Environmental Sustainability Assessment of Bioeconomy Products and Processes – Progress Report 2

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TABLE OF CONTENTS

NOTE TO THE READER

According to the Bioeconomy Strategy and Action Plan[1], in order to cope with an increasing global population, rapid depletion of many resources, increasing environmental pressures and climate change, Europe needs to radically change its approach to production, consumption, processing, storage, recycling and disposal of biological resources. The bioeconomy provides a useful basis for such an approach, as it encompasses the production of renewable biological resources and the conversion of these resources and waste streams into value-added products, such as food, feed, bio-based products and bioenergy. The Bioeconomy Strategy and its Action Plan aim to pave the way towards a more innovative, resource-efficient and competitive society that reconciles food security with the sustainable use of renewable resources for industrial purposes, while ensuring environmental protection.

The Circular Economy Strategy[2] also notes the potential contribution of the bioeconomy. The bio-based sector has shown its potential for innovation in new materials, chemicals and processes, which can be an integral part of the Circular Economy. Bio-based materials can present advantages in terms of their renewability, biodegradability and compostability. However, the lifecycle environmental impacts and sustainable sourcing of biological resources must be taken into account. The European Commission is committed to examine the contribution of the Bioeconomy Strategy to the Circular Economy, and will consider updating it if necessary. The European Commission will also promote synergies with the Circular Economy when examining the sustainability of bioenergy under the Energy Union.

Amongst other activities, the Bioeconomy Action Plan foresees the establishment, in close collaboration with existing information systems, of a Bioeconomy Observatory that allows the European Commission to regularly assess the progress and impact of the bioeconomy, and to develop forward-looking modelling tools.

In February 2013, the setting up of a Bioeconomy Observatory was entrusted to the Joint Research Centre of the European Commission under an intra-institutional agreement (Administrative Arrangement Ref. 341300 – Bioeconomy Information System and Observatory, BISO).

Amongst other tasks in the framework of the Bioeconomy Observatory, the JRC is carrying out a comprehensive, independent and evidence-based environmental sustainability assessment of various bio-based products and their supply chains. The present document compiles the main outputs of this environmental sustainability assessment produced in 2015, as follows:

- ✓ **Eleven environmental sustainability factsheets,** in addition to the fourteen factsheets that were produced in 2014 and published in Progress Report 1[3]. These factsheets are divided into three groups that reflect the three "pillars of bioeconomy": (1) food & feed, (2) bio-based products and (3) bioenergy, including biofuels. The factsheets follow the already established pattern by giving a uniform summary of different bioeconomy value chains and providing information on their environmental performance, based on publicly available data and/or information. In line with the Terms of Reference of the intra-institutional Administrative Arrangement 341300, the environmental sustainability research activities performed in the framework of the Bioeconomy Observatory are built on existing *and* accessible instruments (data, information and analyses) developed by EU, national and international organisations, and on the results of relevant EU-funded projects. The factsheets also contain a knowledge-gap analysis, to highlight where data and/or information do not exist or are inaccessible.

[1] COM(2012) 60 final, 13.2.2012. The text in the paragraph is adapted from it.
[2] COM(2015) 614 final, 2.12.2015. The text in the paragraph is adapted from it.
[3] Environmental Sustainability Assessment of Bioeconomy Products and Processes – Progress Report 1, EUR 27356 EN / 2015

These gaps, in turn, indicate the need for further action at policy level, in order to produce a comprehensive and evidence-based snapshot of the European bioeconomy. The eleven new environmental factsheets from 2015 are:

- Food and feed[4]: Sugar, Tomatoes;
- Bio-based products[5]: Amino acids, Pulp and Paper, Natural Rubber;
- Bioenergy, including biofuels[6]: Smaller-scale heat generation via combustion, Larger-scale heat generation via combustion, Electricity generation via combustion, Electricity generation via co-combustion, Combined heat and power via combustion, Heat and power via anaerobic digestion.

✓ For the reader's convenience, the **brief explanatory document** that provides an overview of the structure and content of the product and process environmental factsheets is included at the beginning of the compilation. This document summarises the **comprehensive, science-based methodology used to assess the environmental sustainability of bio-based products and their supply chains, which is based on a life-cycle perspective[7].** This methodology is largely based on the Product Environmental Footprint (PEF) method developed by the JRC[8] and on previous research proposals of the JRC[9]. It provides a quantitative understanding of a wide range of environmental aspects, and facilitates the assessment of fourteen default impact category indicators, including human toxicity, land use and resource depletion. The application of the methodology may help to identify those parts of the production system that are most environmentally relevant. Hence, it represents a powerful tool for designing actions that reduce the estimated environmental impacts. The methodology can also help to identify gaps in data and/or information availability or accessibility, as well as to focus data collection on those parameters or parts of the production system that most influence its environmental performance.

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[7] Led by Simone Manfredi, simone.manfredi@jrc.ec.europa.eu
[8] The 2013 Recommendation of the European Commission "on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations" (2013/179/EU) supports the use of the PEF method when undertaking environmental footprint studies.
[9] Bioeconomy and sustainability: a potential contribution to the Bioeconomy Observatory, V. Nita, L. Benini, C. Ciupagea, B. Kavalov, N. Pelletier, EUR 25743 EN – 2013

EXPLANATORY DOCUMENT

INTRODUCTION

This document provides an overview of the structure and content of the product and process environmental factsheets available on the Bioeconomy Observatory web pages. These factsheets are divided into three groups that reflect the three pillars of the bioeconomy: (1) **food & feed**, (2) **industrial bioproducts** and (3) **bioenergy.** Compiled based on publicly available data/information collected from studies using life cycle assessment (LCA), they describe different bioeconomy value chains and their environmental performance.

The following describes each of the three sections of the environmental factsheets.

Section 1: PROCESS/PRODUCT INFORMATION

Objective & content

This first section describes the different processes and products involved in the various bioeconomy value chains, taking into account their uses and production flows. It includes:

- A **flow-sheet** that depicts the main steps in the process, from the input used (i.e. type of biomass) to the final product(s), considering the most significant intermediate products and co-products.
- A **technological overview** that provides information on the state-of-the-art technologies and process configurations of the particular bioeconomy value chain. It particularly emphasises the input used.
- The **technology readiness levels** (TRL), which describe the maturity of the technologies and configurations used. TRL 1-3 is used to indicate basic and applied R&D, TRL 4-5 the pilot test stage, TRL 6-7 the demonstration stages and TRL 8-9 the commercial stages. An uncertainty range is provided given that an industrial technology can take 3-5 years to progress to the next TRL level.
- A **SWOT analysis** of the Strengths, Weaknesses, and Opportunities and Threats of the process/product.

Section 2: ENVIRONMENTAL DATA AND INFORMATION

Objective & content

This section maps and presents the available relevant environmental aspects and information regarding the different bioeconomy value chains, and provides an overview of their environmental performance calculated using a life cycle approach. In addition, it aims to:

- Identify knowledge gaps or information availability/accessibility issues that could be addressed by further research.
- Identify and explain the differences and similarities of LCA methodologies and results with regard to the bioeconomy value chains.

The environmental data and information section includes:

- The **system boundaries of the environmental assessment**, which depict and explain the LCA boundaries (see definitions below) considered.
- The **settings and impacts of the environmental assessment**. This is the main section of the environmental factsheet. It reports data collected from the scientific literature in a table that groups LCA results for the different impact categories (focusing on those considered in Table 1) by studies which use the same input to produce the same product within (as far as possible) comparable system boundaries. Maximum and the minimum values are displayed for the same functional unit. This grouped data can, however, include results obtained using different allocation methods (see definitions below) and different geographical coverage, which may bias the robustness of the ranges provided.
- **Comments and interpretation of the environmental performance**, which includes explanations of the LCA results and a graph that depicts all data after normalisation (i.e. not just the maximum and minimum) for the most reported impact categories. This graph allows the reader to:
    1. Further analyse the data mapped;
    2. Compare results across the different impact categories (as all impacts have been normalised and are therefore expressed in the same unit);
    3. Identify the effect of inputs or some key LCA assumptions on the final results.

Table 1. Impact categories provided in the Environmental Sustainability Assessment methodology developed within the Bioeconomy Information System Observatory (BISO) project. This methodology is based on the Product Environmental Footprint, as recommended by the European Commission [3].

Impact Category	Impact Assessment Model	Normalisation Factor for EU / Impact Category indicators
Climate Change	Bern model - Global Warming Potentials over a 100-year time horizon.	$4.60E^{12}$/ kg CO_2 eq.
Ozone Depletion	EDIP model based on the ODPs of the World Meteorological Organization over an infinite time horizon.	$1.08E^{7}$/ kg CFC-11 eq.
Ecotoxicity for aquatic fresh water	USEtox model	$4.36E^{12}$ / CTUe*
Human Toxicity - cancer eff.	USEtox model	$1.84E^{4}$/ CTUh**
Human Toxicity – non-cancer eff.	USEtox model	$2.66E^{5}$/ CTUh**
Particulate Matter/Respiratory Inorganics	RiskPoll model	$1.90E^{9}$/ kg $PM_{2.5}$-eq.
Ionising Radiation – human health effects	Human Health effect model	**$5.64E^{11}$/ kg U^{235} eq. (to air)**
Photochemical Ozone Formation	LOTOS-EUROS model	$1.58E^{10}$/ kg NMVOC eq.
Acidification	Accumulated Exceedance model	$2.36E^{10}$/ mol H+ eq.
Eutrophication – terrestrial	Accumulated Exceedance model	$8.76E^{10}$/ mol N eq.
Eutrophication – aquatic	EUTREND model	$7.41E^{8}$/ fresh water: kg P-eq. $8.44E^{9}$/ marine: kg N-eq.
Resource Depletion – water	Swiss Ecoscarcity model	$4.06E^{10}$/ m^3 water used
Resource Depletion – mineral, fossil	CML2002 model	$5.03E^{7}$/ kg Sb-eq.
Land Transformation	Soil Organic Matter (SOM) model	$3.74E^{13}$/ Kg (deficit)

* Comparative Toxic Unit for ecosystems
** Comparative Toxic Unit for humans

Section 3: REFERENCES / FURTHER INFORMATION

Objective & content

This section gives the references used in the environmental factsheets, and tables further references to the main FP7 projects related to the environmental sustainability assessment of the specific target process / product. More information on these projects can be found in the Community Research and Development Information Service - CORDIS (http://cordis.europa.eu/home_en.html).

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Definitions and clarification of key LCA concepts

Life Cycle Assessment (LCA) [1] – the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (where life cycle means from the extraction of resources to the use of the product and its management after it is discarded – "from the cradle to the grave").

Functional unit – a measure of the function of the studied system. The functional unit provides a reference against which the inputs and outputs can be related. It identifies the function provided, in which quantity, for what duration and to what quality [2].

System boundaries – determine which processes are included in the LCA study. They can be the boundaries between technological systems and nature, geographical areas, time horizons and different technical systems. The main variants (Fig. 1) are: Cradle-to-Grave, Cradle-to-Gate and Gate-to-Gate. The Well-to-Wheel (WTW) is a special approach for biofuels that includes fuel production (Well-to-Tank) and vehicle use (Tank-to-Wheel). The WTW boundary variant usually focuses only on greenhouse gas emissions and energy efficiency and, unlike typical LCA boundaries, does not consider the building phase of facilities/vehicles nor end-of-life aspects.

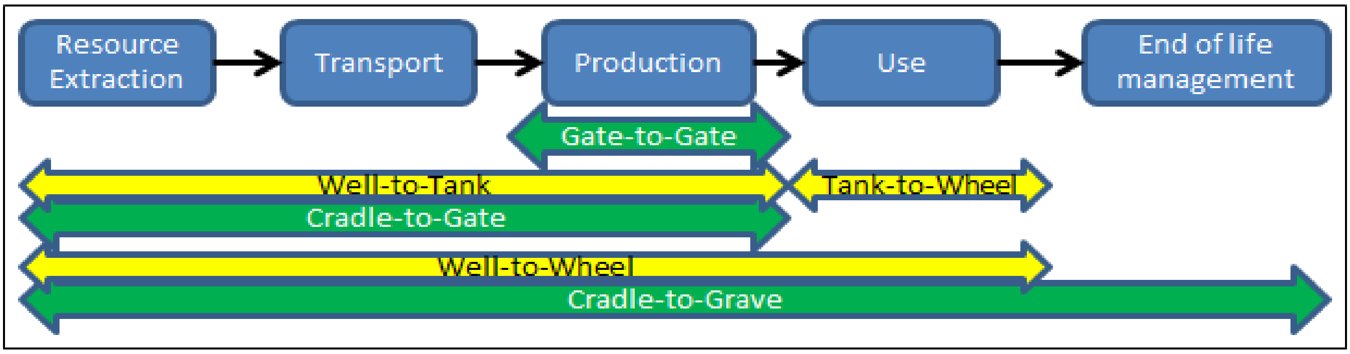

Figure 1. Main variants of life cycle assessment system boundaries

Impact Categories and Models define what classes of impacts are considered in the assessment; these are associated with specific impact assessment models that aggregate the inventory data and calculate the size of their contribution to each impact category using characterisation factors (i.e. values of the impact intensity of a substance relative to a common reference substance for a given impact category, e.g. CO_2 is the reference substance for the category "Climate Change").

