Four not mutually exclusive cost categorisations can be applied in E-LCC: economic typology, life cycle stage, type of activity and detailed cost typology. Since FORKLIFT is a simplified assessment focusing on internal costs, without an analysis of the distribution along the supply chain, costs are categorised around activities (transport and processing) and detailed typology (share of environmental and economic impact from up-stream processes, energy for transport and processing, labour, capital, and disposal cost). Cost systems should be inventoried; this tool contains *market costs* as the reference for the different products obtained from the side flow. External/avoided costs have been not considered, since FORKLIFT has a footprint approach. Revenues have not been included due to lack of reliable and available data. Finally, the tool does not distinguish between different life cycle stages.

Indirect cost allocation: Choice should be based on data availability and the focus of the study. SB and cut-off of FORKLIFT do not require the inclusion of indirect costs, with the exception of maintenance. However, the user can include maintenance as an indirect cost, when it is referred to general investments and machineries by using a fixed percentage of total investment costs.

Discounting: When the focus is only on present cash flows, then no discounting is needed. Since the tool assesses current cost, it does not include any discounting. However, the user can insert discounted values for investment and machinery costs.

Externalities: Externalities that are likely to become internal costs in the future should be included in the financial part of the study but separately from other types of costs. While environmental externalities, like GHG emissions, could become internal costs in the future, it was deemed reasonable to exclude them in the default version of FORKLIFT due to its present time frame. However, the user can apply a monetization method to the final GHG of the tool to get an estimation of cost of externalities.

Cost bearers: Despite that food waste studies might include several actors/cost bearers, this tool does not adopt a multi-actor perspective, since it does not deal with existing supply chains but with generic valorisation scenarios. It provides the user with a simplified assessment of hotspots of cost in the mentioned categories. The user can therefore use results to derive some potential insights on cost distribution in the value chain.

Impact assessment

Selection of LCIA Methodology and Impact Categories (LCA): Climate Change/ Global warming potential (GWP 100) is assessed as a proxy of environmental impact, according to Table 3 in D5.3. The IPCC 2014 characterisation factors from the fifth assessment report are applied (e.g. CH_4: 28 times CO_2, N_2O: 265 times CO_2 global warming potentials over a 100-year time period). The IPCC characterisation factors are recommended by most carbon footprint standards (ISO 14067, GHG Protocol, PAS 2050). Biogenic carbon fluxes are omitted from the assessment, because carbon neutrality is assumed on the basis that the CO_2 release is equal to the CO_2 sequestration from biomass growth, regardless of the difference in timing of uptake and release.

Selection of LCIA Methodology and Impact Categories (LCC): Since the main aim of FORKLIFT is to assess only internal costs, without distinction between different cost bearers, it only assesses cost hotspots categorised by activities and typologies. Additional analysis could be added if potential revenues were known, e.g. to calculate other financial indicators such as net present value and internal rate of return.

Interpretation

FORKLIFT allows designing different scenarios and comparing them. The results of every scenario are shown in a portfolio table. Therefore, results can be easily interpreted in a comparative perspective (from different scenarios and from LCA and E-LCC perspective).

The tool can offer the possibility to interpret results according to the following steps:
1. Identify significant issues.
2. Evaluate the influence of different parameters on LCA/E-LCC results (e.g. simulating different scenarios).
3. Use the results of the evaluation to formulate conclusions and recommendations.

It is possible to use combined results to create plot graphs and other graphical representations, to rank alternative scenarios, identify win-win solutions or trade-offs, measure the elasticity between environmental impacts and costs/profits.

Along with the modelled footprints, costs and GHG impacts are provided for commercial products having the same function. This will not, however, allow the user comparing footprints to judge potential implications of a change in a larger context, considering the limitation provided below.

3.2 Limitations

The FORKLIFT tool is subject to limitations that need to be explicit to guarantee a robust interpretation of results:

- FORKLIFT assesses a static system. It cannot indicate impacts from large-scale interventions. This is only reasonable for larger scale studies, with fewer options where outcomes from market interventions can be clearly determined.

- FORKLIFT *does not provide results* on policy recommendations, as this would demand consequential modelling. However*, it reveals hotspots of the different valorisation options and gives insights on effects of certain choices.*
- FORKLIFT is based on generic and indicative data and therefore does not replace carbon footprint or cost calculations for specific decision-making at company level.

4 Overview of general principles and priorities of FORKLIFT

Given the methodological base for the FORKLIFT tool additional considerations were required to streamline the life cycle inventories (LCI) and populate the spread sheet model. These are explained in detail in this chapter.

4.1 General description of FORKLIFT

FORKLIFT is developed to help stakeholders (policy makers, researchers, professionals, business, etc.) to gain a general understanding of the environmental impacts and costs for selected valorisation routes of a given side flow. It is a learning tool; therefore, it is not intended for full footprint analysis with the purpose of being communicated. It can be considered as a first step in apprehending the dynamics of selected parameters usually controlled by the generator or the user of the side flow.

Specifically, FORKLIFT provides an estimate of GHG emissions and the total (supply chain) costs per tonne of side flow to be valorised. The results are then compared to average footprints of similar products with the same function. It is important to note that the footprints added as comparison should only be taken as an indication on whether the assessed process is better or worse than others, since the results are highly dependent on assumptions made.

The underlying models are based on existing knowledge about processes. GHG emissions are calculated based on available literature and data as well as energy and transport (fuel) cost. However, the tool allows the user to elaborate on critical parameters that can be influenced by the stakeholders, such as energy demand (reflecting the equipment used) and supply (reflecting geography/location), transport mode and distances, as well as capital and labour costs, etc. The user can also modify the assumed costs provided in the model.

The model has a cradle-to-factory gate or grave perspective (depending on valorisation option), starting from the point of generation of the side flow up to its valorisation. GHG emissions from the upstream processes before the side flow was generated, are split between the main product(s) and side flow, based on their actual or estimated economic value (economic allocation). Consequently, an increased value of the side flow will lead to an increased footprint of the product being valorised, but at the same time the footprint(s) of the main product(s) and other co-product(s) will decrease and vice versa. The upstream costs are set equal to the price being paid to the generator of the side flow.

The tool does not consider future market developments and the impact of potential large-scale changes on infrastructures. For capturing such changes, the user is recommended to apply a full consequential LCA-LCC assessment following the guidelines provided in the REFRESH report "Generic strategy LCA and LCC (Davies et al. 2017).

4.2 Principles for the selection of side flows, valorisation options, and products to compare with

4.2.1 Valorisation options

The specific valorisation options of the side flows included in the spreadsheet model were selected based on the following criteria:

1. Market and/near market applications (TRL 9)
2. Available data. It should be noted that cost and LCA data for pilot processes are significantly different from fully developed processes and highly context dependent. By focusing on market applications/near market applications, realistic inventories should be made.
3. Relevant combination of valorisation options illustrating the influence of origin (type of raw material), degree of processing, (e.g. AD vs pectin production) degree of utilisation (full utilisation or only parts are utilised).
4. REFRESH situation (RS2-RS4). When possible and relevant, valorisation options reflecting the different REFRESH situations (RS2-RS4) were selected.

4.2.2 Comparing products

The selection of products to compare with were based on the collective knowledge of the group and to enhance the learning potential.

Criteria used were:

- The comparison products should be a combination of market alternative products providing the same specific function, (functional equivalence) as well as high and low impact alternatives.
- The footprints should reflect commercial production of a comparison product.
- Data quality should be sufficiently good for the purpose.

The impacts/footprints provided are scaled in such a way that reasonable comparisons can be made (e.g. energy content for AD, gelling capacity for thickeners, fibre content or protein content for feed, etc.). Thus, all comparisons products are based on functional equivalence as far as possible. Details on comparing products and scaling is provided in specific descriptions of the models in "*Valorisation spreadsheet tools – Learning tool for selected food side flows allowing users to indicate life cycle greenhouse gas emissions and costs,* Annexes)

4.3 Cost estimates and their justifications

This tool only considers costs relative to LCA inventory items (e.g. energy, fuel, side flow). Optionally, labour and capital costs might be added. All costing data were retrieved from open access databases and sources. The user can also modify some costs and provide further data in the tool. Below, Table 1 provides an overview of costs per stage, while more detailed sources can be found in the Annexes of the REFRESH Report *D6:10 Valorisation spreadsheet tools – Learning tool for selected food side flows allowing users to indicate life cycle greenhouse gas emissions and costs*.

Table 1: Cost items in FORKLIFT and related inputs

Stage	Cost item	Main source input
Environmental and economic impact from up-stream processes	Value/price	User
Processing	Fuel Electricity Heat	EU per country and EU average Can be modified
Transport	Fuel	EU per country and EU average Can be modified
Comparison product	Cost of product	EU per country and EU average Can be modified
Labour	Hourly average worker salary per country	EU per country
Capital	Total cost or yearly depreciation for investment and machineries Maintenance	User
Disposal	Further costs beside transport and energy	User

The upstream cost impact can be added directly by the user, who might have the specific information. This value could be the price or fee paid to the side flow generator or simply represent collection cost.

Default values for energy and fuel costs in the side flow processing scenarios and transports are included in FORKLIFT. Such figures are from statistic offices and market reports. If needed the user can include own figures.

Default labour costs were included based on average wages (data from Eurostat, except for Switzerland - see Annexes to *D6:10 (Valorisation spreadsheet tools – Learning tool for selected food side flows allowing users to indicate life cycle greenhouse gas emissions and costs*).

No default values are included for capital costs. The user can add these items using either the yearly depreciation or the total cost, then allocate such costs on the functional unit through the annual or total operating lifetime relating to the amounts of side flow being processed. Maintenance can also be added as a fixed rate of total capital costs.

Finally, disposal costs not already included in waste management scenarios (energy and fuel) can be added as well by the user. Any local waste taxes and fees can be used as source of information here, but the user should be aware that such figures are likely to be reflected in costs already accounted for in FORKLIFT, and avoid double counting.

5 Generic models for FORKLIFT

Along with the outlined methodological choices described in previous sections, additional *research* was carried out to provide a *common* base for streamlining the Life cycle impact assessment in the FORKLIFT tool. Specifically, this was done for energy production and waste management as these are common processes for the different side flows.
A general overview of the modelling approach for valorisation of higher value compounds/food ingredients is provided as well for the sake of completeness. However, these valorisation options do not require further streamlining in addition to the methodological assumptions provided in the previous chapters, and are thus fully described in the Annexes to D6:10, along with their model inventories.

5.1 Modelling valorisation into valuable compounds

Valorisation to achieve high value compounds/food ingredients generally involves: (1) a processing step aimed to extract the targeted compound (for example pectin, lycopene, or another food ingredient) as well as; (2) a process for the mass remaining after extraction. The costs and GHG emissions of both process (1) and (2) are included in the FORKLIFT model.

Investment costs will vary with situation e.g. if the facility is already in place the costs for investments and labour are considerably lower than if new investments are required. Scale and co-production of other products will significantly influence the capital and labour costs as well. Costs for transportation and energy, however, is less dependent on the actual situation and can be more easily predicted based on tabulated values for a given country.
Because the labour and capital costs cannot be predicted without detailed knowledge of the situation these costs are not incorporated by default in the base scenarios of FORKLIFT, but can be easily added by the user (see section 4.3 and Table 1). This means that only when costs for labour and investments have been added a comparison with other products can be made.