Normalisation is an optional LCA step (under ISO 14044:2006) that follows the characterisation step. Through normalisation, the calculated environmental impacts are converted into the same (dimensionless) unit for all impact categories. This allows for the comparison of environmental impacts across different categories.

Multifunctionality – If a process or product provides more than one function, i.e. delivers several goods and/or services (often also called "co-products"), it is multifunctional [2]. There are several approaches that deal with multifunctionality. Based on the ISO 14044:2006 guidelines, the latest multifunctionality decision hierarchy supported by the European Commission (as from the 2013 EC Product Environmental Footprint guide) reads:

1. *Subdivision or System expansion* – Wherever possible, subdivision or system expansion should be used to avoid allocation (see point 2 below). Subdivision disaggregates multifunctional processes or facilities to isolate the input flows that are directly associated with each product output. System expansion expands the system by including additional functions related to the co-products.
2. *Allocation* – refers to how the individual inputs and outputs are split between the co-functions according to some allocation criteria.
    - **Allocation based on an underlying physical relationship** - When choosing allocation criteria, preference should be given to a physical relationship (i.e. the element's content, mass, etc.). Alternatively, allocation based on an underlying physical relationship can also be modelled via **direct substitution** whenever the actual product substituting the bio-based product is known.
    - Alternatively, **allocation based on different relationships** can be used, such as economic allocation, whereby inputs and outputs associated with multi-functional processes are allocated to the co-product outputs based on their relative market values. If the product that substitutes the bio-based product is not known, allocation based on different relationships can be modelled via **indirect substitution**, whereby the substituted product is represented by the market average.

Assumptions & limitations

The main limitation of this assessment process is the poor availability and/or accessibility of relevant data and information, which may limit the robustness of the environmental analysis (and, in particular, the representativeness of ranges of environmental impacts). The references/studies used for mapping the LCA results in the factsheets were selected based on the following criteria:

- Studies from Framework Programme 7 (FP7). Generally the publicly available LCA data from FP7 projects is limited and aggregated (e.g. reported as comparison percentages) which prevented their use in the environmental factsheets.
- Studies that reported environmental impacts that were calculated in line with the Product Environmental Footprint methodology recommended by the EC [3] (shown in Table 1).
- Studies that focused on a broad range of environmental aspects, i.e. priority was given to studies accounting for the highest number of impact categories.
- Peer-reviewed literature and most cited and most recent studies.
- Studies with obsolete, incomparable or dubious quality data were excluded.

Another limitation is the lack of heterogeneity of the LCA results reported, mainly due to the different assumptions and different methodological choices made in the various LCA modelling exercises. As a consequence, several studies were not used to compile the factsheets, since their inherent differences made a comparison of the results meaningless. These differences mainly relate to:

- The different impact assessment methods used, as different methods may consider, for example, different substances for a given impact category, and different characterisation factors for the same substance.
- The definition of the system boundaries and the stages included in the study (e.g. even if the same general system boundaries are considered - e.g. cradle to gate - some studies may or may not include intermediate transport, construction and decommissioning of buildings, etc.).
- The definition of the functional unit (e.g. as the input, the output product, the agricultural land unit, etc.) [4]. The analysis performed to compile the environmental factsheets mitigates this variability since all the LCA data were converted to the same functional unit whenever possible.
- The consideration of direct and indirect land use change (dLUC and iLUC, respectively) [4].
- The definition of some impact categories (e.g. using different terminology or different units).
- The technology considered in the process and its maturity level.
- The approach used to mode the multifunctional system. For instance, if substitution is used, the reference system selected may have a significant influence on the final LCA results. On the other hand, if allocation is used, the selection of the allocation criteria and the relative contribution of each co-product may considerably influence the results of the assessment.

Normalisation was conducted whenever possible using normalisation factors that represent emissions from the EU-27 for the year 2010, based on the "domestic emissions inventory"[10] reported in the 2014 JRC Technical Report "Normalisation method and data for Environmental Footprints" (available online: https://ec.europa.eu/jrc/sites/default/files/lb-na-26842-en-n.pdf) [5].

The reported data were normalised using a common reference value (i.e. the total emissions in Europe within a certain impact category in the reference substance equivalents) to express all impact values using the same unit so that they can be compared across different impact categories. These impacts also represent the relative contributions of the system to the total environmental impacts caused by European domestic emissions. For example, with respect to climate change, if the system were estimated to have an impact value of 10 kg CO_2-eq., and if the normalisation factor for climate change in Europe were 1 000 kg CO_2-eq., then the normalised impact value for climate change would be 10/1 000 = 0.01, which means that the system assessed contributes 1% of the total impact on climate change associated with all domestic emissions in Europe.

For impact categories different from those listed in Table 1, normalisation factors for EU emissions were taken from the ReCiPe impact assessment method [6] and, for the primary energy category, the factor of 4.03×10^{13} MJ was used [7]. The ReCiPe method is a widely used LCIA (Life Cycle Impact Assessment) method that, like the Product Environmental Footprint method, transforms the emissions of the analysed value chains into impact scores[6,8].

References for this explanatory document

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[8] http://www.lcia-recipe.net/home

[10] The "domestic emissions inventory" includes all emissions originating from activities taking place within the European Union territory.

Food & Feed Pillar

ENVIRONMENTAL FACTSHEET: ***Sugar***

PRODUCT INFORMATION

Sugar for use in food corresponds mainly to crystallised white sugar (composed of sucrose, a disaccharide of glucose and fructose). It is extracted from the stem of sugar cane or the root of sugar beet through a refining process (Fig. 1). Processes also exist to produce sugar from corn and wheat starches, however they represent a very small part of the sugar consumed in the European Union. The EU is the world's biggest producer of beet sugar and the largest importer of raw cane sugar for refining. Sugar cane typically contains 12-13 % sugar, of which 30-100 % can be extracted, while sugar beet contains about 16 % sugar, of which 40-80 % can be extracted [2].

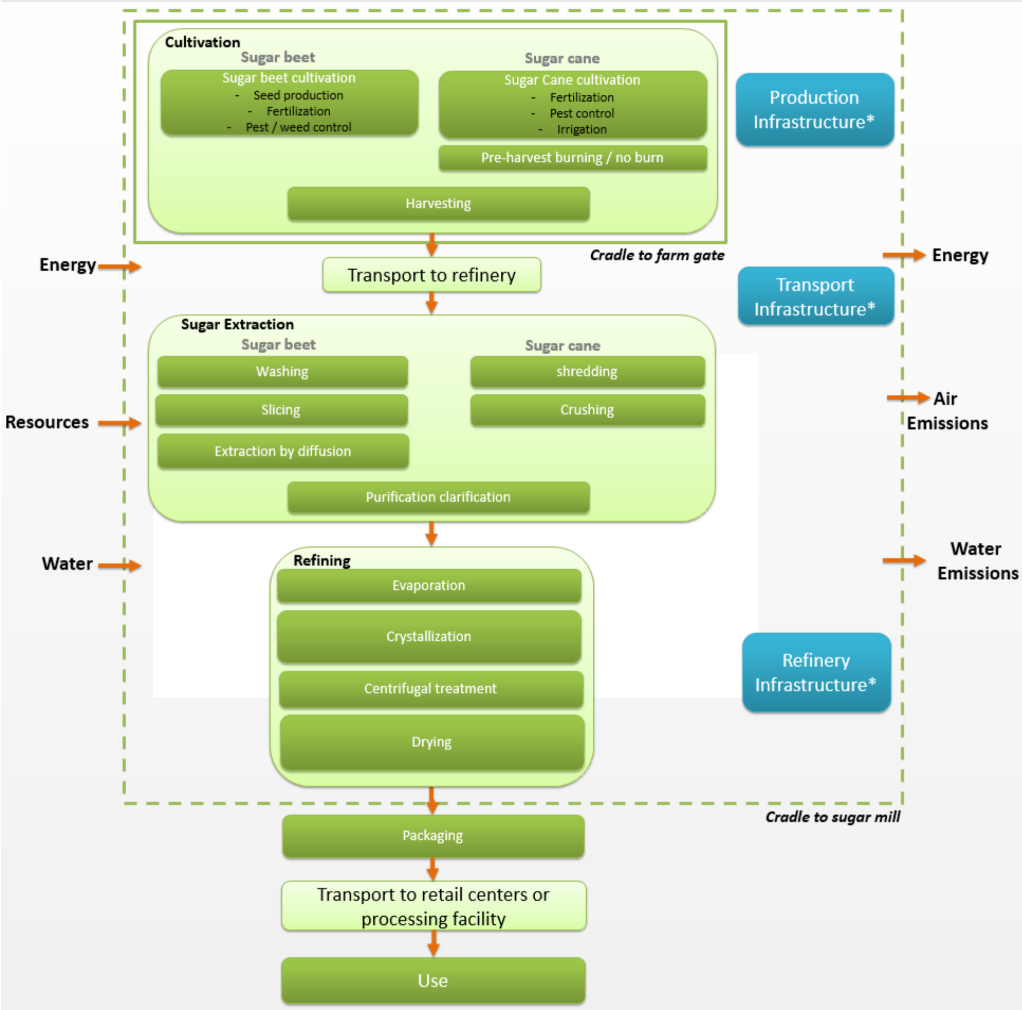

Figure 1. *Sugar production chain and system boundary (* the study by [1] did not incorporate the emissions associated with the generation of the farming, transport and refinery infrastructure, it only account for the emissions resulting from their use).*

EU production:
— 109 million tonnes of sugar beet, equivalent to 17.5 million tonnes of sugar (2013) [3].

Co-products:
— sugar cane: bagasse (mainly cellulose, hemicellulose and lignin) and molasses (64.1 % sugars and 5.5 % protein) [4];
- sugar beet: pulp (mainly cellulose, hemicellulose and pectin) and molasses (sugar 63.2 % and 14.3 % protein [5]), calcium carbonate and stones (from beet washing) [6].

Pulp and molasses are often used as animal feed.

Only sugar beet is cultivated in Europe, and the vast majority of sugar cane is imported (although a small amount is cultivated in European overseas territories). The cultivation of both sugar beet and sugar cane and the process of refining of sugar from these crops are well known and operate at full commercial scale. Although organic practices for the cultivation of sugar cane exist, production is minimal. The technology readiness levels of sugar crop cultivation and sugar extraction are presented in Figure 2. Research activities principally focus on the development of new crop varieties that are resistant to herbicides (sugar beet and cane) or draught tolerant (mainly for sugar cane). New varieties of tropical sugar beet are now becoming available and could possibly compete with sugar cane in drier tropical areas.

Since 2006, the EU sugar market has been regulated by production quotas, a minimum beet price and trade mechanisms. However, out-of-quota industrial white sugar does not have a fixed buy price. The total EU production quota is 13.5 million tonnes of sugar (2013) [3]. Sugar imports (3.3 million tonnes) are mainly in the form of raw cane sugar for refining (64 %) and white sugar (26 %), from the African, Caribbean and Pacific states and least developed countries, which benefit from quota-free, duty-free access to the EU market. Imports from other countries are subject to high import duties (€339 per tonne on raw cane sugar for refining and €419 per tonne on white sugar).

Apart from food applications, sugar and sugar molasses are also used in the production of bio-based products (such as biopolymers, organic acids and amino acids) and bioethanol, through fermentation processes. For these applications, research is also targeting new feedstocks for the production of sugars, such as lignocellulosic materials.

Technology readiness levels

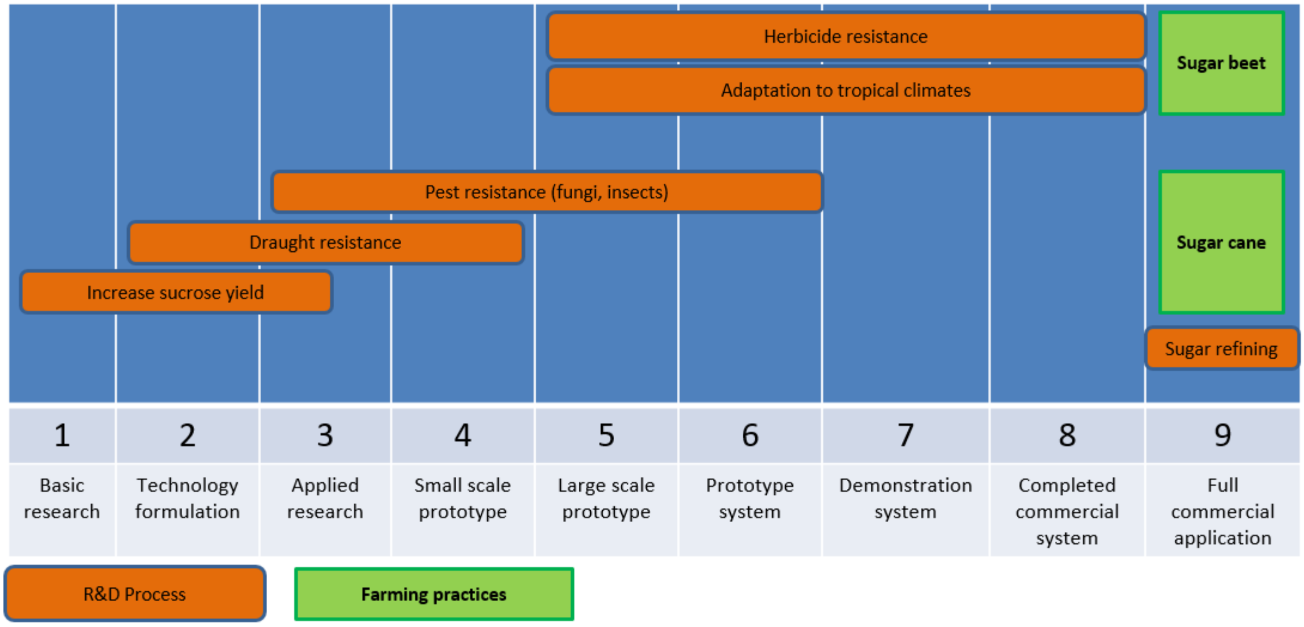

Figure 2. *Technology readiness levels for sugar production systems*

SWOT analysis (Strengths-Weaknesses-Opportunities-Threats)

S1. Sugar is produced in many countries, and both the production of the sugar crops and the process of sugar refining are well known. **S2.** The sugar cane and sugar beet industries benefit from strong research and development and a wide range of crop varieties is available.	**W1.** Sugar production can be strongly affected by seasonal variations in climatic conditions such as drought (particularly sugar cane). **W2.** Sugar is the main source material for the production of ethanol and a possible competition (post 2017) between use for food or fuel could lead to increased price variability.
O1. The EU production quota will end in 2017, possibly allowing an increase in production. **O2.** Future increases in atmospheric CO_2 have potential to increase sugar beet yields (experiments showed increases of sugar beet yield by up to 26 %).	**T1.** Increases in temperature associated with climate change could lead to lower biomass production in sugar beets. **T2.** The cultivation of sugar cane is often associated with the destruction of natural habitat and environmental degradation which could lead to a negative response from consumers.

ENVIRONMENTAL DATA AND INFORMATION

System boundaries of the environmental assessment (Figure 1)

1. **Cradle to farm gate**: includes the processes of cultivation of the sugar crops, pre-harvest burning (for sugar cane) and harvesting. None of the cradle-to-farm-gate studies investigated incorporated emissions associated with the making of the production infrastructure.
2. **Cradle to sugar mill**: includes the same elements as cradle to farm gate, as well as transport of the crop to the refinery, the process of extraction and concentration of sugar to raw form and then to white sugar, by separation of the molasses from the sucrose. Most studies ([1] excepted) incorporated emissions associated with the making of the production infrastructure. The majority of sugar cane brought into Europe as raw sugar undergoes extra transport and refining into white sugar. The emissions associated with these extra steps were incorporated by [7] only.

The results presented in Table 1 illustrate the environmental indicators associated with the production of sugar from sugar cane, sugar beet and other crops. The most widely reported impact categories are climate change, acidification, eutrophication and energy (water consumption, not presented here, is also reported in some studies). Few or no results were found for the remaining impact categories. The studies used a variety of functional units (kg of monosaccharide in juice form, kg of extractable sugar, raw sugar, tonnes of harvested canes or beets and kg of crystallised white sugar) and we performed a harmonisation into kg of extractable sugar.

Environmental assessment: settings & impacts

***Table 1**. LCA result for different sugar production systems and system boundaries. Functional unit in kg of extractable sugar*

Sugar crop type	Sugar cane	Sugar beet	Corn / wheat	Sugar cane	Sugar beet
References	[1, 6-9]	[6, 7]	[6, 7]	[9, 10]	[11]
Study boundary	Cradle to sugar mill gate	Cradle to sugar mill gate	Cradle to sugar mill gate	Cradle to farm gate	Cradle to farm gate
Geographical coverage	Australia, Mauritius, Brazil	United Kingdom, EU	United States	Australia, United States	Germany
Impact categories from environmental sustainability assessment methodology					
Climate change ($kgCO_2eq$)	-0.05 – 0.76	0.242 – 1.3	0.64 – 1.16	0.042 – 0.251	0.196 – 0.234
Additional impact categories					
Acidification (kg SO_2 eq)	-4.7E^{-2} –1.33E^{-3}	2.96E^{-3} –4.84E^{-3}	7.83E^{-3} – 0.01	-4.70E^{-3} – 8.56E^{-4}	2.26E^{-3} – 7.64E^{-3}
Eutrophication — aquatic ($kgPO_4$ eq)	1.38E^{-4} –4.20E^{-3}	6.40E^{-4} –1.20E^{-3}	2.3E^{-3} –3.36E^{-3}	1.38E^{-4} –4.23E^{-4}	2.57E^{-3} –3.64E^{-3}
Energy use (MJ/kg)	-10.05 – 3.59	4.35 – 6.3	5.9 - 7	8.65E^{-3} – 1.96	N.A.

***Note:** N.A. = Not Available*

Comments and interpretation of environmental performance (Table 1 and Figure 3)

- On a normalised scale for the EU-28, eutrophication and energy use represent the most important environmental impact associated with sugar, mainly because of fertiliser use and heating needs for the refining process.
- The lowest impacts for energy use were reported for sugar cane, principally beacause of the use of bagasse to generate energy.
- The effects of study boundary are particularly visible for acidification and eutrophication where the inclusion of the sugar milling processes reverse the performance of sugar cane from lowest emitter to highest emitter.

The normalisation presented in Fig. 3 is performed using the normalisation factors provided in the JRC 2014 methodology [12] and ReCiPe normalisation values (see explanatory factsheet).

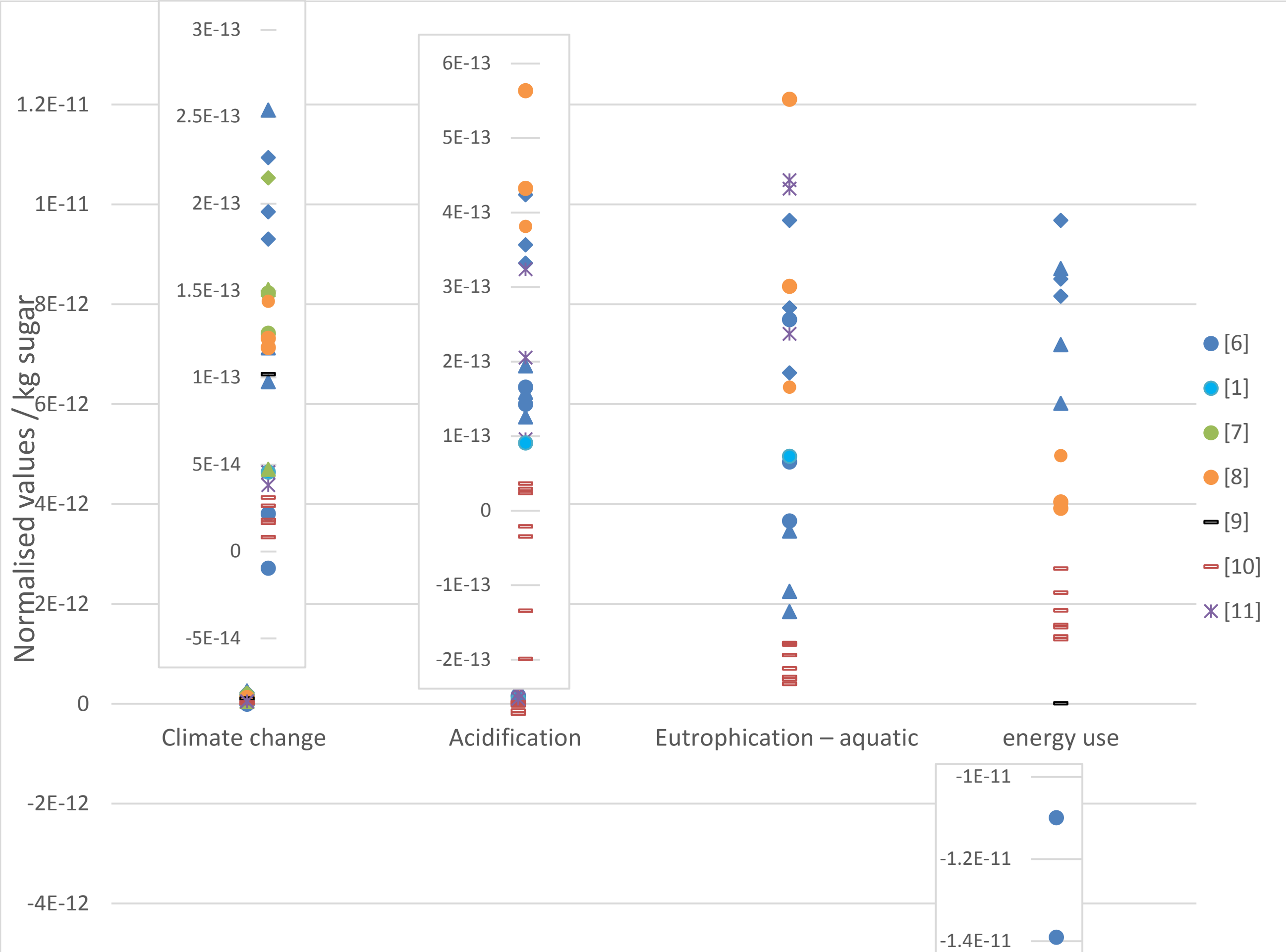

Figure 3. *Environmental performance expressed as normalised impact categories. Circles correspond to cane sugar, triangle correspond to sugar beet, diamond for corn or wheat (cradle to sugar mill). Crosses correspond to sugar beet and horizontal bars correspond to sugar cane (cradle to farm gate).*

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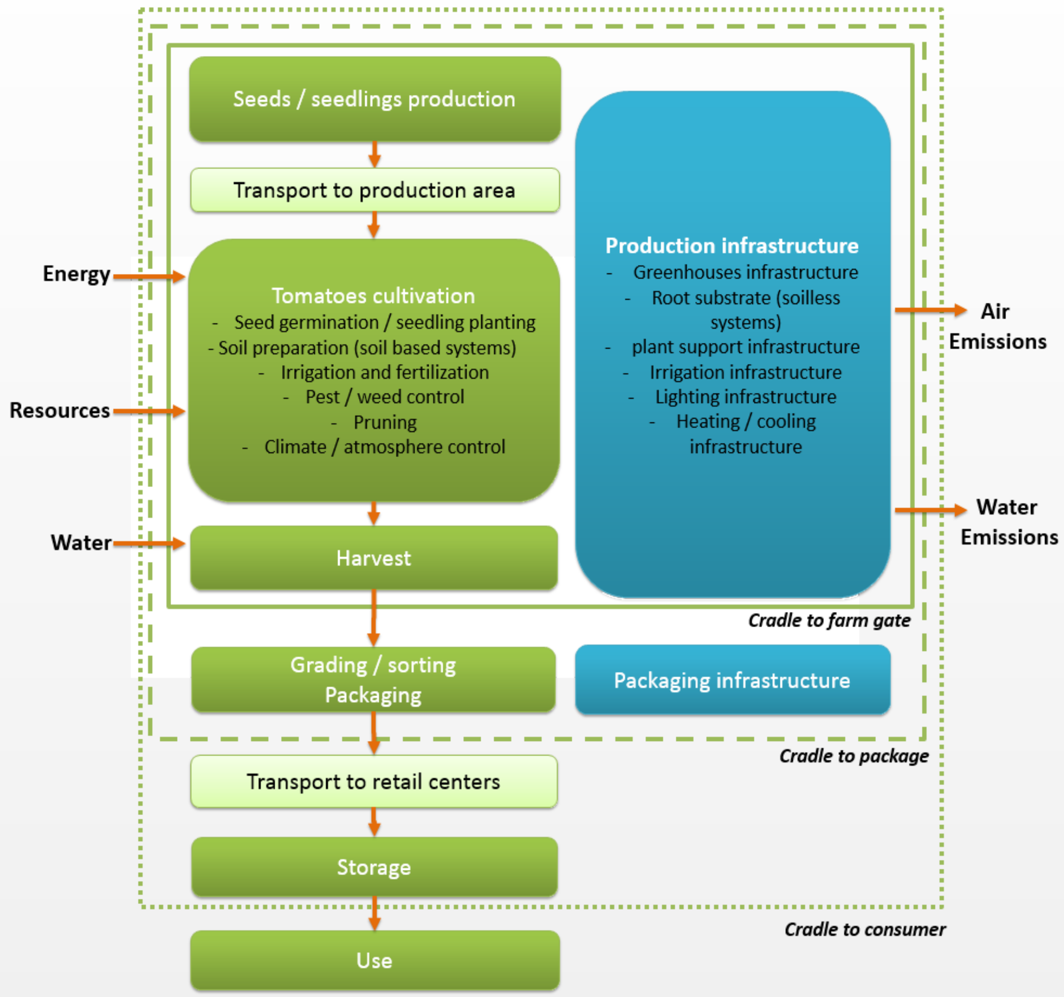
ENVIRONMENTAL FACTSHEET: **Tomatoes**

The tomato is the fruit of *Solanum lycopersicum*. It is cultivated worldwide and represents a common vegetable in most of the world's cuisines. Tomatoes are consumed either fresh or processed. Fresh tomatoes are composed mainly of water (94 %), sugars (glucose and fructose, 2-3 %), fibres (1-2 %) and proteins (0.8-0.9 %). However, significant differences exist between the 7 500 varieties of tomatoes available. Tomatoes represent the world's eighth most valuable agricultural product and they are grown across all EU countries.