The calculation of GHG emissions and costs are based on a combination of interviews with processors and literature studies and are *unique* for each targeted side flow and product. For this reason, the research and the full descriptions of these valorisation options are provided in the Annex to D6:10 Valorisation Spreadsheet Tools according to the outline of the FORKLIFT toolbox (Section 0 and Figure 1)

5.2 Modelling fertiliser application

5.2.1 Goal and scope of the assessment

The valorisation routes for fertiliser can involve two pathways in the tool: (1) the production of an organic fertiliser from a food side flow (e.g. in the case of blood), (2) the use of digestate from an anaerobic digestion plant as organic fertiliser. The direct application of food side flows without treatment on land may also have fertilising effects where nutrients and organic matter additions are in quantities that are beneficial for agricultural soils. However, in general the side flows for land spreading are assumed to have a low content of valued nutrients having zero-value (farmers do not pay for it) and are therefore handled as on option for RS4 and described in 5.4 Modelling . The economic value of digestate as organic fertiliser is arguable. In the tool, the user has the option to include the commercial use of digestate as organic fertiliser. As it is a learning tool, it seems beneficial to provide the user those options as comparison products.

5.2.2 Product system to be studied and system boundaries

The system boundary of fertilising in the tool covers three steps:

- Organic fertiliser production incl. up-stream processes (descriptions can be found in respective chapters 'Production of blood meal as organic fertiliser, or anaerobic digestion)
- Field application
- Comparison product (mineral fertiliser equivalent)

The application of organic fertiliser, such as digestate to the field shall be compared to the application of mineral fertiliser.

The functional unit is 1 tonne (t) of food side flow (e.g. apple pomace).

The system boundary within REFRESH includes all life cycle stages from cradle to "factory gate" (see Figure 6 and Figure 7). The life cycle stages of organic fertiliser production are documented in the respective chapters.

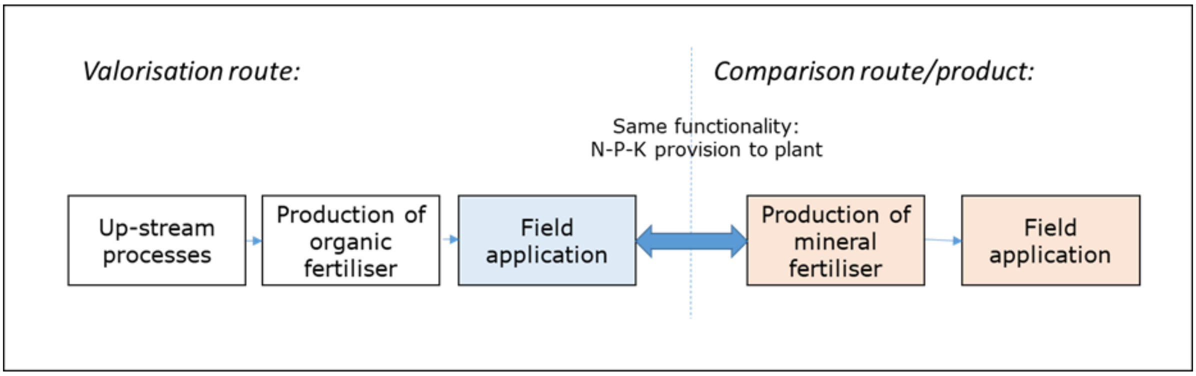

Figure 7: System boundaries for the model describing fertiliser application

5.2.3 Field application

Application of organic fertiliser

The functional unit is 1t of food side flow (e.g. apple pomace). Following anaerobic digestion, the mass decreases to about 0.8t.

Diesel required for application of organic fertiliser is substantially higher per kg of N-P-K applied. This is due to the lower nutrient concentration as well as heavier machinery required for field application (KTBL 2014). The application of 0.8t of digestate to agricultural land with a tractor and spreader requires 1.6 l of diesel (KTBL 2014). Supply and combustion of diesel leads to emissions of 1.2 kg CO_2e.

N_2O emissions

The application of Nitrogen fertiliser to soils lead to direct N_2O emissions as well as indirect N_2O emissions through leaching and volatilisation. Following the IPCC (2006) Guidelines for National GHG Inventories, direct N_2O emissions as well as indirect N_2O emissions through leaching are the same for organic and mineral fertilisers. Indirect N_2O emissions from volatilisation are higher for organic fertilisers due to a higher volatilisation rate.

Calculation method for organic fertilisers:

$$N_2O\text{-}N_{\ (ATD)} = \text{kg N}_{\ org} \times \text{Frac}_{\ gas\ org} \times EF4$$

Calculation method for mineral fertilisers:

$$N_2O\text{-}N_{\ (ATD)} = \text{kg N}_{\ min} \times \text{Frac}_{\ gas\ min} \times EF4$$

Where:

$N_2O = N_2O\text{-}N \times 44/28$

kg N_{min} = kg Nitrogen applied, mineral fertiliser

kg N_{org} = kg Nitrogen applied, organic fertiliser

$Frac_{gas\ min} = 0.1$

$Frac_{gas\ org} = 0.2$

$EF4 = 0.01$

Figure 8: Calculation of indirect N_2O emissions from volatilisation of organic vs. mineral fertilisers (Formula 1)

Nitrification and denitrification processes of the organic fertiliser applied (2.9 kg total N, 2.3 kg mineral N fertiliser equivalent) lead to N_2O emissions of 13.6 kg CO_2e (IPCC 2016).

Carbon sequestration

Additionally, digestate adds 45 kg of CO_2e to the soil carbon pool based on (Arbeitsgruppe BEK, 2016) and KTBL (2016). Sequestration of soil carbon has not been considered in FORKLIFT. Other standards require this to be reported separately (ISO 14067).

5.2.4 Comparison product

Within the scope of the scenarios the following assumptions regarding functionality are made:

The macronutrients N-P-K present in organic fertilisers displace macronutrients provided by mineral fertilisers. Functional differences between organic and mineral fertilisers that are accounted for are:

- Nutrient availability is higher for mineral fertilisers than for organic fertilisers. Nitrogen availability of compost and digestate is assumed to be as calculated in literature with the amount of soluble nitrogen (NO_3-N and NH_4-N) and 30% of the organic bound nitrogen is released evenly over six years (Lampert et al. 2011).

- Organic material added to soils through the application of compost or digestate can improve soil fertility and increase the soil carbon content. The soil carbon formation potential can be calculated according Vdlufa (2014) and Arbeitsgruppe BEK (2016). It is required to be reported separately by ISO 14067 and has not been included in the tool.

Functional differences that are not accounted for:

- The organic fertiliser has a given nutrient composition while nutrients from mineral fertiliser application can be adjusted to the plant requirements. However, when using organic fertilisers good crop husbandry should account for this and make appropriate adjustments with supplementary fertilisers (e.g. following standard guidance[3]).

<u>Mineral fertiliser equivalents</u>

The reference flow for the comparison is 0.8t of digestate with a nutrient composition of (based on KTBL 2016):

2.9 kg N (2.3 mineral N equivalent)

1.9 kg K (2.29 kg K_2O to kg K)

5.5 kg P (1.21 kg P_2O_5 to kg P)

This equals the following amounts of mineral fertilisers.

6.87	kg Ammonium Nitrate	(AN)	(33.5% N)
7.25	kg Potassium Chloride	(KCl)	(60% K_2O)
14.47	kg Triple Super Phosphate	(TSP)	(46% P_2O_5)

<u>Application of mineral fertiliser</u>

The application of 9.7 kg of mineral fertiliser (6.87 kg AN, 7.25 kg KCl, 14,47 kg TSP) requires 0.2 L of diesel. Supply and combustion of diesel leads to emissions of 0.3 kg CO_2e.

The calculation of N_2O emissions from the application of mineral fertilisers follows Formula 1. Nitrification and denitrification processes of the mineral fertiliser applied (2.3 kg N) lead to N_2O emissions of 12.7 kg CO_2e (IPCC 2016).

The supply of mineral fertilisers is associated with CO_2e emissions according to Fertiliser Europe:

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[3] E.g. UK's RB209

6.87	kg AN (33.5%N)	8.0 kg CO_2e
7.25	kg KCl (60% K_2O)	1.5 kg CO_2e
14.47	kg TSP (46% P_2O_5)	3.3 kg CO_2e

Production of mineral fertilisers required to displace 0.8t of digestate emit 11.4 kg of CO_2e.

5.3 Modelling anaerobic digestion

5.3.1 Goal and scope of the assessment

Anaerobic digestion (AD) is suitable for wet and less structured materials. Side flows of the food supply chain are therefore very suitable for fermentation. The main characteristic of an AD is that the digestion occurs under exclusion of air, so without oxygen. Input materials (in this case side flows) can be mixed with other materials and also diluted with press water to generate the most suitable substrate for the fermentation process.

The inventory on anaerobic digestion shall provide average environmental impacts on European level. However, the choice of substrate for the anaerobic digestion, the installed technology, operational practice at fermentation (dry or wet fermentation) and operational practice concerning the digestate (separation, type of storage) as well as the use of the biogas (e.g. to provide energy, or fuel) clearly influences the results, which makes it difficult to provide a generic data inventory for side flows selected for assessment. In the same time the tool shall provide an assessment in the most consistent and coherent way for all side flows.

Anaerobic digestion in this tool therefore comprises parameters which are substrate specific and parameters which are process specific. Process specific data, such as type of fermentation technology, use of biogas and digestate products, CHP efficiency are assumed to be the same for all side flows. Substrate specific parameters have been aligned to the type of side flow as far as possible. Parameters influenced by the substrate are: biogas yield, methane content, composition of the digestate, emissions.

5.3.2 System characterization

Technology

Biodegradable substances such as agricultural residues or food residues can be used in an anaerobic digestion process to produce biogas. The digestion process runs through four stages each with specific bacteria: hydrolysis, acidification, acetic acid formation, methane formation. Long-chain polymers such as carbohydrates, fat and proteins are split to monomers and dimers (amino acids, fatty acids, sugar). Finally, after several stages of transformation of metabolic products, methane, carbon dioxide and hydrogen are produced (Kern et al. 2010).

There are different fermentation technologies. Dry fermentation runs at thermophile or mesophile temperature with an average dry matter (DM) content of 30 to 35%. The DM-content needs to be more than 25%, but 40% as a maximum.

The feeding of the substrate can occur continuously or in stages (batch fermentation). Wet fermentation can run as well in mesophile or thermophile conditions, but DM-Content is 10% on average. Water, mostly press water of the digestate, is added to the substrate so that a DM-content of up to 15% can be adjusted so that the substrate stays pumpable and mixable.

The temperature under mesophile conditions is 33°C to 37 °C and under thermophile conditions 55 °C to 60 °C. The temperature regulates the degree of digestion and the biogas yield. In general, process conditions in the thermophile area has a higher biogas yield. On the other hand, the process in the mesophile area is more stable. If food waste is used as a substrate, thermophile fermentation may be of advantage as an additional hygienisation is not needed (due to higher temperature). At mesophile conditions a separate hygienisation step after fermentation may be of relevance (Kern et al. 2010).

Food waste has in general a high water content and is soft which is mainly suitable for wet fermentation (Lampert, Tesar, and Thaler 2011). Although food side flows assessed in this tool have a different water content, the specific DM content can be reached by mixing the substrate with water out of digestate.