EU production: 14.9 million tonnes (2013).

Co-products: plant stems, prunings and damaged tomatoes.

Two main types of production systems are used:
(1) soil-based systems, where tomatoes are planted directly in the ground; and
(2) soil-less (hydroponic) systems, where plants' roots are bathed directly in a nutrient solution or supported by an inert medium.

Figure 1. *Tomato production chain and system boundary*

Both soil-based and soilless tomato-production systems are operating at full commercial scale. Soil-based systems are usually seasonal and produce tomatoes either in open fields or under light greenhouse structures typically made of polyethylene sheets on a steel structure, which can be moved from parcel to parcel.

Soilless systems produce tomatoes all year round in permanent greenhouses structures where light, temperature, CO_2 concentration, nutrients and irrigation can be tightly controlled.

While open-field practices represent a significant part of tomato production in southern Europe, these practices were considered by a few studies only [1-3], and the majority of published LCA studies focused on greenhouse-based production systems (both on soil and soilless).

Technology readiness levels for both production systems are presented in Fig. 2. Major research efforts are spent on the continuous development of pest- and disease-resistant tomato varieties grown in both systems. Major research efforts focus on soil management in soil-based systems to overcome issues associated with soil-borne pathogens. Soilless systems benefit from continuous research and development in hydroponics (greenhouses, lighting systems, combination with power/heat generation systems, etc.), as well as in fertigation (injection of fertilisers into the irrigation system) systems.

Technology readiness levels

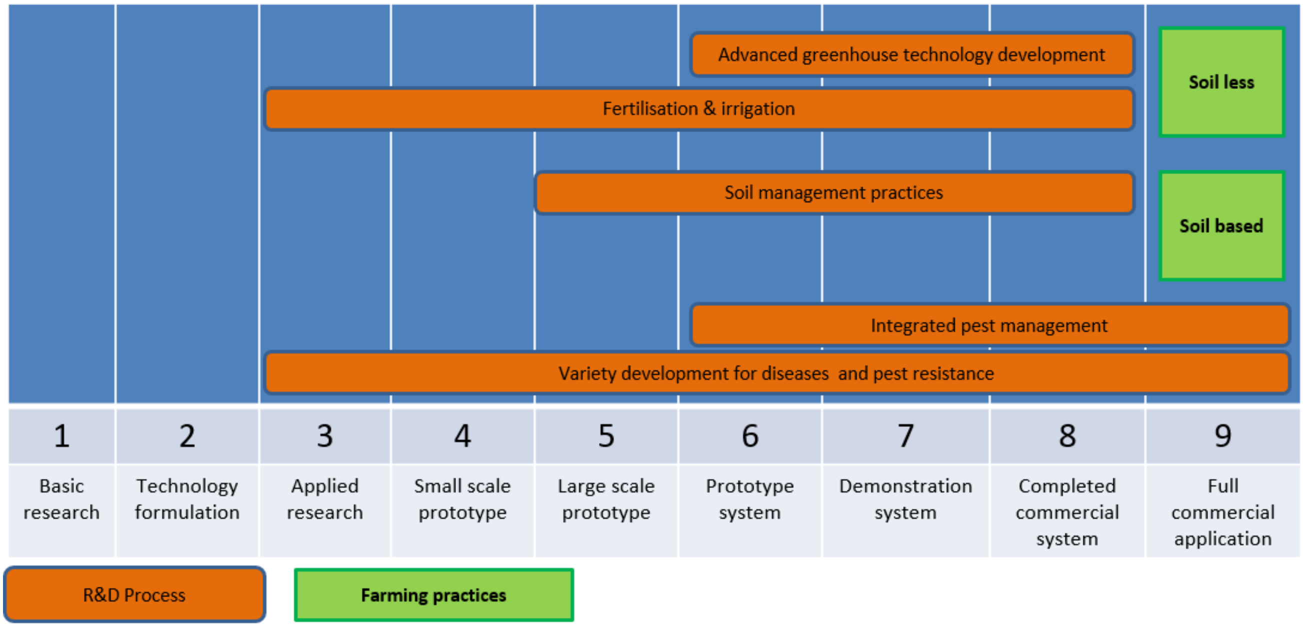


Figure 2. *Technology readiness levels for tomato production systems*

SWOT analysis (Strengths, Weaknesses, Opportunities, Threats)

S1. Tomatoes are produced worldwide. A large range of tomato varieties are available and continually being developed. **S2.** Soilless (hydroponic) tomato cultivation is very technologically advanced. Its production methods are well known and optimised. **S3.** Soilless systems can produce tomatoes outside conventional production zones (rooftops, etc.)	**W1.** Open-field tomato production in southern Europe is less productive than both soil and soilless greenhouse-based systems. **W2.** Large costs are associated with greenhouse infrastructure, labour and functioning. **W3.** The breeding of tomato seeds is very labour intensive (often requiring hand pollination).
O1. The development of aeroponics (a system where plant roots are grown in a nutrient-rich mist, without physical support) has the potential to increase production efficiency. **O2.** Tomato cultivation generates large amounts of plant waste which could be valorised into compost or fibre packaging, bio plastics, etc.	**T1.** Since the 2009 EU ban on methyl bromide (a soil fumigant), the management of soil-borne pathogens (mainly fungi, bacteria, viruses, nematodes and protozoa) has become more problematic for soil-based systems, and replacement methods are still being investigated. **T2.** Pests and diseases can greatly decrease tomato production in all production systems.

ENVIRONMENTAL DATA AND INFORMATION

System boundaries of the environmental assessment (Figure 1)

1. **Cradle to farm gate**: includes the processes of seed production, cultivation of tomatoes and harvesting. Emissions associated with the building, maintenance and functioning of the production infrastructure are also taken into account.
2. **Cradle to package**: includes the same elements as cradle to farm gate, as well as grading and packaging processes.
3. **Cradle to consumer**: includes the same elements as cradle to package, as well as transport to retail location and product storage until sale.

The results presented in Table 1 represent the environmental indicators associated with the production of 1 tonne of fresh tomatoes.

Environmental assessment: settings & impacts

Table 1. LCA results for different tomato production systems. Functional unit: 1 000 kg of tomatoes

References	[1, 2, 4-12]	[13, 14]	[3, 15, 16]
Study boundary	Cradle to farm gate	Cradle to package	Cradle to consumer
Geographical coverage	Spain, Columbia, Iran, Mediterranean, EU, France, China	Italy	Spain, Austria, Italy
Impact categories from environmental sustainability assessment methodology			
Abiotic depletion (kg sb eq)	0.526 – 14.68	N.A.	1.79 – 6.91
Climate change (kgCO_2eq)	-980 – 2080	740 – 1233.6	0.26 – 3590
Ozone depletion (kg CFC-11 eq)	1.88E^{-6} – 5.14E^{-4}	4.00E^{-4} – 4.30E^{-4}	N.A.
Ecotoxicity for aquatic freshwater (CTUe)	439 – 976	N.A.	N.A.
Eutrophication — aquatic (kgPO_4eq)	-4.06 – 3.00	1.60 – 2.80	4.90E^{-4} – 0.88
Photochemical oxidation (kg C_2H_4)	9.76E^{-3} – 0.883	0.30 – 1.20	N.A.
Additional impact categories			
Freshwater ecotoxicity (kg 1.4 DB eq)	5.81 – 205.0	194.5	N.A.
Human toxicity (kg 1.4 db eq)	0.124 – 37.6	430.40	8.90E^{-2} – 170.0
Marine ecotoxicity (kg 1.4 db eq)	17497.61 – 50000	313.10	N.A.
Terrestrial ecotoxicity potential (kg 1.4db eq)	0.24 – 31.686	2.90	N.A.
Acidification (kg SO_2 eq)	0.37 – 4.00	4.70 – 8.40	1.08E^{-3} – 3.14
Water use (m^3)	14.06 – 4000.00	67.2 – 96.7	105 – 122.6
Cumulative energy demand (MJ eq)	1340 – 255380	N.A.	4.31 – 16.3
Energy use MJ/kg	1502.346 – 1740.58	14200 – 21000	35000 – 95500
Land occupation (m^2)	47 – 90	N.A.	N.A.

Note: N.A. = not available.

Comments and interpretation of environmental performance (Table 1 & Figure 3)

- Categories for which fewer than nine references were available were excluded from the normalisation.
- On a normalised scale for the EU-28, freshwater ecotoxicity represented the most important environmental impact (higher normalised impacts were reported for marine ecotoxicity but these results were supported by only three studies, with only one of them from Europe).
- Negative impacts for climate change and eutrophication were reported by [1] as they incorporated the 'avoided environmental burden' associated with the composting (rather than dumping) of tomato by-products.
- The impacts across categories vary widely. However, the study by [15], considering a hypothetical rooftop hydroponic tomato production, reported the lowest environmental impacts in all but one category (abiotic depletion). Soil-based systems, including open fields, appeared in the lower bounds for climate change emissions but in the higher bounds for

eutrophication (because nutrients applied to soils cannot be recovered as in closed hydroponic systems).

The normalisation presented in Fig. 3 is performed using the normalisation factors provided in the JRC 2014 methodology [17] and ReCiPe normalisation values (see explanatory factsheet).

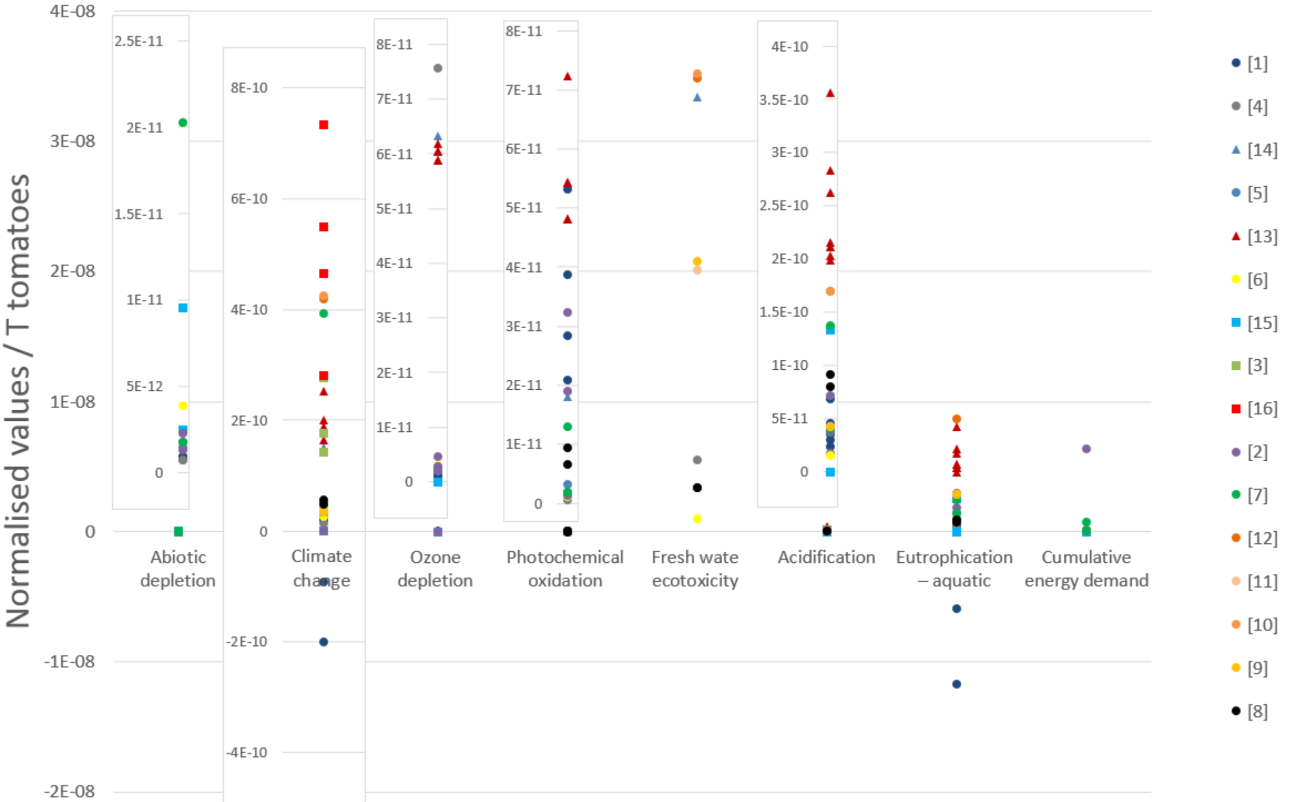


Figure 3. *Environmental performance expressed as normalised impact categories. Circles correspond to cradle-to-farm-gate studies, triangles correspond to cradle-to-package studies and squares correspond to cradle-to-consumer studies. Blue is used for Italy, red for Spain, orange for France, green for the whole of the EU, purple for the Mediterranean region, black for China, yellow for Iran and grey for Columbia.*

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Bio-based Products Pillar

ENVIRONMENTAL FACTSHEET: ***Amino acids***

PRODUCT INFORMATION

Amino acids are essential compounds for life metabolic processes, containing an amine and a carboxyl acid chemical functional group. Industrially produced amino acids are widely used in animal feed and human nutrition because they are building blocks for the production of proteins or important metabolic intermediates. Several of them cannot be synthesised by humans or animals (e.g. in the case of humans: essential amino acids such as lysine, methionine, threonine, tryptophan, histidine, phenylalanine, valine, leucine, isoleucine) [1]. Other uses include flavour enhancers (such as L-glutamic acid) and pharmaceutical products [2].