Most of the biogas plants are installed in Germany. Feedstock used in biogas plants in Europe are energy crops, agricultural residues, bio- and municipal waste, industrial (food and beverage) waste, sewage and other residues. The type of feedstock used varies from country to country. The highest share in Europe using industrial food and beverage waste as feedstock is found in Belgium (58%) and Poland (49%). In the case of bio-waste and municipal waste as feedstock, high shares occur in Austria (24%), Finland (22%), Portugal (23%) and Switzerland (52%).

<u>Use of the product biogas</u>

Biogas can be used for the production of heat and electricity in a co-generation plant or in a boiler with steam turbine or via a gas turbine. The most common system is co-generation using a gas engine and generator to directly produce electricity with the exhaust fumes used for heat generation. Currently AD plants in Europe produce 60644 GWh electricity and 146 895 TJ heat (Stambasky et al. 2017). The number of biogas plants is increasing steadily with 173176 plants in total in 2015 (Stambasky et al. 2017).

Biogas can also be further treated to enrich the content of methane to supply the natural gas grid or for use as a fuel. Currently 459 so called biomethane plants are available in Europe. The role of biogas as a product is likely to further increase in future. In Sweden and Iceland nearly all of the produced biomethane is used as a fuel. In other countries (most of the plants are in Germany) the biomethane is fed into the natural gas grid.

This study considers biogas producing energy in a CHP (combined heat and power) unit, as this reflects the current situation in Europe.

<u>Digestate</u>

Digestate can further be separated in a solid and liquid phase through a centrifuge, belt press or screw separator. The solid phase can be composted and reused as humus. The liquid phase can be used to mix with the substrate to generate the wanted water content or be used as liquid fertiliser.

Currently, most of the biogas plants in operation in EU have open pools where the digestate is collected after fermentation (de la Vega, 2017). The release of ammonia and methane is the consequence of these open storage tanks and are highly relevant in terms of climate change. The emissions can be reduced if the tanks are covered with a protective layer (e.g. air tight membranes or flexible storage bags) (Boulamanti et al., 2013; Liebetrau et al., 2011). The trend in Germany and Austria is that new biogas plants are built with such a protective layer. A proposal of the new RED Renewable Energy Directive which will come into force, presumably in 2021, recommends building closed storage tanks for digestate (de la Vega, 2017).

Some plants also have storage facilities for biogas to balance the fluctuations of biogas production and to guarantee a continuous supply of biogas for further treatment. Storage facilities may typically hold 30 to 50% of the daily gas yield.

Use of the product digestate

The product digestate contains valuable nutrients, which can be used as a fertiliser in agriculture. In studies with environmental assessment of biogas plants (Kern et al. 2010, Lampert, Tesar, and Thaler 2011, Pertl and Obersteiner 2011, Boulamanti et al. 2013) it is most common to consider that the digestate is used as a fertiliser in agriculture. This is also assumed in this study.

Influence of future developments

The National and European average electricity mix used for the substituted electricity highly influences the environmental performance. If renewable energy increases (this is reflected by the comparison option 'green electricity and heat from wood chips'), then benefits of the substituted electricity will decrease as most of the benefits can be attributed to fossil-based energy.

The tool reflects the average situation in Europe. It is a fact, that most of the installed biogas plants in Europe use biogas to produce electricity and heat. Only a few biogas plants upgrade the biogas to feed into the gas grid or to use it as a fuel for transport. This situation may change. Biomethane production is gaining popularity, because it reduces reliance on natural gas imports. Another reason which speaks for biomethane production according to Stipits (2017) is the economic benefits for using it as a fuel. Electricity fed to the grid often needs to be substituted so that biogas plants run in an economic way. If fed-in tariffs are not substituted, then biogas as fuel may bring better economic results. Stiptis (2017) calculated the costs for his plant and came to the result that higher economic yield can be obtained when biogas as a fuel is produced (costs are 76 Cents per litre Diesel-equivalents).

Another point of influence is the digestate. Treated digestate can be put on the market as 'organic fertiliser'. However, experts reported that this 'organic fertiliser' is becoming more and more restricted for use by specific industries (e.g. dairy industry). The market for digestate from biogas plants which use food waste need to be investigated. Furthermore, the economic radius for transporting digestate as a fertiliser is extremely limited due to the high water content and to the relatively unknown nutrient balance (Heberlein, Jung, and Stenzel 2017). That is why the comparison option of using digestate for fertilising was only considered in the tool in one product system.

5.3.3 Biogas production

Biogas composition

Biogas typically consists of mainly methane (CH_4) and carbon dioxide (CO_2). Nitrogen (N_2), oxygen (O_2), hydrogen (H_2), hydrogen sulphide (H_2S) and ammonia (NH_3) are contained in small shares. The methane content depends on the substrate. The methane content in biogas can be enriched through processing steps to remove CO_2. Then biogas can achieve the quality of natural gas (production of biomethane). Steam and hydrogen sulphide in the biogas can cause problems for the further use of gas through corrosion.

The biogas yield depends on the substrate and the digestion technology. The biogas' methane content provides its useful energy. AD plants, therefore, strive towards a good operation process which maximises the use of energy from digesting substrates.

The **biogas yield** for bio-waste as a substrate ranges from 80 to 130 m^3/t wet mass (Kern et al. 2010). For kitchen waste as a substrate a value of 150 m^3/t wet mass was assumed in Pertl and Obersteiner (2014). Lampert, Tesar, and Thaler (2011) even mentioned 170 m^3/t input of food waste. In Refresh specific side flows of the food supply chain shall be assessed. Therefore, the theoretical biogas yield of each of the side flows is determined.

A further important parameter for biogas production is the **methane content**. In Jungbluth et al. (2007) a methane content of 67% is assumed and in Pertl and Obersteiner (2014) 60%. The methane content for the specific side flows selected for this study are calculated from the protein, fat and carbohydrate content in each side flow.

Theoretical biogas yield

Different feedstocks show significant variation in biogas production capacity. In general organic wastes from municipalities and industries as well as crops and crop residues are better than sludge from wastewater treatment or animal manure (Huttunen et al., 2014). Next to the composition of the input material (share of dry organic matter) and the quality and quantity of co-substrates, also the duration of digestion and the temperature inside digestion tank are important factors for the quantity and quality of biogas (Werner et al., 2007).

An accurate manual calculation of the biogas yield is not feasible, as the concentration of the individual nutrients in the mixture of the input material is not always known. Furthermore, a manual calculation is subject to certain assumptions. So, it is assumed that 100% of all organic substances are decomposed, which is not true in practice (FNR 2006). However, the theoretical biogas yield can be quantified. As the digestion process of ruminants is similar to the digestion at biogas plants specific parameters of animal feed can be considered.

Table 2: Calculation of the theoretical biogas yield on the example of apple pomace (on the basis of (FNR 2006)

	Dry matter (%)	*Ash*	Protein	Fat	Fibre	N-free extract matter	Carbo-hydrate	Total per kg input (fresh)
Dry matter*	28.0							
Parameters of the input material [g/kg DM]*		25	68	42	207	658		
Digestibility			57%	82%	63%	78%		
Organic part in dry matter (DM) [% DM]*		97.5						
Digestible matter [kg/kg DM][1]			0.04	0.03	0.13	0.51	0.64	
Digestible matter [kg oDM][2]			0.04	0.03	0.13	0.50	0.63	
Specific biogas yield [l/kg oDM]			600-700	1000-1250			700-800	
CH4 content [Vol.-%]			70-75	68-73			50-55	54.7%[7]
Theoretical biogas yield [l], [m3/t][3]			24.6	37.8			470.7	145.5[5]
Theoretical CH4 content [l][4]			17.8	26.6			247.1	79.6[6]

1 Digestible matter = Parameters of the input material * Digestibility / 1000
2 Digestible matter per oDM = Digestible matter * oDM
3 Theoretical biogas yield = Digestible matter per oDM * Average of Specific biogas yield
4 Theoretical CH_4 content = Theoretical biogas yield * Average of CH_4 content/100
5 sum of Theoretical biogas yield * oDM * DM
6 Sum of Theoretical CH_4 content * oDM * DM
7 Theoretical CH_4 content/Theoretical biogas yield

The calculated theoretical biogas yield shall not be used for operational or economic decisions, because of mentioned uncertainties. However, it can be used to estimate tendencies and to compare different input materials (FNR 2006). The latter is the objective of the Excel tool produced in Refresh, which looks at different side flows of food production to valorise their usage.

Other influencing factors are the residence time of the input material in the fermentation, the dry matter content, potential inhibiting substances and the digestion temperature.

5.3.4 Energy balance

Internal use of energy

Anaerobic digestion plants require for the production of biogas both heat and electricity. Electrical energy is needed for the pre-treatment (shredding, depacking or hygienisation), the mixing in the fermenter and the operation of the CHP. In addition to that electricity is needed for the pumps which move the substrate from one step to another step of the process and for the feeding of the substrate. Heat is needed to pre-heat the substrate or to keep the temperature at fermentation stable. This is of high relevance at thermophile process operations and during winter time. The internal energy consumption for discontinuous dry fermentation is the lowest with 3% to 10% internal electricity use and 10% to 20% internal heat use. For wet fermentation process more electricity and heat is needed than for other technologies. The range is very large though and depends on the process design and management (Kern et al. 2010). Upgrading biogas to biomethane will require additional energy.

The range of internal used electricity found in literature is wide. It is very much depending on the input material (Lampert, Tesar, and Thaler 2011). Bio-waste as input requires a pre-treatment (e.g. hygienisation). Jungbluth et al. (2007) relates the energy needed for pre-treatment, fermentation and dewatering in a ratio of 37.5:50:10. The type of substrate influences therefore the electricity and heat use of pre-treatment. However, an influence of the type of substrate to the amount of heat and electricity used in fermenter or in the CHP cannot be given according to Lampert, Tesar, and Thaler (2011). The internal electricity use is therefore set to a default value according to used values in the literature for bio-waste, which is 70 kWh per ton input for both wet and dry fermentation. The internal heat use is assumed including a consideration of a hygiensation step (1 h at 70°C) with 50 kWh per ton input for wet fermentation and 70 kWh per ton input for dry fermentation. A separation of the digestate into liquid and solid fractions requires furthermore electricity. It is 0.4 kWh per m^3 digestate for screw press and separator and 7 kWh per m^3 digestate for decanter separator.

In this study it is assumed that internal energy demand is entirely covered with produced energy.

Net energy production

The net energy production of anaerobic digestion plants depends on

- the energy content of the biogas
- the efficiency of the CHP
- minus the own used energy

The biogas yield depends on the substrate (methane content of the substrate). The theoretical biogas yield is calculated for each side flow (see 5.3.3) Modelling anaerobic digestion). The energy content of biogas is calculated by the lower heating value (LHV) of different gas components. Methane has a LHV of 35.885 MJ/Nm^3 and hydrogen sulfide 23.413 MJ/Nm^3. The formula for the calculation of the energy content was taken out of Jungbluth et al. (2007).

$$HV_{Biogas} = HV_{CH_4} * v_{CH_4} + HV_{H_2S} * v_{H_2S}$$

Formula (1)

The calculation of the heating value depends on the composition of the biogas. The biogas composition varies from side flow to side flow. The average value was taken out of Jungbluth et al. (2007) who consider a composition of 67% CH_4, 32% CO_2, 0.7% N_2, 0.0005% H_2S and 0.25 O_2.

Table 3 Parameters for calculating the lower heating value (LHV) of biogas

v	35.885	MJ/Nm3
LHV of H2S	23.413	MJ/Nm3
Density CH4	0.714	kg/m3
Density H2S	1.517	kg/m3
Share CH4	67	%
Share H2S	0.0005	%
LHV	24.043	MJ/Nm3

The efficiency of the CHP can reach 46% for heat and up to 44% for electricity according to Kern et al. (2010). Lampert, Tesar, and Thaler (2011) assume a thermal efficiency of 45% and an electrical efficiency of 35%. This was also considered in this model. In practice the utilisation of heat is however not always constant. In winter the heat use can be 100% whereas in summer it can drop to a very low level (Demand for hot water is given but not for heating). In this study an average heat utilisation of 50% is assumed.

Kern et al. (2010) give a range of 190 to 290 kWh el per ton input for dry fermentation and around 170 to 270 kWh el per ton for wet fermentation. Heat ranges from 190 to 310 kWH th/ t input (dry) and 145 to 320 kWh th/t input (wet). A biogas throughput (biogas yield) of 80 to 130 m3t input. The biogas yield for food waste is assumed to be higher (up to 170m3 in case of Lampert, Tesar, and Thaler (2011)). In this study the value is calculated for each specific side flow. As an average value 150 m^3 per ton input is assumed. It leads to a net energy production of 327 kWh_{el} and 205 kWh_{th} per ton input.

5.3.5 Emissions of anaerobic digestion

The treatment of food waste in an AD plant is linked with greenhouse relevant emissions, coming on the one hand from energy use in the plant and on the other hand from biological process of the degradation of material as well as due to technical losses of biogas utilisation (e.g. methane slip). Additionally, emissions occur at digestate storage and application on land. In case of AD relevant greenhouse gases occur in form of methane (CH_4) and nitrous oxide (N_2O). Additionally, odour and other emissions are occurring e.g. in form of ammonia (NH_3).

Emission sources are: delivery and conditioning of the substrate (material handling), storage of fermentation residues (digestate), fermenter, before and after exhaust gas treatment (acid scrubber and bio-filter) and exhaust of CHP unit as well as post-composting and application of digestate. It needs to be distinguished between direct emissions from e.g. gas engine and diffuse emissions from different components of the plant because of leakages (open storage) or bad operation conditions. The latter is not easy to quantify. An overview of the emissions of each step of an anaerobic digestion plant in the framework of this study is outlined in Figure 9.

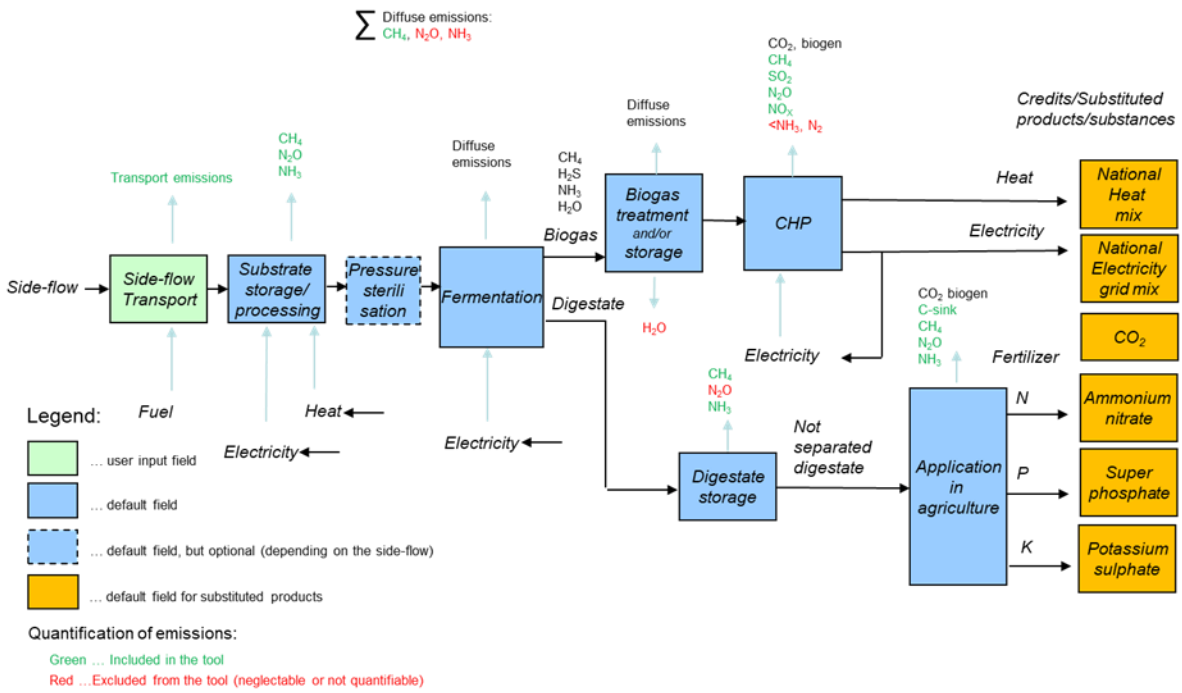

Figure 9: Flow-diagram of AD process, incl. assessed emissions and neglected emissions as well as their functional equivalents, to be potentially credited/substituted the system to keep the function of the system unchanged.

Data inventory used in Jungbluth et al. (2007) covers the assessment of a plant where biogas is produced for upgrading (biomethane production). If the aim is to upgrade biogas the biogas throughput in the plant shall be optimised. In this case, the required heat and electricity is not taken from the produced energy but obtained from conventional energy carriers. Furthermore, emissions from the combustion of biogas (e.g. via a gas engine) are not accounted here. As the EU market has currently only a low share for biogas upgrading (Stampasky et al. (2017)), the values of Jungbluth et al. (2007) are not applicable for the tool in this study.

A direct transformation of the biogas composition to the emissions of the plant is not possible as certain process steps such as desulphurization or dewatering influence the gases. Process specific emissions of the combustion such as carbon monoxide and nitrogen oxides are depending on the operating conditions. Sulphur dioxide emissions are depending on the sulphur hydrogen load of the desulphurization. Emissions are calculated based on values out of Boldrin et al. (2011) and Lampert, Tesar, and Thaler (2011).

The **transport** side flow transport to the AD plant depends on many regional factors. Transport distance and transport vehicle can therefore be added by the user.

The **substrate storage and processing** step depends on the type of substrate.

Some side flows may demand a **size reduction** to use in AD, especially if green waste is mixed to the input material. In Jungbluth et al. (2007) shredding and size separation is assumed before bio-waste can be used in AD. In this study size reduction is not assumed, as materials with less structure is used.

However, emissions may occur by **handling** of input materials before it goes to fermentation. A certain degradation of organic substances is the consequence which creates emissions. Lampert, Tesar, and Thaler (2011) use emission factors of open composting sites to assess these emissions. CH_4, N_2O and NH_3 emissions are accounted here.

A **pre-treatment** of the substrate, such as a **pressure sterilisation,** is necessary in case of some specific side flows such as animal by-products. Side flows of slaughter house can be divided into different health risk categories (European Commission 2009). Cat. 1 side flows (e.g. spinal cord, brain from cattle) has to be incinerated and therefore cannot be used as substrate for AD. Cat. 2 side flows need to treated before using as a substrate for AD to prevent risk of contamination with other animal diseases (sterilisation at 133°C and 3 bar for a minimum of 20 min, size reduction to <50 mm). Category 3 side flows (e.g. side flows from healthy animals slaughtered for human consumption; blood) can be used after thermal treatment at 70°C for 60 min and particle size reduction to <- 12 mm (Ortner et al. 2014). The increased energy demand for sterilisation and thermal treatment of animal by-products increases the own used energy balance and decreases the energy output. The additional thermal pre-treatment of the substrate is considered in the internal heat use.

The combustion of biogas in the **CHP unit** creates relevant greenhouse gas emissions such as CO_2, CH_4 and N_2O emissions. CO_2 is though from biogenic source and is therefore not accounted here. Not all CH_4 contained in the biogas can be combusted therefore a certain amount of methane is emitted here. This is called methane slip. Additionally, N_2O emissions can be created due to this incomplete combustion process, which is partly not avoidable. The emissions can be decreased if the engine is adapted to the composition of the biogas, a continuous biogas production and regular maintenance (Kern et al. 2010). A methane slip of 1% of the methane input according to Lampert, Tesar, and Thaler (2011) was used. SO_2 is created when hydrogen sulphide contained in the biogas is burned. SO_2 can be reduced by a catalyst. However, co-generation plants which use biogas don't use catalyst as the H_2S contained in the biogas can lead to deactivation and can destroy the catalyst. SO_2 can be reduced if the combustion temperature is lower. Boldrin et al. (2011) reported emissions for SO_2, CO, NO_X and N_2O, which are also used in this study.

In Jungbluth et al. (2007) it is stated that about 12% of the total nitrogen is emitted as ammonia. This can be reduced by 95% if a **biofilter** is installed (Jungbluth et al. 2007). Boldrin et al. (2011) even report a reduction of 98%. However, N_2O cannot be restrained with a biofilter and need to be accounted. Furthermore, it happens that the biofilter generates N_2O. It is recommended in Daniel-Gromke et al. (2015) that the exhaust gases shall also be treated with acid scrubbers to deposit NH_3 and minimise N_2O formation in the biofilter.

Diffuse emissions range from 0 to 3% of the produced biogas in literature (Pertl and Obersteiner, 2014). Open storage tanks, inadequate aeration directly after fermentation or less aerated post-composting processes can cause considerable methane (CH_4) emissions. Furthermore, ammonia (NH_3) and nitrous oxide (N_2O) are relevant GHG generated at biogas plants and by use and application of digestate at agricultural land. High emissions are mainly due to open storage of digestate and due to bad process operation. Diffuse CH_4 emissions due to leakages are assumed to be 2% of biogas yield (Pertl and Obersteiner, 2014). In addition to those diffuse emissions, emissions from open storage tanks shall be considered, as most of the plants in Europe have open storage pools according to de la Vega (2017). Emission from open storage tanks have rarely been quantified in the past. However, the importance has been acknowledged as CH_4, N_2O and NH_3 emissions from **digestate storage** can occur with a large range. The quantities depend on many factors, such as type of storage or covering and fermentation time. The shorter the fermentation time the higher is the gas potential in the digestate, consequently the higher are the CH_4 emissions from digestate. For this reason, estimations were often considered in past LCA studies to fill this data gap. In this study it is assumed that internal energy demand is entirely covered with produced energy. Kern et al. (2010) mentioned a range of 1 to 10% CH_4 emissions at digestate storage of the utilised biogas. Lampert et al. (2011) modelled three scenarios: 2%, 5% and 10% losses at open storage. The scenario with 2% still resulted in negative GHG balance of the plant, the other scenarios with 5% and 10% losses resulted in positive GHG balances of the plant. For this study directly measured emissions published by Hrad (2016) were considered. She determined that 4% of the utilised CH_4 was emitted at plants if digestate storage tanks were filled and 3% when the tank was empty. This results in CH_4 emissions of the digestate storage tank of 1% of utilised CH_4. In a multi-source reconstruction it resulted in 1.2% of uitilised CH_4.