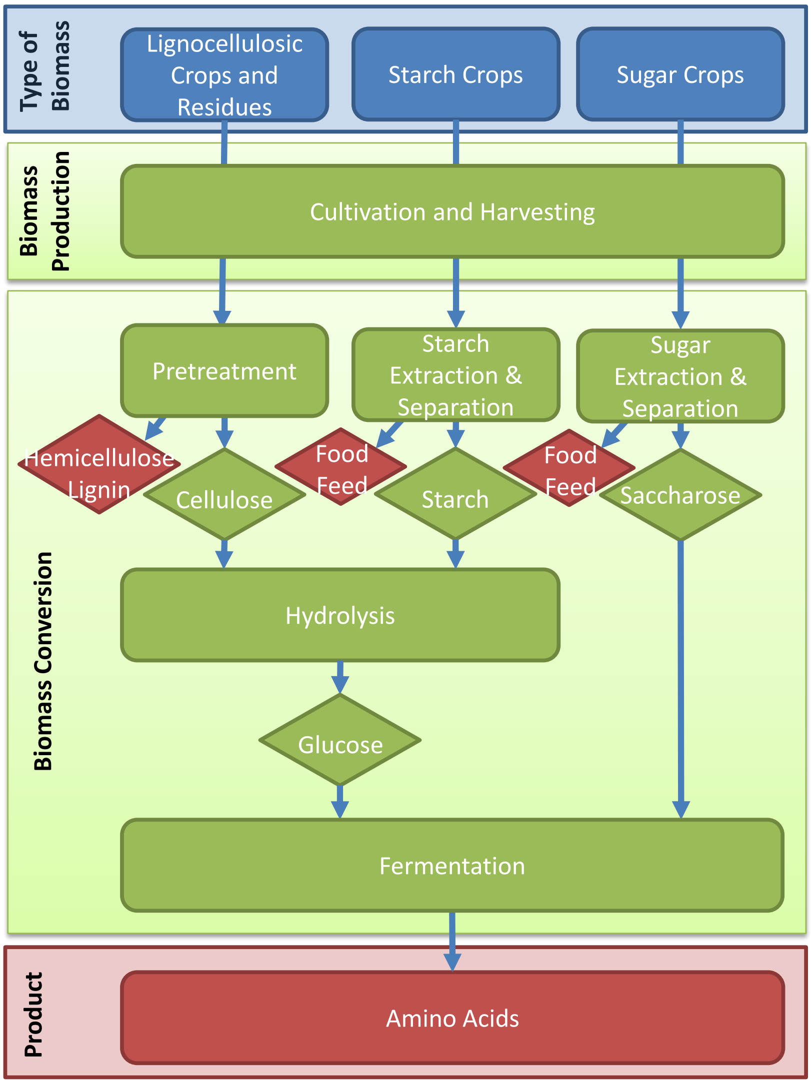

Figure 1. *Amino acids production chains*

Amino acids can be obtained through chemical synthesis (such as methionine), extraction from protein hydrolysates (such as cysteine), enzymatic synthesis and fermentation of sugars.
The chemical synthesis produces racemic mixtures of amino acids. However, the biochemical active isomer is usually the L isomer, therefore biotechnology processes are preferable to chemical ones, because they produce a pure isomer and avoid complex purifications. The amino acid methionine is an exception because animals can produce both D and L isomers, and therefore its racemic mixture is typically obtained through chemical synthesis.
Amino acid production through protein hydrolyses processes depends on the availability of feedstocks such as animal feathers or hair.
The most common bio-based industrial pathway for amino acids (e.g. Lysine and monosodium glutamate) is fermentation (Figure 1). *Corynebacterium glutamicum* is the most used bacteria for amino acid manufacturing and it was first isolated for glutamate production in Japan. Afterwards, several *C. glutamicum* mutant strains were developed for the synthesis of lysine and other amino acids. Today, bacterial strain development continues in order to increase yields and strain resistance and to obtain new amino acids.

The feedstocks used in these fermentations are cane molasses, beet molasses (sugar crops) or starch hydrolysates [2]. Research is also targeting the development of new bacterial strains able to process other feedstocks such as lignocellulosic derivatives (including pentoses), lactate and glycerol [1]. The downstream processes of amino acid production include: (1) centrifugation or filtration to remove microbial cells; and (2) purification steps such as ion exchange and crystallisation.

Technology readiness levels

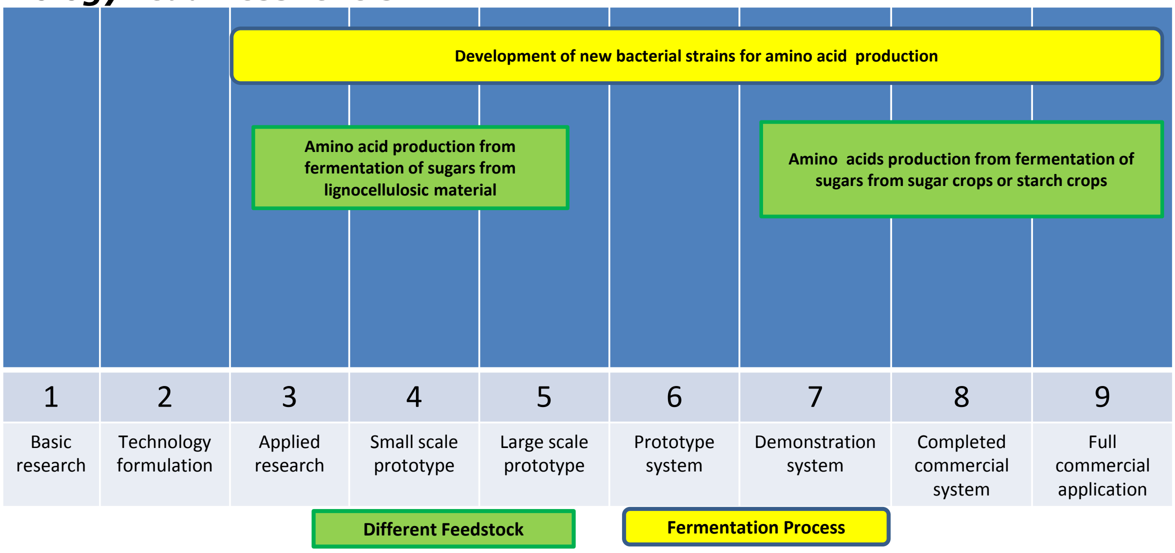

Figure 2. *Technology readiness levels for amino acids production*

SWOT (strengths, weaknesses, opportunities, threats)

S1. Amino acids have an important role in animal and human nutrition.	**W1.** The bio-based pathway of some important amino acids is still under development (e.g. Methionine) [1].
O1. Development of new bacterial strains for amino acid production. **O2.** Discovery of important functional amino acids that regulate key metabolic pathways in human and animal development [1].	**T1.** Biomass availability, competition with energy.

ENVIRONMENTAL DATA AND INFORMATION

The environmental performance of amino acids is summarised in Table 1, based on the available relevant LCA data for amino acids production through fermentation of sugars using different raw materials (corn, sugar cane and corn stover) and purification methods such as ion exchange chromatography, spray drying and adsorption.
Most of the values refer to the cradle-to-gate (see Figure 3) LCA approach. Climate change results were also found for cradle-to-grave systems, in the BREW project report [2].
For references [5] and [6] the LCA values of amino acid production were reported in studies of LCA for animal feed.
The available results were found mainly for climate change, freshwater eutrophication, acidification, land use, primary energy and non-renewable energy. No results were found for the remaining impact categories described in the environmental sustainability assessment methodology that was developed in the context of this project (see explanatory document).

System boundaries of the environmental assessment

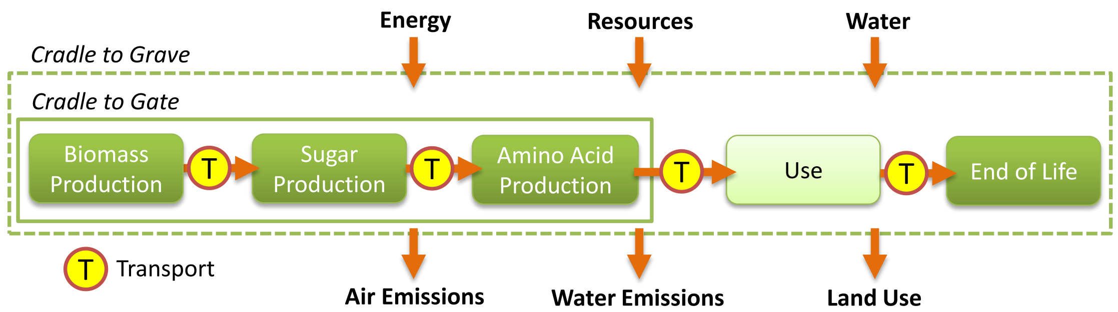

Figure 3. *LCA system boundaries for amino acids production and end-of-life*

1. **Cradle to gate:** includes resources extraction (energy, materials and water), transport and the production steps until the gate of the amino acid factory.
2. **Cradle to grave:** in addition to the cradle to gate activities, this system includes transport and distribution of the product, use of the amino acid and its end-oflife.

Environmental assessment: settings & impacts

Table 1. LCA results for one kg of amino acid in a cradle-to-gate system

Raw material input (feedstock)	Corn		Sugar cane	Mix: sugar, corn and wheat starch		Corn stover
Allocation/substitution	A ($-m), S	A ($-m), S	A ($-m), S			A ($-m), S
Geographical coverage	Germany, Denmark, France and EU	Germany, Denmark and France	Brazil	EU	EU	EU
Product	Lysine	Threonine	Lysine	Lysine/Threonine	Tryptophan/Valine	Lysine
References	[3,4]	[3]	[4]	[5,6]	[6]	[3]
Impact categories from environmental sustainability assessment methodology						
Climate change (kg CO_2 eq)	(1.9-8.9) ***1***	(13.0-19.7) ***2,3***	(-2.1-5.9) ***1,4***	4.3	8.5	(0.6-6.9) ***5***
Photochemical ozone formation (kg NMVOC eq)	(2.6E^{-2}-2.8E^{-2})[3]	(4.0E^{-2}-4.6E^{-2}) ***2***	N.A.	N.A.	N.A.	N.A.
Freshwater eutrophication (kg P eq)	(1.1E^{-3}-4.1E^{-3})[3]	(1.6E^{-3}-1.1E^{-2}) ***2***	N.A.	2.5E^{-3}	6.3E^{-3}	N.A.
Additional impact categories						
Acidification (kg SO_2 eq)	(2.7E^{-2}-3.0E^{-2})[3]	(5.5E^{-2}-6.4E^{-2}) ***2***	N.A.	1.3E^{-2}	2.7E^{-2}	N.A.
Fossil fuel consumption (kg oil eq)	(2.2-2.8)[1]	(5.6-7.6) ***2***	N.A.	N.A.	N.A.	N.A.
Land use (m^2)	(3.6-5.8)	(6.4-6.6) ***2***	(3.7-5.9)	2.3	4.7	(1.5-2.4) ***6***
Terrestrial ecotoxicity (kg 1,4-DB eq)	N.A.	N.A.	N.A.	2.3E^{-2}	4.6E^{-2}	N.A.
Primary energy (MJ)	(121.6-248.4)[4]***1***	N.A.	(139.3-273.2) ***1***	119	237.5	(125.9-254.5)
Non-renewable energy (MJ)	(65.9-189.1)[4]	N.A.	(4.8-136.8) ***4***	N.A.	N.A.	(31.9-160) ***5***

Notes: N.A.: not available. A.: allocation ($ — economic; E — energy; m — mass). S.: substitution. SE: system expansion.

The normalisations presented in Figure 4 were performed using the normalisation factors provided in the JRC methodology [7] and the ReCiPe normalisation factors (see explanatory document).