So in total CH_4 losses can be summed up to approximately 4% (1% methane slip at CHP, 2% due to leakages at plant, 1% due to open storage facilities). This emission factor is considered plausible as it is within the IPCC guidelines range. The default emission factor for anaerobic digestion of organic waste according to IPCC guidelines is 5% for CH_4 emissions from unintentional leakages.

N_2O emissions can occur under anaerobic digestion from denitrification and in aerobic conditions via nitrification. According to literature found in Lampert, Tesar, and Thaler (2011) those emissions are neglectable and are not assessed in this study.

High amounts of NH_3 emissions are the consequence of not covered digestate storage tanks. Lampert, Tesar, and Thaler (2011) assumes 0.7 kg NH_3/t digestate.

Application and use of digestate: Digestate produced in biogas plant can be used as fertiliser to recycle nutrients and to avoid consumption of industrial products. However, if digestate is applicated at any time of the year when there is little plant uptake, it can result in nutrient leaching and contamination of ground and surface waters. It is therefore practiced applying digestate as fertiliser while plant growth. The rest of the year, digestate is stored.

In any case, emissions from the application of the digestate to agricultural land (N_2O emissions as well as NH_3 emissions) needs to be considered (Boulamanti et al., 2013). Lampert et al. (2011) considers 7 g CH_4, 85 g N_2O and 2,100 g NH_3 emissions per ton of organic waste.

5.3.6 Comparison products

Electricity produced with biogas can be compared with functionally equivalent products e.g. electricity produced by conventional energy sources (which can be mainly fossil). If exhaust heat can be utilised then also conventional (fossil) fuels used for heat supply can be used as comparison products. Furthermore, digestate (solid and liquid) can be used as a fertiliser to which industrial mineral fertiliser can be used as comparable products, allowing for functional equivalence in nutrients available for plant growth.

Electricity and heat

The energy source biogas produces electricity and heat. Each net exported kWh **electricity** feeding into the electricity grid (produced amount of electricity minus own use of electricity) can be comparable to a kWh electricity generated from the grid mix. The grid mix depends on the country where the plant exports its electricity to. The country can be selected by the user of the tool.

For comparable heat sources several options are possible. Biogas plants can be situated next to an industrial or commercial user of heat, which guarantees a continuous demand for heat for a whole year (100% heat usage). It can be situated next to a town or village, with a district heating system, where a fluctuation in demand is more likely during winter and summer time (e.g. 50% overall heat usage) (Lampert, Tesar, and Thaler 2011).

If the comparison heat source is natural gas which is fossil based, then the benefits are higher than if it is biomass. The comparison heat source firstly depends on the heat user (industry or household) and also on the national conditions. For this reason, the comparison heat source can be adjusted by the user in the tool. In Lampert, Tesar, and Thaler (2011) a mix of light oil, natural gas and biomass (wood pellets) is used.

Mineral fertiliser

Digestate which is produced from anaerobic digestion can be used in agriculture for nutrient balancing and consequently may replace/substitute the use of conventional fertiliser.

The production of mineral fertiliser (especially nitrogen fertiliser) is energy intensive. If digestate is used in agriculture, the production emissions associated with the functionally equivalent quantity of mineral fertiliser should be included in for comparison. The difficulty is finding the relation of functional equivalence between digestate and mineral fertiliser. The composition and the quality of the digestate depends on the substrate used for fermentation and the processing steps of the digestate (separation of liquid and solid phase, post-composting of digestate).

Daniel-Gromke et al. (2015) analysed which **kind of product** (finished compost, fresh compost, liquid fermentation residues, solid digestate) can replace which industrial fertiliser product according to the nutrient content (nitrogen, phosphorus, potassium amounts). Generally, solid digestate can substitute mineral fertiliser, but also peat in certain cases (e.g. finished compost). It has also benefits for humus accumulation in soils and humus reproduction. Liquid digestate can also substitute mineral fertiliser in some cases and also reproduced humus. According to Pertl and Obersteiner (2011) compost or composted digestate which can be used as a peat (fossil resource) alternative. In the case of this study digestate is assumed to be used as fertiliser in agriculture. Therefore, digestate was assumed to be functionally comparable to fertiliser but not peat.

In Lampert, Tesar, and Thaler (2011) functionally equivalence was based on the amount of **nitrogen** and **phosphorous**. However, in contrary to mineral fertiliser the nitrogen and phosphorus in the compost or digestate is only partly available. The bio availability for nitrogen and phosphorus in the digestate is considered on the basis of Lampert, Tesar, and Thaler (2011).

The nitrogen availability of compost is calculated in literature with the amount of soluble nitrogen (NO_3-N and NH_4-N) and 30% of the organic bound nitrogen (yearly release of 5% over six years). The bio availability of phosphorus in the compost is 100%. It is assumed that the same bio availability applies to digestate.

For non-separated digestate the value of NH_4-N plus 30% of the organic bound nitrogen is taken in Lampert, Tesar, and Thaler (2011).

Furthermore, by substituting the use of mineral fertiliser **N_2O emissions** generated at fertiliser application can be reduced. In Lampert, Tesar, and Thaler (2011) it was assumed that 1.25% of the available nitrogen can be substituted.

By using compost or digestate in agriculture can also serve as a **carbon sink** as a certain amount of bound carbon is stored. This carbon storage depends on literature stated to be 8% (Lampert, Tesar, and Thaler 2011) up to 14 to 23% (Pertl and Obersteiner 2011) of the bound carbon in the digestate/compost. The rest of the carbon is transformed to CO_2 during a time horizon of 100 years. A contribution to climate protection is given. However, most benefits are due to the humus accumulation in soils which doesn’t count as climate protection but serves as a relevant contribution to the improvement of soils.

5.3.7 Data inventory

The major input data for specific side flows used in the AD model to calculate total GHG emissions is presented in the table below.

Table 4: Data inventory for "anaerobic digestion" of specific food side flows

Parameters	Apple pomace	Blood, fresh blood from animals	Tomato pomace	Brewers spent grain, fresh	Whey permeate	Unit
Theoretical biogas yield	145.50	62.00	117.00	93.00	388.00	m3/t FM
Theoretical CH_4 content	54.70	72.00	59.00	60.00	53.00	%
LHV	19.63	25.80	21.20	21.50	19.14	MJ/t FM
Dry matter content	28.00	19.10	25.30	21.20	96.30	% DM
Nitrogen	3.72	2.64	5.69	7.38	0.69	N kg/t FM
Phosphorous	3.36	0.78	1.11	1.23	0.60	P kg/t FM
Potassium	1.60	0.00	0.33	0.28	3.63	K kg/t FM
Net Electricity	207.68	85.52	171.15	124.40	652.00	kWh/t FM input
Net Thermal energy	128.51	49.98	105.03	74.97	414.15	kWh/t FM input
Digestate	813.68	934.01	856.47	887.07	544.91	t FM/t FM input
Emissions AD	73.78	44.10	69.59	62.73	166.32	kg CO_2e/t FM input

5.3.8 Recommendations to further reduce environmental emissions

All studies have in common that production of biogas as an energy source substantially contributes to mitigating GHG emissions by reducing emissions from fossil-based energy systems and by reducing emissions from the storage of animal manure. However, the potential to decrease environmental emissions during operation of the biogas plant can be significant in some cases. Therefore, the following recommendations can be considered to further improve environmental performance (based on (Daniel-Gromke et al., 2015; Liebetrau et al., 2011):

Key recommendations (Daniel-Gromke et al., 2015):

- Utilisation of exhaust heat of electricity production has also a positive influence on the GHG performance

- The use of digestate shows GHG savings due to substitution of mineral fertiliser
- Composted digestate can contribute to humus accumulation (carbon sink) and humus reproduction of digestate
- Generally, the more waste processed and digestate treated (by post-composting process) the better the GHG comparison may be with impacts of more (functionally equivalent) fossil based products (electricity, heat, fertiliser,peat).
- avoidance of any open storage of digestate and fermentation residues (gas-tight storage tank for fermentation residue and integration into biogas utilisation)
- the use of acidic scrubbers in front of the bio-filter (to deposit NH_3 and minimise N_2O formation in the bio-filter)

When creating compost out of the digestate the following aspects need to be addressed (Daniel-Gromke et al., 2015):

- intensive aeration of the (solid) digestate after fermentation
- aerated compost windrows combined with sufficient structural materials and frequent turnover

Reduction of odours and noise (Jeitler 2017):

Anaerobic digestion plants often have to face the problem of odour and noise emissions. Especially if residential areas are situated in the near neighbourhood of the plant, it is often necessary for the operator to reduce those emissions to a minimum. In order to foster a good relationship with the neighbourhood, certain measures to reduce odours were tested by a biogas plant at a brewery in Austria. Jeitler (2017) came to the conclusion that

- the installation of a deionisation before the CHP, activated carbon filter and biofilter after the CHP reduces odour emissions to an acceptable level (equivalent to nine pigs or four cows). However, deionisation and activated carbon filter equipment is costly and increases the production costs. Reducing odour emissions is not commonly a necessity by law, but can be necessary to earn acceptance among the population. It needs to be decided case by case, if such equipment is feasible.
- measures to reduce noise emissions can be easily implemented. However, it needs to be kept in mind that those measures can increase the temperature of e.g. engines.

5.3.9 Limitations of the model

Users of the tool need to be aware of limitations around the applicability of certain pathways (valorisation routes) for specific side flows. The assessment in this study is on a level where certain assumptions need to be taken in order ensure a harmonised and comparable approach within the tool.

When choosing the **anaerobic digestion** route, it needs to be kept in mind, that the biogas yield and composition is based on theoretical assumptions. It is based on side flow specific parameters. In practice, a mixture of different substrates is often used in AD to generate the most optimal input for fermentation, which fits to the technology (dry or wet fermentation) and which fits to the objective of the plant (produce energy or biogas upgrading). Furthermore, it is assumed that 100% of all organic substances are decomposed, which is not true in practice (FNR 2006). So the theoretical biogas yield can be seen as the maximum yield a biogas plant can generate using a specific food side flow. Furthermore, side flows of slaughter houses can be divided into different health risk categories (European Commission 2009). Cat. 1 side flows (e.g. spinal cord, brain from cattle) has to be incinerated and can therefore not be used as substrate for AD. Cat. 2 side flows need to be treated before using as a substrate for AD to prevent risk of contamination with other animal diseases (sterilisation at 133°C and 3 bar for a minimum of 20 min, size reduction to <50 mm). Category 3 side flows (e.g. side flows from healthy animals slaughtered for human consumption; blood) can be used after thermal treatment at 70°C for 60 min and particle size reduction to <- 12 mm (Ortner et al. 2014).

Slaughterhouse waste has limitations as an AD feedstock, since nutrients such as Ni, Co or Mo are lacking which are essential for microbial growth and enzyme activity. Furthermore, this side flow has a high nitrogen and sulphur concentration. A mono-digestion of these side flows is in practice not carried out. In practice, it is often mixed with e.g. less N-rich substrates (sewage sludge, energy crops, food waste). Mono-fermentation of slaughterhouse waste was tested on a lab scale to achieve best process performance and to investigate potential need of additives in Ortner et al. (2015).

5.4 Modelling disposal

5.4.1 Goal and scope of the assessment

Selected food side flows in Europe are mostly valorised either into animal feed, sent to anaerobic digestion or even for processing into another ingredient for a food product as described in the chapters above. However, it may happen that producers of such side flows don't have a buyer (e.g. butchers, or small juice producers) or have simply no use or no ability to reuse or recycle these materials. The consequence is that it is discarded for disposal. Those options count to Refresh Situation 4 (RS4) and can be related to the last step of the waste hierarchy.

The tool covers RS4 options which are both realistic and accepted by law. It also depends on the individual side flow. Land spreading is the most common option for most of the selected food side flows and practiced by farmers all over Europe. It is therefore selected as RS4 options for e.g. apple and tomato pomace. The situation is different in the case of blood. Blood from small slaughterhouses or butchers may be discharged into the sewer (if certain legal requirements can be met). The sewer is connected to the municipal waste water grid system which feeds into a municipal waste water treatment plant. In certain situations, food side flows may even end up in the municipal waste collection system and mixed with residual waste from households and small companies. Only a part of the municipal solid waste is recycled, the rest is deposited in landfills or incinerated. Large discrepancies appear among European Member States (MS). In six MS less than 3% of municipal solid waste was landfilled in 2011, whereas in 18 MS more than 50% was landfilled and in some MS even 90% (European Commission 2015b). This is despite the ban of landfilling untreated waste which is regulated in the Landfill Directive 1999/31/EC

Current practice in European MS show that there is still great potential to increase resource efficiency (European Commission 2015b). This is also encouraged by the EU action plan of the circular economy package (European Commission 2015a). Consequently, the European Commission adopted a legislative proposal to review waste-related targets in the Landfill Directive which shall aim at "phasing out landfilling by 2025 for recyclable waste (including plastics, paper, metals, glass and bio-waste) in non-hazardous waste landfills, corresponding to a maximum landfilling rate of 25%". Facing these regulations, the option of landfilling food side flows is getting less likely and are therefore landfill has not been covered in the tool.

Instead incineration is seen as the another possible RS4 option if food side flows are mixed to municipal solid waste. In this case the assessment is limited to the incineration in a municipal solid waste incineration plant with mixed waste inputs (so that a certain calorific value for incineration can be achieved).

Please bear in mind that producers of food side flows are not encouraged to choose options of RS4 by the tool since there is no functionally equivalent comparison product to compare with for these disposal options. Although food side flows may have a specific nutritional value (phosphorus, nitrogen, potassium) which would be beneficial for agriculture it is usually accounted as a zero-value commodity (farmers do not pay to receive apple pomace or sewage sludge). In that respect it cannot be seen as a valuable fertiliser. Only costs and emissions accompany these situations where the goal of a resource efficient and competitive circular economy in Europe cannot be achieved. However, it is beneficial to include them in the tool as

- User has more scenarios available to compare with
- User sees a clear environmental benefit if food side flows are valorised instead of disposed

5.4.2 Landspread

Landspreading of food side flows is associated with similar processes and technologies as the application of digestate described in section 5.2. Landspreading is seen as a waste disposal option while the application of digestate is seen as a waste recovery option. This means the function provided by digestate application (providing nutrients to a crop) are considered to be comparable to a proportion of mineral fertiliser (and its associated production impacts) while we assume that disposal of side flows through landspreading does not provide additional functionality to compare with other products, except that of disposal operations.

Processes considered in the landspread scenario are: transport to the field, application and nitrous oxide emissions resulting from the application.

For the transport to the field a distance of 20 km with a tractor and trailer is assumed. For application it was assumed that diesel required per tonne of product is similar to the application of digestate, which is 0.25 litre per tonne of side flow (KTBL 2014).

Direct N_2O emissions caused by microbial nitrification and denitrification of nitrogen applied through the side flow as well as indirect N_2O emissions associated to volatilisation, leaching and runoff from soils are calculated based on the nitrogen content of the side flow and IPCC (2006).

5.4.3 Waste Water Treatment

Certain side flows of slaughterhouses, such as fat, faeces and also blood may enter waste water. This contaminated waste water requires processing in a waste water treatment plant (WWTP). Slaughterhouses can be divided into those which treat their waste water on-site and discharge directly to the local water course and those which discharge their waste water to the local WWTP. For the discharge to a local WWTP slaughterhouses need to comply with specified conditions in trade effluent discharge consents in line with legislative requirements (European Commission 2005). The tool covers this situation as a possible disposal route for small slaughterhouses or butchers.

The route "blood disposed via sewer" is modelled in the tool with a dataset of Ecoinvent (Ecoinvent Centre, 2004) "waste water treatment" (Doka 2009). A specialised waste water treatment plant for industries is seen out of scope here, as it is assumed that industries which deal with larger amounts of blood as a side flow of their production facilities, rather use other valorisation routes (out of economic reasons and also due to legal requirements for waste water). The dataset of Ecoinvent comes together with a calculation tool which allows a calculation of an inventory of specific waste water.

The model covers the following steps: transport in sewers, waste water treatment plant, sludge digestion with biogas incineration, digested sludge disposal by application in agriculture or by incineration.

Sewer system: For the sewer system grid different capacity classes are possible which highly influence the results (it can range from 2.5 to 7.6 m per capita) (Doka 2009). A capacity of 4.4 m of sewer grid per capita is considered in the tool.

Wastewater purification process: The waste water treatment covers two parts: a three-stage purification of the waste water (mechanical and biological and chemical treatment) and a digestion of the raw sludge which is an output of the purification process. The following pollutants or parameters are modelled in this process:

- Carbon compounds are monitored by BOD, COD, DOC or TOC
- Phosphorus is presented by phosphate PO_4 or as particulate phosphorus
- Sulphur is presented by dissolved sulphate SO_4 or particulate sulphur
- The modelled nitrogen species are ammonium NH_4, nitrate NO_3, nitrite NO_2, dissolved organic nitrogen Norg,solv and particulate nitrogen Npart.

- Other elements such as metals, calcium, magnesium, halogens etc.

Transfer coefficients in the plant and specifications for emissions are set in the calculation tool for the WWTP which is used for the tool.

The magnitude of pollutants in the waste water is also influenced by the amount of water released with waste water. For example, if a substance is released with 1 litre of water it will influence the concentration.

In the biological treatment step of the waste water some gaseous nitrous oxides N_2O can be formed which are relevant GHG's.

Sludge digestion: According to Directive 86/278/EEC the use of raw sludge on agricultural land is prohibited. Raw sludge has to be treated to reduce its fermentability and to reduce health hazards resulting from its use. This model considers anaerobic digestion of raw sludge. Energy is produced from incinerating the digester gas. Doka (2009) states a production of electricity of 0.043 kWh/m^3 sewage and heat of 0.663 kWh/m^3 sewage on average. It depends, however, on the carbon content of the material.

A range of diffuse CH_4 emissions can result from anaerobic digestion plants (please see chapter 'anaerobic digestion' for GHG emissions resulting from this process).

Treatment of sewage sludge: In Directive 86/278/EEC the use of sewage sludge is regulated to prevent harmful effects on soil, vegetation, animals and man. With implementation of this directive the use of sewage sludge in agriculture should be encouraged as the organic matter and nutrients contained in sewage sludge are valuable for soils. To this end, the Directive prohibits the use of untreated sludge on agricultural land unless it is injected or incorporated into the soil. Treated sludge is defined as having undergone "biological, chemical or heat treatment, long-term storage or any other appropriate process so as significantly to reduce its fermentability and the health hazards resulting from its use".

A revision of the sewage sludge directive is currently under evaluation by the European Commission. Several EU member states have implemented stricter values for heavy metals and set requirements for other contaminants. Some countries have more stringent regulations (such as the Netherlands or Sweden) than other because of differing situations (i.e. a high rate of production per inhabitant, high rates of nitrogen and phosphate in the soil) (European Commission 2002). Sewage sludge can generally go different routes in Europe: the most common use is via agriculture (landspreading), but the relevance for incineration of sewage sludge is increasing due to saturated farm nutrient budgets (esp. phosphorus), but also due to concerns about pollutants (Doka 2009). The two options are considered in the tool with 53% incineration and 47% landspreading.

Data inventory

Input parameters for animal blood are taken from ECN Phyllis (2018) and are shown in the table below. Total GHG emissions excluding the biogenic carbon result in 37 kg CO_2-eq./m3 and 0.04 kg CO_2-eq./kg respectively.

Table 5: Data inventory for "animal blood in waste water treatment plant"

Parameters		Animal blood
Carbon	COD [kg/m3]	400
	BOD [kg/m3]	200
Sulphur	Total Sulphur [kg/m3]	1.05
Nitrogen	Total Nitrogen [kg/m3]	30
Phosphorus	Total Phosphorus [kg/m3]	7.875
Other	Chlorine [kg/m3]	1.365
	Chromium [kg/m3]	0.005
	Nickel [kg/m3]	0.018
	Lead [kg/m3]	0.024
	Calcium [kg/m3]	3.15
	Sodium [kg/m3]	19.425

5.4.4 Incineration of municipal solid waste

An open model of GaBi for "Waste incineration of biodegradable waste fraction in municipal solid waste" (Thinkstep 2016) enables to assess specific waste flows which can be adjusted with input specific parameters. The thermal treatment of a single waste fraction like paper or plastic or even specific wastes like Polyamide 6 is not done in reality in a WtE plant for MSW. The waste is always homogenized to obtain a relative constant calorific value and to comply with the emission standards. Nonetheless the model and settings used for the average MSW allows attribution of an environmental impact (emissions and also resource consumption of auxiliaries), energy production as well as the credits (metal scrap export) to a single fraction or specific waste incinerated within an average MSW. In the case of selected food side flows it is likely that a functionally equivalent product cannot be identified (due to low calorific value and high moisture content, no energy can be produced), instead an additional environmental impact may be attributed (for additional energy demand = auxiliary fuel).

Input dependent parameters, for example the input of C, H, Cl, F, S, N, are linked with the emissions caused by these elements in the open model. Those input parameters for specific side flows can be collected from the waste composition database REFRESH (2018). Thomé-Kozmiensky (1998) state the borderline for combustion without auxiliary fuel is 5 MJ/kg with a dry matter content of 40%. Below this threshold an auxiliary energy demand is needed. Food side flows often have a water content around 80%, so auxiliary fuel is needed in order to burn the material. This auxiliary energy demand is assumed to come from mixed municipal solid waste (e.g. plastics, paper).

The model is therefore limited to emissions of incinerating food side flows and resource consumption of auxiliaries for the incineration. Energy production is not realistic due to high water content and low calorific value.

Data inventory

Input parameters for BSG to calculate the emissions are derived from Mathias Santo et al (2016). Values are set in comparison to input parameters and emissions if biodegradable waste in incinerated (out of Thinkstep, 2016).