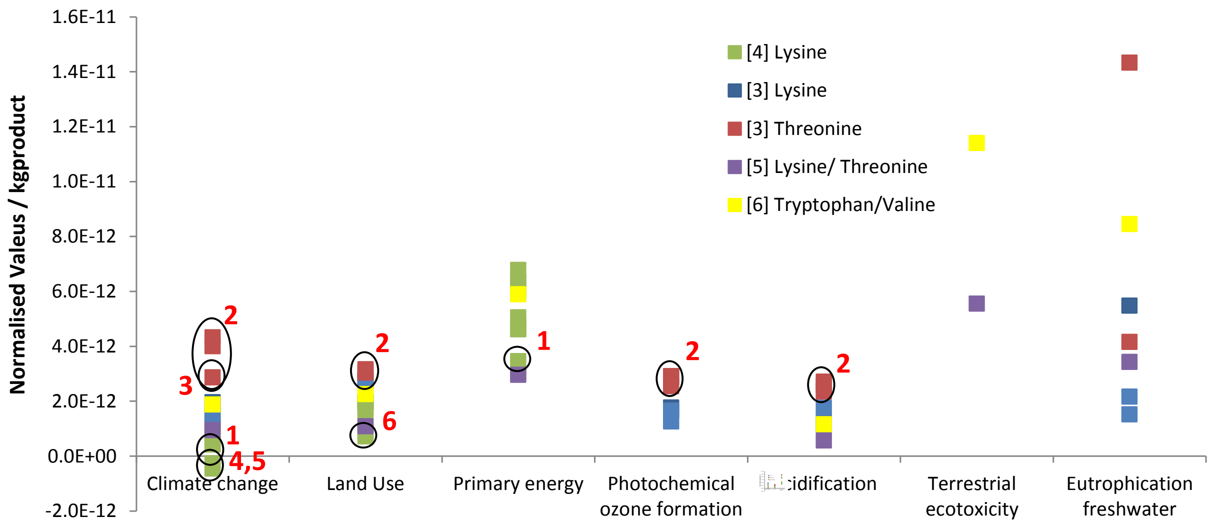

Figure 4. *Environmental performance expressed as normalised impact categories*

Comments and interpretation of environmental performance (Table 1 and Figure 4):

1. The authors of reference [4] reported lower climate change impacts and energy requirements for lysine produced using spray drying as a purification process when compared with ion exchange chromatography and adsorption.
2. The highest impacts were found for threonine when compared with other amino acids.
3. The authors in reference [3] reported lower climate change impacts for the production of threonine and lysine in France when compared with the production in Denmark and Germany. This is due to the lower impacts of the French electricity mix that has a higher share of nuclear power.
4. The lowest values found for climate change and non-renewable energy demand were obtained for the production of amino acids from sugar cane, owing to the high productivity yields of sugar and the credits assigned to the process [4] for the energy surplus, generated from bagasse burn.
5. Reference [4] considers burning of lignin-rich waste (obtained in the pre-treatment (hydrolyses) (see Bioalcohols via fermentation factsheet) of corn stover) to produce power and heat. This results in decreased impacts in non-renewable energy demand and climate change categories.
6. The land requirements for amino acids production from corn stover are lower compared to those from corn and sugar cane. This is due to the fact that economic allocation is applied [4], which assigns a lower economic value to corn stover than to corn kernels.

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ENVIRONMENTAL FACTSHEET: *Pulp and Paper*

PRODUCT INFORMATION

Pulp wood is a fibrous material used in a wide variety of applications from paper and paperboard production (main applications) to construction materials, and also more refined applications such as cellulose derivatives and nanocrystalline cellulose. Paper is a versatile material produced from pulp. It can be shaped into different products for applications such as printing, writing, journals, magazines, packaging and hygiene paper. The European pulp/paper industry is an important sector, with an annual turnover of EUR 75.3 billion [1].

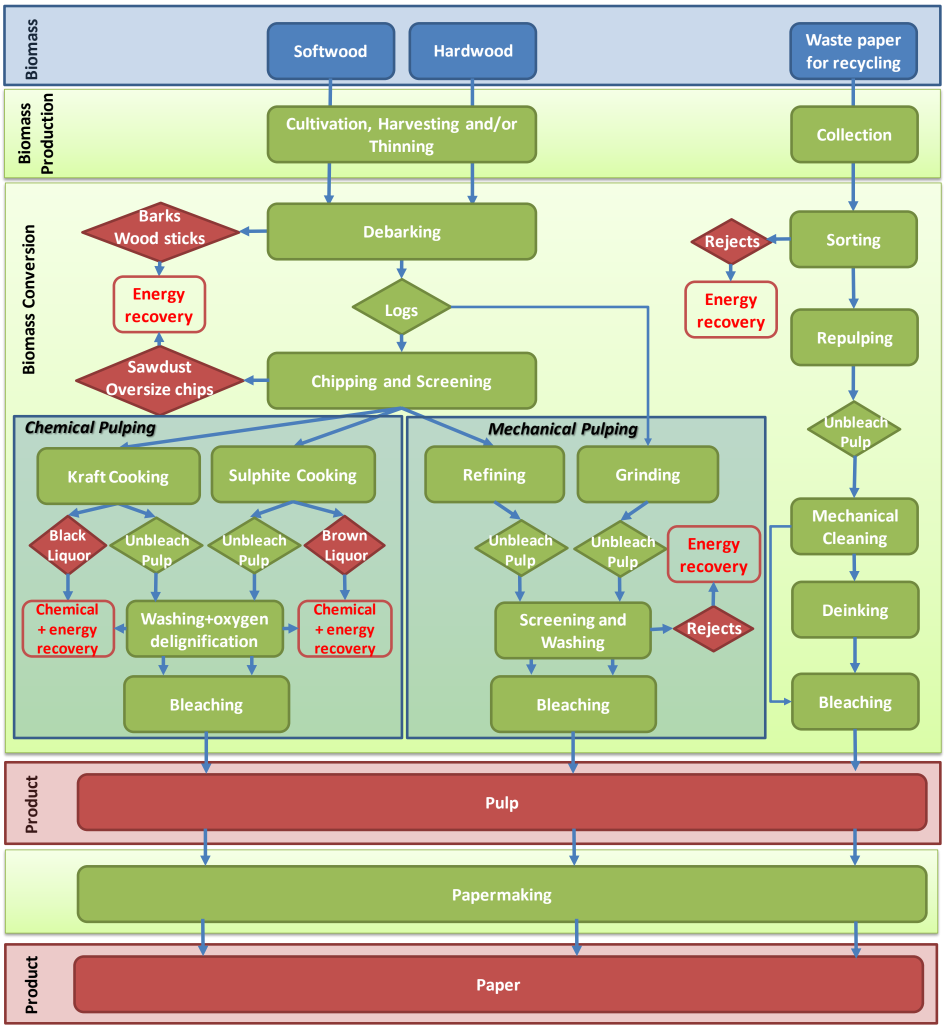

Figure 1. *Pulp and paper production chains [2]*

Pulp and paper can be obtained from different raw materials: hardwoods (such as eucalyptus, oak, poplar), softwoods (such as pine), recovered paper and other less used fibres (such as straw, grass, cotton and hemp) [2]. During the process of pulp and paper production several by-products and residues are used for energy recovery. The European pulp and paper industry generates more than half of its own electrical energy needs, and 95.2 % of the energy is obtained from combined heat and power facilities [1]. Additionally, in most cases the chemicals used in the process are produced and recovered within the pulp mill.

The wood used in pulp and paper mills is first debarked, cut down into small and uniform chips and screened to reject oversized chips (which can then be reprocessed). The bark, wood sticks, sawdust and oversized chips are burned for energy recovery. Pulp is produced by three types of pulping processes: chemical, mechanical and chemi-mechanical [2]. In chemical pulping wood chips are cooked in a digester (at high pressure and temperature) within a chemical solution (typically called white liquor) to dissolve lignin and hemicellulose and obtain cellulose fibres. Most of the pulp is produced via the so-called Kraft process, which uses white liquor composed of sodium hydroxide and sodium sulphide (alkaline conditions). Chemical pulping can also be performed using sulphite and bisulphite. This process can be performed at a wide range of pHs, resulting in pulps with different specifications. The process yields fibres with a lower strength than the Kraft process and the recuperation of the cooking chemicals is less efficient. After cooking, further delignification can be achieved through oxygen delignification and bleaching.

The cooking process produces a liquor – black liquor for the Kraft process and brown/red liquor for the sulphite process, which liquor is rich in lignin. Lignin is burned for energy recovery. Cooking chemicals are also recovered from the liquor.

In mechanical pulping higher pulp yields are achieved with low lignin removal. The pulps produced present lower strength and brightness than the chemical ones, and are typically used in newsprint due to their high ink absorption. Four methods exist in mechanical pulping: (1) stone groundwood, where log fibres are separated by rotating grinding stones; (2) refiner mechanical pulping, where wood chip fibres are separated through log friction between two rotation discs in the presence of water; (3) thermomechanical pulping, similar to mechanical pulping but performed under higher pressures and temperatures; (4) chemical-thermochemical pulping, which applies chemicals prior to the friction process [2,3]. In the mechanical processes the bleaching stage is different from the one in the chemical process. Its main objective is to reduce the colour of the pulp without compromising the high pulp yield of the mechanical process.

Pulp can also be produced by repulping waste paper (recycling). This is performed with hot water and chemicals, used for pH control and first separation of inks. Paper recycling also includes initial sorting, mechanical cleaning (weight and size screening of fibres), deinking (optional) and bleaching to obtain the pulp [2].

The bleached pulp slurry, acquired through any of the processes described above, can be dried and used for further transformation into different products or directly processed (without drying) in the factory for production of paper in the case of combined pulp and paper mills.

Paper production starts with the addition of paper additives to induce various paper properties, for example brightness, texture or opacity. Then the pulp slurry is processed in a papermaking machine, where paper roll is obtained upon a series of drying and pressing stages. The paper roll can be further refined through different paper finishing processes (include paper coating) to obtain the final paper properties [2].

Technology readiness levels

Several technologies are being developed to increase the efficiency of pulp and paper mills. A summary of some of these technologies and their technology readiness levels are presented in Figure 2. Development efforts are focused on: (1) increasing pulping efficiency (e.g. pre-treatment technologies for pulping, or organosolv pulping); (2) new energy and chemical recovery technologies (e.g. black liquor gasification); (3) increasing paper dewatering efficiency; (4) deinking and paper finishing processes.

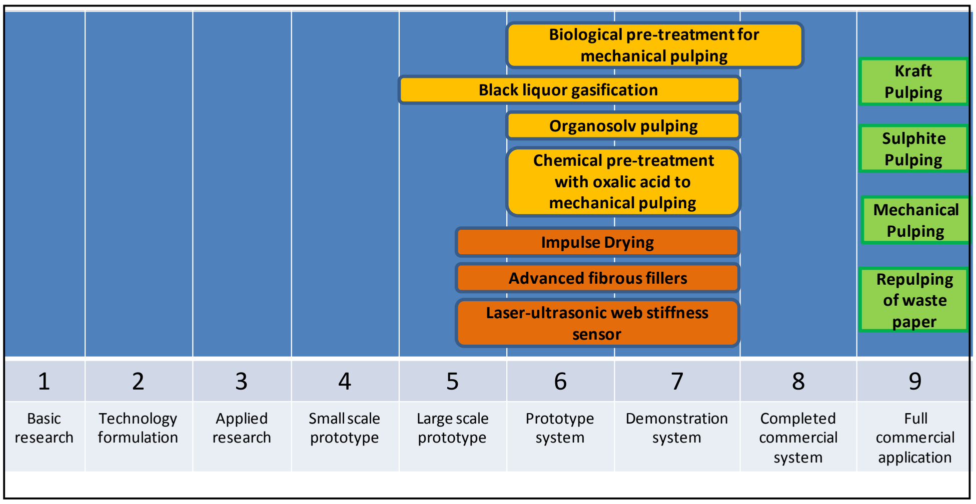

Figure 2. *Technology readiness levels for pulp and paper production [2-5]*

SWOT (strengths, weaknesses, opportunities, threats)

S1. Well-established bio-based industry. **S2.** Highly developed and optimised technology for *in situ* energy and chemical recovery.	**W1.** Processes for pulp/paper production are energy intensive.
O1. Development of technologies that can increase energy efficiency. **O2.** Development of biorefinery concepts for pulp/paper mills, i.e. incorporate the manufacturing of other bio-based products (such as lignin) and bioenergy.	**T1.** Biomass availability, competition with energy and other materials. **T2.** Declining paper demand due to the increasing digital information support.

ENVIRONMENTAL DATA AND INFORMATION

The environmental performance of pulp and paper is summarised in Table 1, based on the available relevant LCA data for the different products. Most of the values refer to a cradle-to-gate LCA approach, including the resource extraction (energy, materials and water), transport and pulp/paper production steps until the gate of the paper mill. Reference [9] considers a cradle-to-grave LCA approach where the paper final disposal scenario includes landfilling, incineration, recycling and composting.

Environmental assessment: settings & impacts

Table 1. LCA results for one kg of product

Product	Newsprinting paper	Super calendered	White paper		Pulp		Testliner paper
Raw material input (feedstock)	Unspecified wood	Unspecified wood	Eucalyptus		Eucalyptus	Hemp	Waste paper
LCA boundaries	Cradle to gate*	Cradle to gate*	Cradle to gate	Cradle to grave	Cradle to gate	Cradle to gate	Cradle to gate
Geographical coverage	Norway	Norway	Brazil, Slovakia	Portugal	Spain, Portugal	Spain, Portugal	Romania
References	[6]	[6]	[7,8**]	[9]	[10,11]	[11,12]	[13***]
Impact categories from environmental sustainability assessment methodology							
Climate change (kg CO_2 eq)	0.2-0.6	0.3 – 0.6	0.8 – 1.4	1.8 – 2.4	0.4 – 0.5	7.0 – 8.5	0.7 – 0.8
Ozone depletion (kg CFC-11 eq)	$2.6E^{-8} – 5.9E^{-8}$	$3.2E^{-8} – 6.0E^{-8}$	$1.7E^{-8}$ [7]	N.A.	$3.5E^{-8}$ [10]	$4.9E^{-4}$ [12]	N.A.
Ecotoxicity (CTUe)	N.A.	N.A.	$3.4E^{-2}$ [7]	N.A.	N.A.	N.A.	N.A.
Human toxicity — cancer effects (CTUh)	N.A.	N.A.	$9.0E^{-11}$ [7]	N.A.	N.A.	N.A.	N.A.
Human toxicity — non-cancer effects (CTUh)	N.A.	N.A.	$7.4E^{-9}$ [7]	N.A.	N.A.	N.A.	N.A.
Ionising radiation (kg U235 eq)	$3.7E^{-2} – 7.7E^{-1}$	$6.8E^{-2} – 6.4E^{-1}$	N.A.	N.A.	N.A.	N.A.	N.A.
Photochemical oxidation (kg NMVOC)	$2.7E^{-3} – 3.8E^{-3}$	$2.3E^{-3} – 3.2E^{-3}$	N.A.	N.A.	N.A.	N.A.	N.A.
Freshwater eutrophication (kg PO_4 eq)	$1.5E^{-4} – 2.8E^{-4}$	$2.6E^{-4} – 3.4E^{-4}$	N.A.	$1.8E^{-3} – 1.9E^{-3}$	$7.0E^{-4}$ [10]	$3.9E^{-2}$ [12]	
Marine water eutrophication (kg N eq)	$2.1E^{-4} – 2.7E^{-4}$	$1.5E^{-4} – 2.1E^{-4}$	N.A.	N.A.	N.A.	N.A.	$6.4E^{-4} – 7.5E^{-4}$
Additional impact categories							
Freshwater ecotoxicity (1,4-DB eq)	$2.3E^{-3} – 3.4E^{-3}$	$2.5E^{-3} – 3.3E^{-3}$	N.A.	N.A.	$3.2E^{-2}$ [10]	0.3 [12]	0.2
Marine ecotoxicity (1,4-DB eq)	$1.5E^{-3} – 2.7E^{-3}$	$2.2E^{-3} – 3.0E^{-3}$	N.A.	N.A.	N.A.	N.A.	N.A.
Terrestrial ecotoxicity (1,4-DB eq)	$2.9E^{-4} – 8.1E^{-4}$	$9.0E^{-5} – 3.8E^{-4}$	N.A.	N.A.	$9.4E^{-4}$ [10]	$2.6E^{-2}$ [12]	N.A.
Human toxicity — non-cancer effects (kg 1,4-DB eq)	$9.5E^{-2} – 2.1E^{-1}$	$1.3E^{-1} – 2.1E^{-1}$	N.A.	N.A.	$3.9E^{-2}$ [10]	1.1 [12]	N.A.
Particulate matter formation (kg PM10 eq)	$9.3E^{-4} – 1.7E^{-3}$	$8.7E^{-4} – 1.4E^{-3}$	N.A.	N.A.	N.A.	N.A.	N.A.
Photochemical oxidation (kg C_2H_4 eq)	N.A.	N.A.	$2.4E^{-4}$ [7]	$9.6E^{-5} – 3.5E^{-4}$	$1.4E^{-4} – 1.9E^{-4}$	$1.0E^{-3} – 1.2E^{-3}$	$8.8E^{-4} – 1.0E^{-3}$
Acidification (kg SO_2 eq)	$2.6E^{-3} – 4.3E^{-3}$	$2.4E^{-3} – 3.5E^{-3}$	$1.1E^{-2}$ [7]	$1.4E^{-2} – 1.5E^{-2}$	$2.3E^{-3} – 2.8E^{-3}$	$8.6E^{-3} – 3.9E^{-2}$	$1.6.E^{-2} – 1.8E^{-2}$
Non-renewable energy (MJ)	11.3 – 23.5	12.4 – 20.6	3.1 – 24.5	16.2 – 19.6	N.A.	N.A.	N.A.

* Forest management excluded from the system boundaries. **Different coatings of paper.*** Papers with different impurities.

Note: **Super calendered** is a dense, smooth and gross paper produced in a calender machine. **Testliner** is a strong paper produced from recycling paper used in packaging.

The normalisations presented in Figure 3 were performed using the normalisation factors provided in the JRC methodology [14] or the ReCiPe normalisation factors (see explanatory document).

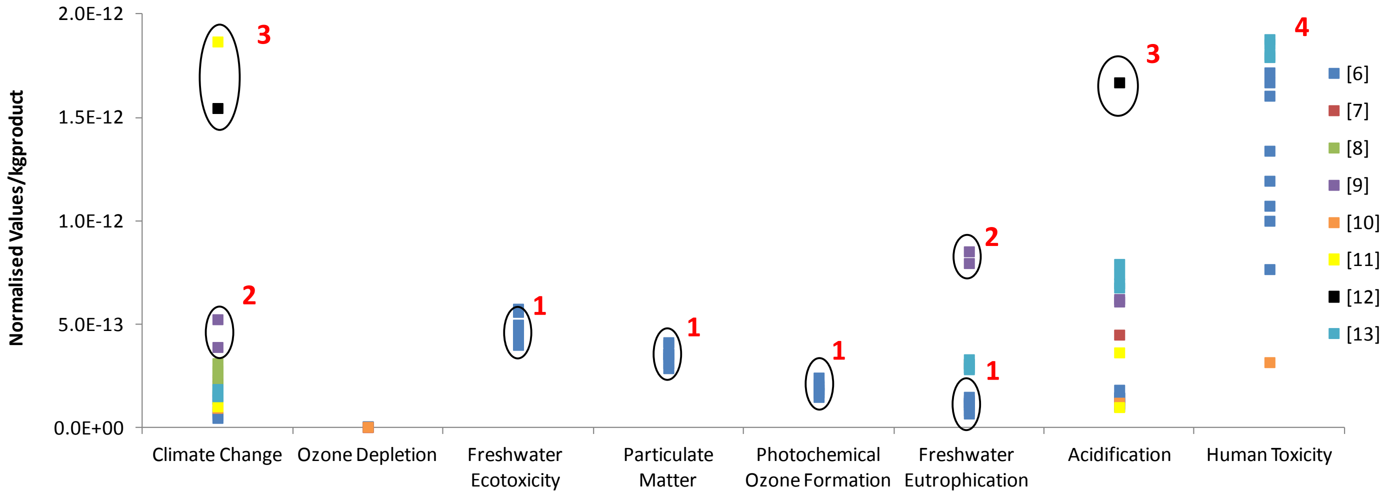

Figure 3. *Environmental performance expressed as normalised impact categories*

Comments and interpretation of environmental performance (Table 1 and Figure 3):

1. The reported impacts [6] for the production of newsprinting paper and super calendered paper showed no substantial differences.
2. Higher impacts were associated with cradle-to-grave systems because more life cycle stages were considered when calculating the impacts.
3. Higher impacts were associated with the use of hemp fibres for the production of pulp compared to the use of wood fibres.
4. When reported, human toxicity appears to have a high relative impact when normalised with the overall EU domestic impacts.

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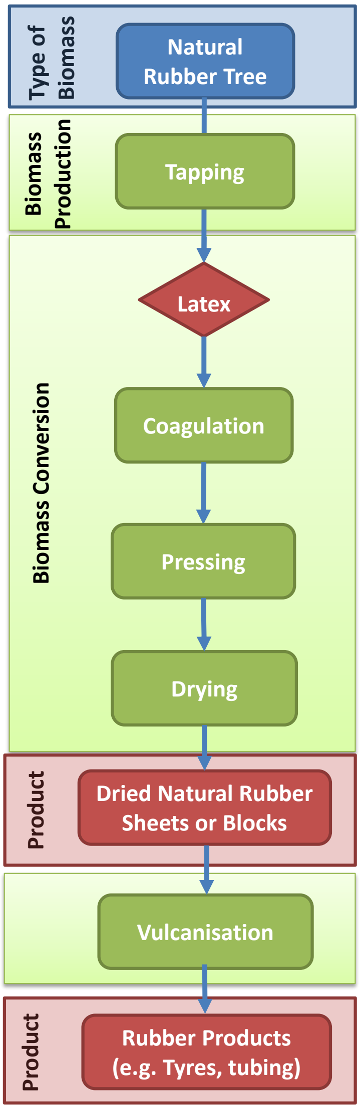
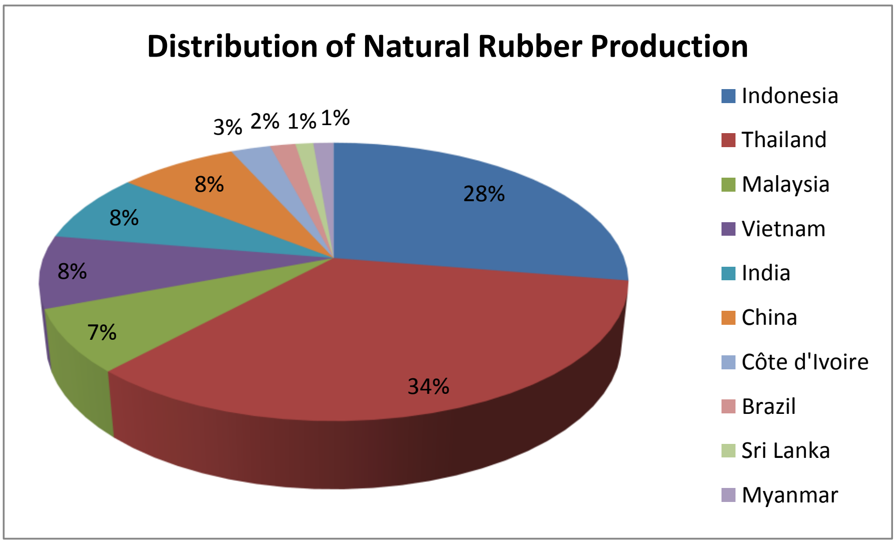
ENVIRONMENTAL FACTSHEET: ***Natural Rubber***

RAW MATERIAL INFORMATION

Natural rubber is manly harvested (rubber tapping) from the rubber tree *Hevea brasiliensis* in the form of latex, which is a white emulsion. Other tree species can also be sources of latex but its applicability is not as straightforward as the one extracted from *Hevea brasiliensis*.
Natural rubber is extracted by making a cut in the rubber tree bark. The rubber can start to be harvested when the tree achieves at least 45 cm in circumference which corresponds to a tree age of about 6 years and it can last until the tree reaches around 30 years. After this period the tree can be harvested to provide wood for furniture.
Hevea brasiliensis is a native species of the Amazon region but it has been introduced in several other regions for rubber production. At the moment Southeast Asian countries, mainly Indonesia and Thailand (see Figure 2 a, source FAOstat), are the biggest global producers and suppliers of rubber to the EU.
After tapping, the latex can be processed into different rubber products and grades. Traditionally it is coagulated, using formic or acetic acid and then pressed between pairs or rollers to form sheets or crepes. In the final process natural rubber is washed and dried (Figure 1).





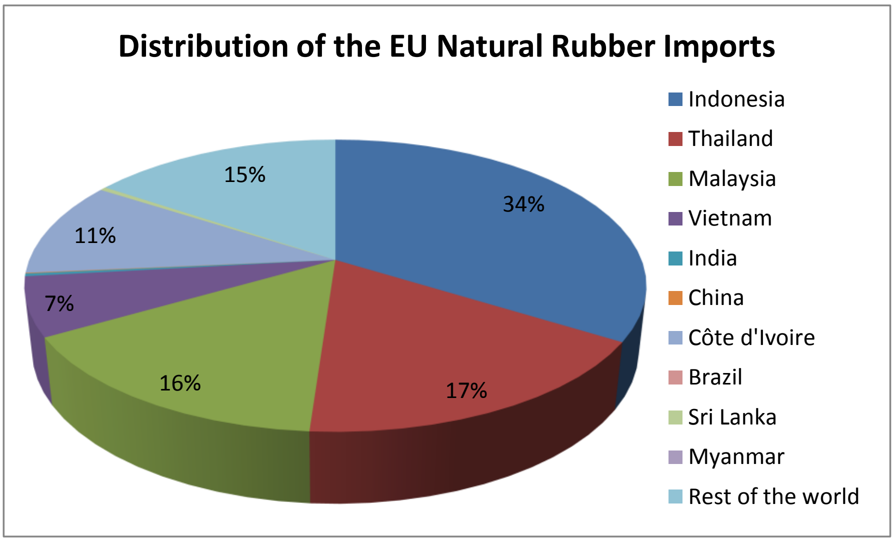


Figure 1. *Natural Rubber production chain.* ***Figure 2.*** Distribution of Natural rubber production ***(a)*** and EU Imports ***(b)*** *by origin*.