Table 6: Data inventory for "brewer spent grain to municipal waste treatment"

Parameters	Biodegradable waste	Brewer spent grain (BSG)
Moisture (kg/t feedstock)	589	826
Ash (kg/t feedstock)	113	7
Biogenic Carbon (kg/t feedstock)	174	91
Nitrogen (kg/t feedstock)	10	7.5
Net calorific value in MJ/kg	5.9	3
Emissions of combustion at domestic waste incineration plant (GaBi) in kg CO_2-eq./t feedstock (excl. biogenic carbon)	50	33
Functionally equivalent products: electricity and steam	Yes if >5 MJ/kg and Moisture <60%	No

6 Results and discussion

The FORKLIFT spreadsheet tools are created to show life cycle costs and greenhouse gas emissions of different valorisation, recovery and disposal options of specific food side flows in a given context chosen by the user. Deciding whether one option is more environmentally or economically sound than another is very much dependent on the context. With the help of the tool those context specific parameters can easily be detected and their effects on the results immediately displayed. Generic models in the tool are set with default values which are reasonable in a European context but can be adjusted to user specific values and to side flow specific values. Thus, the criteria and assumptions in the background system of the models are set in the European context (e.g. efficiency, technology), but some crucial parameters can be changed, e.g. the transport distance to the next valorisation facility, the price (market value) of a side flow, the type of heat used or the country specific electricity mix. The resulting emissions and costs therefore depend on the values set by the stakeholder and on the type of food side flow. Depending on the set values, costs and emissions of the chosen valorisation option might be lower or higher than comparison products. Stakeholders that generate or utilise a side flow can interpret the results regarding the effects of interventions themselves, as they are also often the ones who know the market conditions best.

By developing a set of models for different side flows based on the same approach the FORKLIFT tool can provide comparable results considering e.g. boundary conditions, functional unit (FU), allocation and baseline data for costs and energy.

Insights gained from FORKLIFT -illustrative examples

The generic models provided in the FORKLIFT tool can reveal learning effects by pointing at hot spots such as labour and capital costs (in the pectin case), or by changing the contexts (in the case of the AD model) and by looking at options which don't have a realistic comparison product (in the case of disposal models). Some examples are provided below. However, it must be stressed that costs for the investments in machinery and labour has not been included in these examples due to that they are highly site specific, but are included in the comparison products. Thus, the results shown below only provide an indication on how large investment and labour costs can be afforded compared to other functionally equivalent products.

The first example (Figure 10) shows the greenhouse gases from producing pectin from apple pomace. The **production of pectin** from apple pomace with default settings which excludes investment cost and labour costs. The process generates pectin (used a thickener) and a fibre residual (assumed to be used as feed). The pectin produced carries all emissions from the pectin process, assuming economic allocation but no impact from the primary production.

Results from the model indicate that the GHG emissions are higher than for the comparison products, while costs are lower.

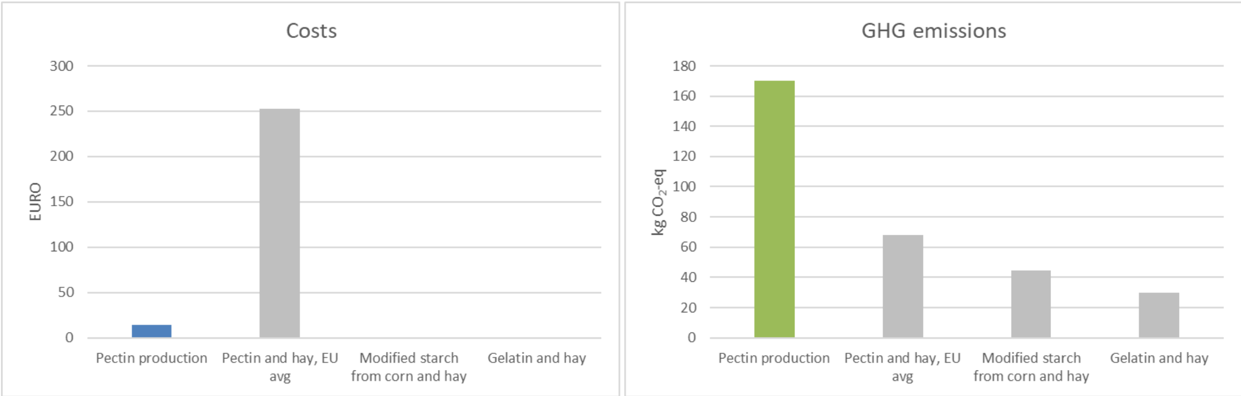

Figure 10. GHG emissions and costs for producing pectin assuming a European electricity mix

For the cost the determining factors are the investments in machinery and labour. Pectin is generally produced in highly optimised factories in large scale (as are gelatine and starch thickeners) often together with other additives, meaning that investment cost can be split between several products. For the environmental impact the drying of the raw material/apple pomace is critical – the drying is done to stabilise the raw material, so it can be stored before the processing. The drying of the apple pomace generally takes place at the site of the juice processor after which it is transported to the pectin processor. In addition, the pectin content differs from different sources, 10-15% for apple pomace and 20-35 % citrus peels (e.g Herbstreith-fox, 2018), which needs to be considered when comparing the costs and environmental impacts for the pectin impacts from apple pomace to other commercial pectin products.

This is a typical scenario from a small-scale production of a highly valorised product. Investment costs/labour costs and the energy used are determining factors for the costs and environmental impacts.

The second example shows the estimated environmental benefits (GHG) of producing bioenergy out of the apple pomace side flow in Poland (Figure 11). Poland is a country with a relatively high portion of fossil energy carriers in their energy mix, compared to e.g. Norway (Figure 12) which has a small portion of energy from fuel. The production of electricity and heat from the anaerobic digestion of apple pomace produces less GHG emissions compared to the combination of electricity produced in Poland and EU average heat, but higher emissions compared to electricity produced in Norway in combination with EU average heat (first comparison product). This is due to the high share of fossil fuels used in Polish electricity production. The majority of electricity in Norway is produced from hydro power. Hydro power is a renewable energy source, therefore, the release of GHG emissions to the air is only due to building of the infrastructure or the production of auxiliaries used in hydro power plants. These emissions are lower compared to the emissions of the AD plant. If hydropower is considered together with heat from wood chips, emissions result in the lowest value (second comparison product). Compared to EU average electricity and heat mix the emissions of the AD using apple pomace are lower (third comparison product). If the use of digestate as a fertiliser is considered next to the use of electricity and heat, then additional savings of 20 kg CO_2-eq. per ton apple pomace can be generated (fourth comparison product).

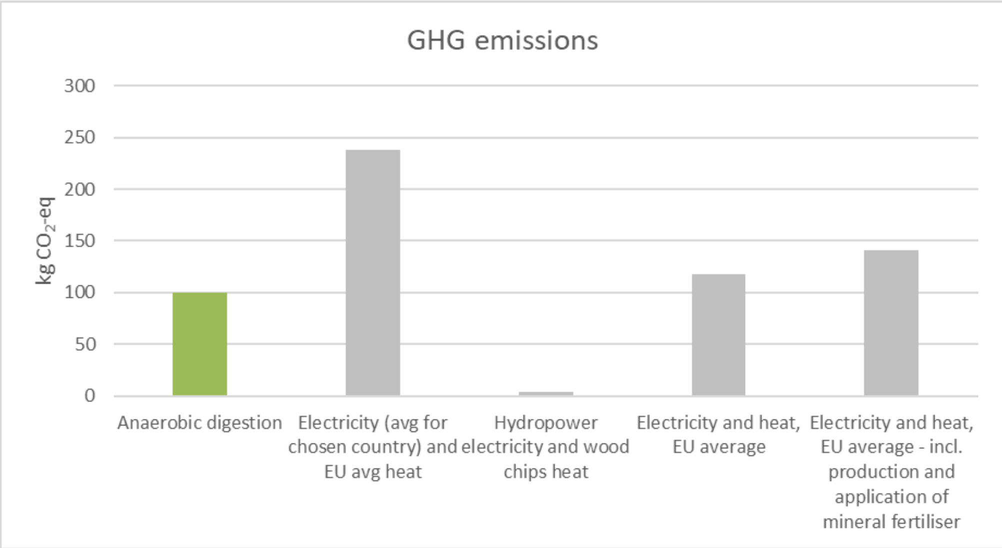

Figure 11 Energy production by anaerobic digestion with apple pomace as a source compared to the energy mix being relatively high in fossil-based electricity (in this case represented by a Polish electricity mix)

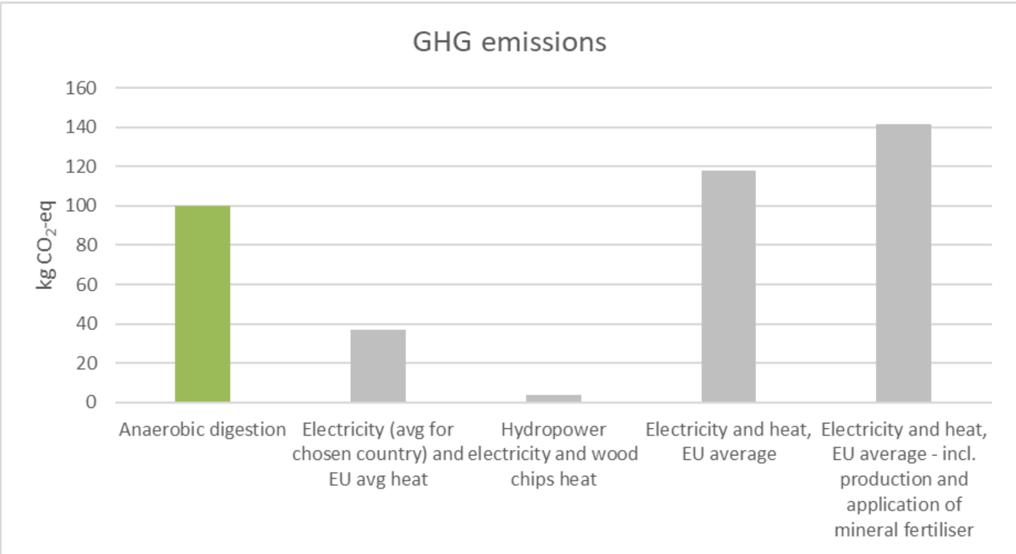

Figure 12 Energy production by anaerobic digestion with apple pomace as a source compared to a green electricity mix (in this case represented by Norwegian electricity mix)

Generic models in this report also cover disposal options such as land spreading, waste water treatment or the disposal in a municipal waste incineration plant. Examples are given in Figure 13 for the land spreading of apple pomace, in Figure 14 for blood being disposed via the sewer entering a waste water treatment plant, and in Figure 15 for brewers' spent grain disposed via other waste fractions in a municipal waste incineration plant. If apple pomace is spread onto land the transport to the land and distribution on land creates emissions due to fuel use and field application which creates direct and indirect N_2O emissions, which is a relevant greenhouse gas. The difference to the other options explained above here is that no product can be substituted. The spreading onto land may have some fertilising effect for the land, but it cannot be directly compared to the effectiveness of mineral fertiliser. This means that the spreading of apple pomace on land only creates emissions but does not replace another product. Therefore, the environmental impact is in any case apparent. The same applies for blood in a waste water treatment plant or BSG in a waste incineration plant, neither case generates valuable outputs such as energy. Those options can be allocated to the last step of the waste hierarchy. No comparison product can be considered, meaning no other product can be substituted on the market.

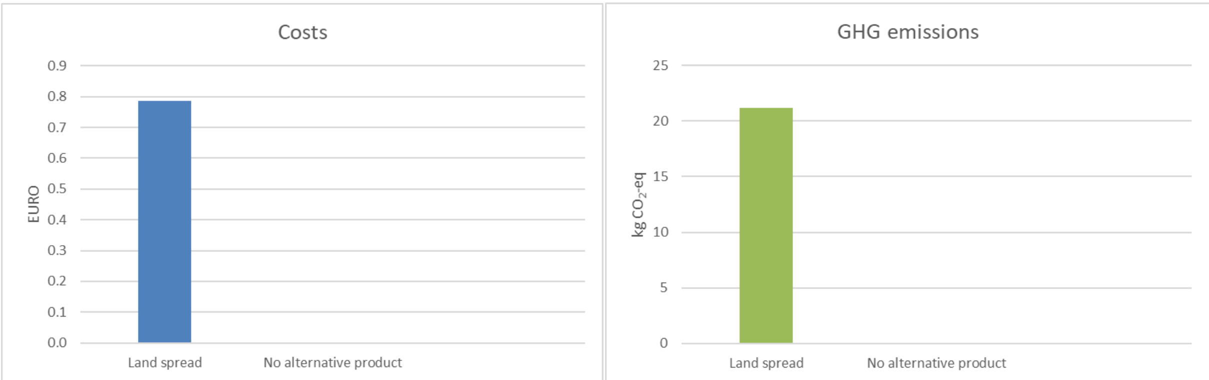

Figure 13 Costs and GHG emissions of land spreading of one tonne apple pomace

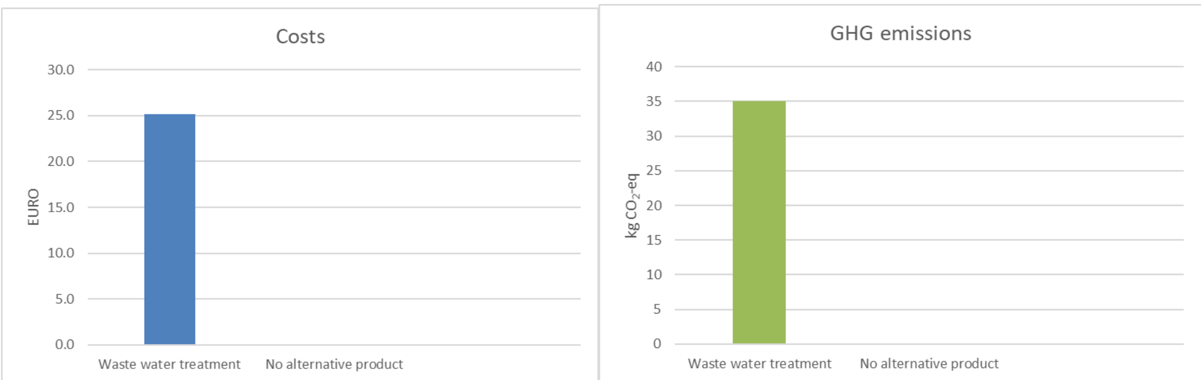

Figure 14 Costs and GHG emissions of one tonne blood in a waste water treatment plant

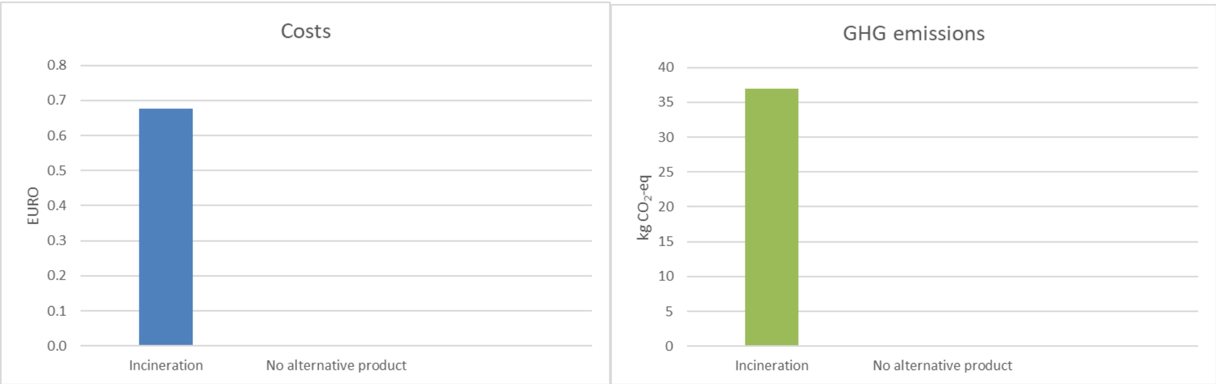

Figure 15 Costs and GHG emissions of one tonne BSG in a municipal waste incineration plant

Advantages and disadvantages of the FORKLIFT approach

However, one limitation of the tool related to decision making is that it only assesses static systems. Costs and emissions in the tool are seen in view of the whole life cycle and not from the perspective of one stakeholder. So, costs and emissions do not necessarily correlate with the costs and emissions from the stakeholder. Never the less, a cost must be covered by the stakeholder(s) and by providing anticipated costs for the full valorisation route and highlighting cost changes, potential implications upstream and downstream can be highlighted.

A second limitation is that the tool is based on predefined scenarios that are not exactly the scenarios looked after by the stakeholder. This is a true limitation, but the strength of this approach is that the scenarios generated are comparable between the cases since they are based on the same approach, considering boundary conditions, functional unit (FU) allocation and base line data for costs and energy.

A third limitation of the tool is that the model has no default data on investments and labour since these are site specific, however the user can add them to the model. The possibility of adding costs assure that the best-known costs are used and without these the model still gives a hint on the margins that can be allowed by answering the question: What investments and labour costs can be afforded to make this product profitable? By that, the approach taken still provides important insights and at the same time acknowledge the importance of correctly estimated labour and investment cost.

Further, since the tool is designed for comparison of two or more static but separate systems that do not interfere with each other, large scale changes cannot be accurately represented. Large scale changes have an implication on market and infrastructures, which most likely have an impact on costs as well as on environmental impacts (e.g. transports, the building of new facilities etc), but which are hard to predict. The choice of static systems allows for evidence-based models that can be reasonably validated. It is not possible to accurately predict the future market and the needs for new infrastructures in a standardised way, since this would require a quantification of all *future* linkages between the different side flows and main flows, which in turn would lead to speculative solutions impossible to validate.

The options incorporated in the tool have a high TRL level, rather than focusing on new innovative processes that can be seen as a solution for the future. This is both a strength and a limitation of the tool. This approach was taken based on the knowledge that industrial processes are more cost effective (e.g. considering energy use) than pilot processes and lab scale processes. The GHG emissions per unit product may differ by more than an order of magnitude comparing a lab/pilot scale to full scale production unit. This drawback was addressed by a careful selection of valorisation options covering both highly valuable compounds being extracted by advanced processing methods, to waste management options as AD and even land spread for the different categories of side flows. To further select between different valorisation options the data availability was considered. For any quantitative model data of sufficient quality in relation to the purpose of the model is a pre-requisite.

FORKLIFT in relation to the food use hierarchy

By using FORKLIFT, the user can gain an understanding of a system from an environmental and cost view. The spreadsheet tool developed can point towards areas of high impact (hotspots) and can support decisions for interventions by proving supplementary guidance to the food use hierarchy (Figure 16) highlighting the *context specific circumstances*, as being illustrated in the examples above, when choosing valorisation route of a side flow.

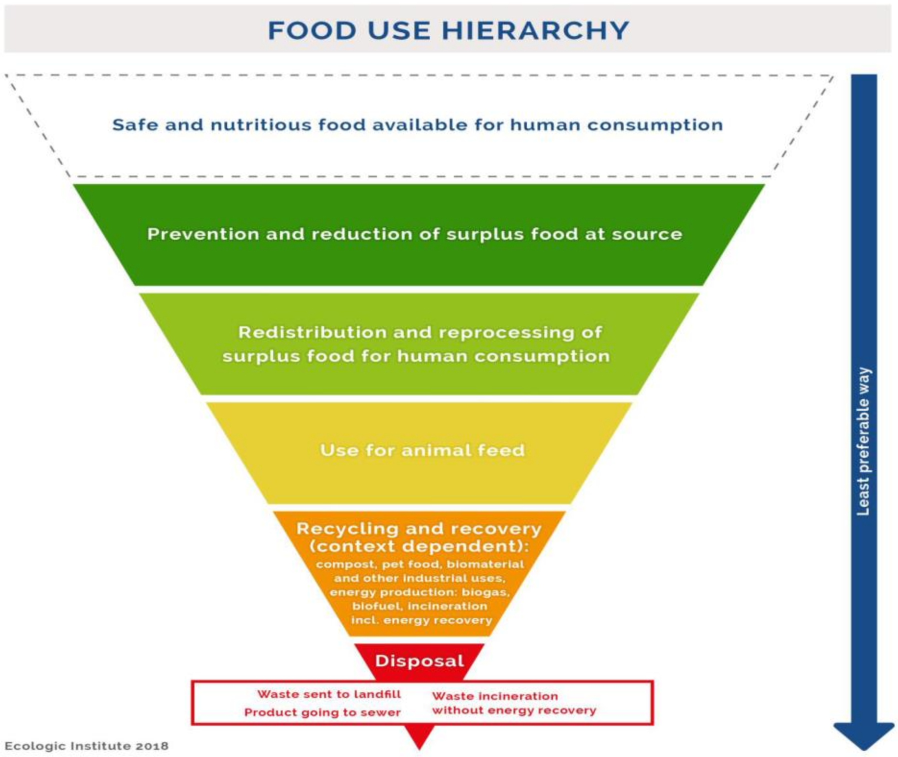

Figure 16 The food use hierarchy (Wunder et al, 2018)

The user of the spreads sheet tool has the possibility to compare static systems which are reasonable to consider and to change default values according to his/her contexts' specific situation (e.g. nationality, means of transport, heat source). Effects of the change are immediately shown in the result figure which enables the user to try different parameters and watch the effects. Emissions and costs of the valorisation option are set in relation to a range of comparison products, being functionally equivalent as far as possible. The tool covers in its current state different food side flows, from different product categories which are different in terms of nutrients, fats, proteins, carbohydrates and fibres allowing the user to compare results in a broader context.

The strength of the food use hierarchy is that no quantitative data are needed but that is also its weakness. In FORKLIFT quantitative data has been gathered and streamlined and made available for the user in a user-friendly format for selected important side flows and thus to some extent sought to fill the gap between qualitative models and quantitative models.

7 Conclusions

FORKLIFT (FOod side flow Recovery LIFe cycle Tool) was developed to help stakeholders gain a general understanding and to highlight the environmental impacts and costs for selected valorisation routes of a given side flow. It comprises a set of easy to use tools which enable the user to change different parameters and to try out how these changes affect the life cycle costs and emissions. It is therefore a suitable learning tool with the additional effect of making it possible to compare the results with alternative systems currently available on the market. A stakeholder that generates or utilises a side flow can interpret the results regarding the effects of interventions themselves, as they are also often the ones who know the market conditions best.

The tool clearly shows that many parameters influence the outcomes and that it is not easy to conclude, in general statements, if an option is environmentally or economically better since it is dependent on the context (country, energy sources, substituted products at the markets). Thus, the tool may serve as an important complement to the food use hierarchy and decision-making systems when information on the system is limited

Finally, and most importantly, the tool may enhance stakeholders' possibilities to pinpoint environmental and cost related hotspots in a given context. As such it can support the stakeholder in the early phase of development taking informed decisions of a valorisation process/waste management option without having a full inventory at hand and thus contribute to the development of economic and environmentally sustainable handling of food side flows.

The framework developed and the specific spreadsheet models, which are thoroughly described, can be extended to include other side flows in the future. The current work provides a thorough foundation to build upon.

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