Dried natural rubber is usually vulcanised, a chemical process that involves heating and addition of sulfur or other cross-linking additives and will improve the elasticity and durability of the untreated natural rubber. Volcanised rubber is then further processed into different rubber products.

Natural rubber is mainly used in the production of tyres, responsible for about 75% of the EU total consumption. The remaining 25% is spent in tubing, foot wear, construction materials and food contact materials. On average, a car tyre contains 15% of natural rubber, while a truck tyre contains an average of 30% [1].

The tyre manufacturing is an important industrial sector in the EU. The members of the European Tyre & Rubber Manufacturers Association produced 4.67 million tonnes of tyres in 2013 accounting for 20% of world tyre production. Europe is completely dependent upon imports of natural rubber and the detailed distribution of supplying countries is presented in Figure 2 b (Source EUROSTAT).

SWOT (Strengths, Weaknesses, Opportunities, Threats)

S1. Natural rubber is widely used in tyre production. **S2.** Tyre industry is an important industry in the UE representing 20% of the world tyre production in 2013.	**W1.** The supply of natural rubber is totally dependent on extra-EU countries.
O1. Creation of certification schemes to guaranty sustainable production of natural rubber (e.g. Sustainable Natural Rubber Initiative (SNR-i)).	**T1.** Natural rubber supply may be highly affected by a fungal disease *Microcyclus ulei* (South American leaf blight). **T2.** Competition with palm oil plantations for land availability.

ENVIRONMENTAL DATA AND INFORMATION

The environmental performance of natural rubber production is summarised in Table 1, based on the available relevant LCA data for the various products. Different system boundaries are reported in the literature and described in Figure 3.

Cradle to gate: includes resource extraction (energy, materials and water), natural rubber forest maintenance, transport, tapping and the production steps until the exit gate of the natural rubber processing factory.

Gate to gate: includes resource extraction (energy, materials and water) and all the production steps required in the natural rubber processing factory.

Cradle to farm gate: includes resource extraction (energy, materials and water), natural rubber forest maintenance, transport and tapping activities.

Most of literature studies on natural rubber report only climate change indicators and the majority consider only emissions of CO_2, N_2O and CH_4. Reference [4] compares the impacts when natural rubber plantations replace previously existing forests (including direct Land Use Change emissions (dLUC)) and when such a displacement doesn't occur (no dLUC).

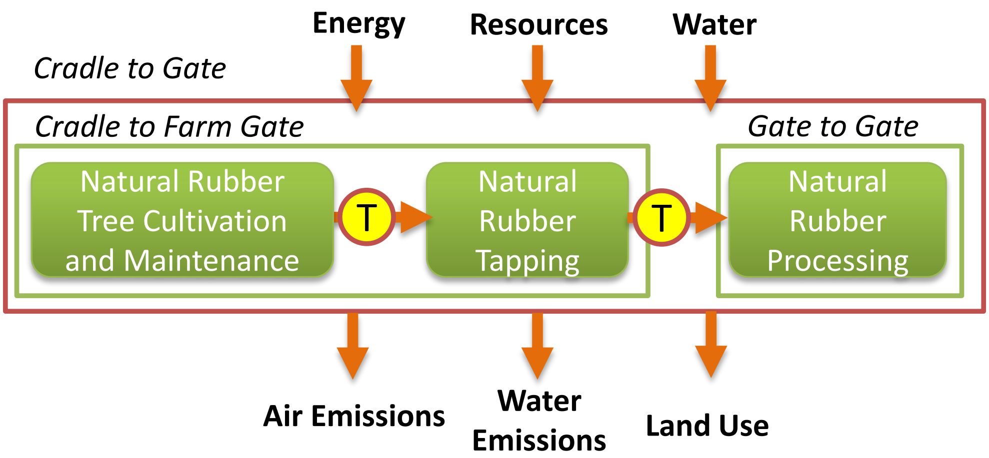


Figure 3. *LCA system boundaries for natural rubber production.*

Environmental assessment: settings & impacts

Table 1. LCA results for different natural rubber raw products

Product	Fresh latex	Concentrated latex	Concentrated latex		Block rubber (STR 20)		Ribbed smoked sheet		Rubber band
Geographical coverage	Thailand	Thailand	Thailand		Thailand		Thailand		Sri Lanka
Functional unit	one ha of rubber plantation during 25 years	1 kg of product	1 kg of product		1 kg of product		1 kg of product		1 kg of product
LCA boundaries	Cradle to farm gate	Gate to gate	Cradle to gate		Cradle to gate		Cradle to gate		Gate to gate
			dLUC	no dLUC	dLUC	no dLUC	dLUC	no dLUC	
References	[2]	[3]	[4]	[4]	[4]	[4]	[4]	[4,5]	[6]
Impact categories from environmental sustainability assessment methodology									
Climate change (kg CO_2 eq)	0.032	0.16- 0.17 ***1***	13 ***3***	0.54	13 ***3***	0.7	21 ***3***	0.4-0.7	1.2-1.5 ***2***
Freshwater eutrophication (kg PO_4 eq)	N.A.	$2.1E^{-4} – 2.1E^{-4}$	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Additional impact categories									
Carbon stock (kg CO_2 eq)	0.574	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Human toxicity — non-cancer effects (kg 1,4-DB eq)	N.A.	$3.6E^{-2} – 3.8E^{-2}$	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Photochemical oxidation (kg C_2H_4 eq)	N.A.	$7.6E^{-5} – 7.6E^{-5}$	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Acidification (kg SO_2 eq)	N.A.	$1.6E^{-3} – 1.6E^{-3}$	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Non-renewable energy (MJ)	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	8	N.A.

The normalisations presented in Figure 4 were performed using the normalisation factors provided in the JRC methodology [7] or the ReCiPe normalisation factors (see explanatory document).

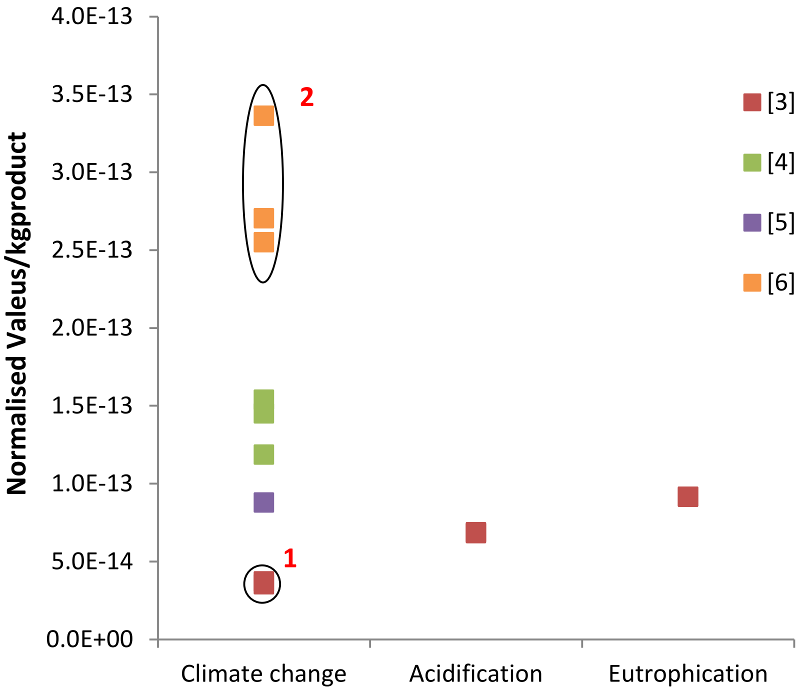


Figure 4. *Environmental performance expressed as normalised impact categories*

Comments and interpretation of environmental performance (Table 1 and Figure 4):

1. Lower impacts are associated with studies that only report gate to gate activities for the production of crude natural rubber derivatives such as concentrate latex.
2. Reference [6] reports the highest impacts because it considers the manufacturing of a finalized natural rubber product "rubber bands".
3. The highest impacts are associated with the systems that consider direct land use change impacts due to displacement of natural forests by commercial rubber monoculture plantations. Such a displacement raises also concerns related to loss of biodiversity in natural rubber cultivation areas.

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Bioenergy Pillar

ENVIRONMENTAL FACTSHEET: **Smaller-scale heat generation via combustion**

PROCESS INFORMATION

Domestic heating is the most classic energy application of biomass (Figure 1), and the technologies are well known and established. The main characteristics of biomass burning are as follows:

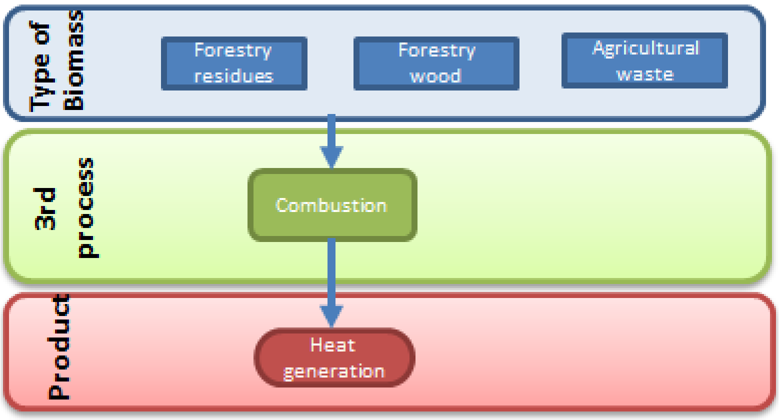


Figure 1. *Flowsheet of the **combustion** process*

- During burning, different reactions occur simultaneously: heating and drying, devolatilisation, gasification and combustion (i.e. tar, char and gases oxidation) [1].
- The pre-processing phase (i.e. drying, pelletising, chipping, etc.) is important since high combustion efficiency is obtained at low moisture content and with small-sized biomass particles.
- Wood is the most common feedstock for domestic heating. Agricultural residues such as straw can also be used [2].
- Other forms of biomass combustion are: larger-scale heat generation (i.e. district and process heat supply) see Larger-scale heat generation via combustion factsheet), power generation (see Electricity generation via combustion factsheet) and combined heat and power production (see CHP via combustion factsheet).
- The ash left after biomass combustion can be used as low-grade fertiliser, provided it is not mixed with other types of ash (e.g. coal ash). Otherwise it must be treated as a municipal waste.

Technological overview

For domestic heating there is a range of technological solutions (Fig. 2). The thermal efficiencies lie within a broad spectrum — from below 10 % (and even sometimes negative) for simple fireplaces to the most advanced heating systems, which may reach up to 90 % thermal efficiency owing to the use of automatic fuel in-feed, catalytic gas cleaning and standardised fuel (e.g. chips, pellets or briquettes) [3,4]. Depending on the feedstock used (log / briquettes, pellets or chips) the smaller-scale burning systems can be classified as follows [5]:

- Log stoves and fire inserts are traditional and simple technologies that release energy by radiation and convection. They are fed manually, mainly with firewood (i.e. logs) or briquettes. Modern stoves achieve efficiencies of around 70-80 % and are available with outputs from 3.5 to 20 kW. They can be equipped with a catalytic combustor to reduce emissions and can include a back boiler option to produce heat water. A special design is the heat-storing stove, which can accumulate heat and radiate it over a long period after the fire has gone out.
- Log boilers offer very high efficiency (up to 90 %). Logs are fed manually and burned in a high-temperature environment. The energy produced is stored as high-temperature water that can provide space heating through a heat exchange system and/or domestic hot water. Their nominal power output can be from 20 kW up to about 70 kW, i.e. they can be considered as a medium-sized technology for heating single large buildings.
- Pellet stoves play a similar role to log stoves. Pellet stoves spread the heat through convection rather than radiation. Most of them are fully automatic, presenting automatic ignition and feeding with pelletised bio-material — mostly from wood, but recently also from straw. Some electricity is needed for the motorised systems. It is also possible to add a back boiler. Pellet stoves run at over 90 % efficiency and their nominal power output can reach 12-20 kW.
- Pellet boilers are also similar to log boilers. Boilers are a more recent technology with continuous automatic combustion of pelletised bio-material. Their efficiency can be over 90 % and the nominal thermal output starts from 15 kW.
- Chip-fired appliances include pre-ovens, burners and boilers. Due to the more sophisticated technological configuration, they are more suitable for larger scales compared the other technologies. The nominal output usually ranges from 20-40 kW, but it may well reach several MW in power stations (see Electricity generation via combustion factsheet). These appliances use

automatic operation and the emissions tend to be lower due to the continuous combustion and more sophisticated combustion control systems.

Emissions usually decrease as the size of the combustion installation increases owing to improved cost-effective possibilities for process control and flue gas cleaning. Particulate emissions from smaller-scale wood combustion can be significant. It is important to use good-quality wood fuel and to optimise the combination between fuel characteristics and combustion technology.

Concerning the feedstock, wood (in all possible forms: logs, briquettes, pellets and chips) is the most used. Pellets and chips allow the use of automated feeding systems, while logs must be manually fed. The energy density of pellets is higher comparing with logs and chips, and hence on equal terms pellets take up less storage space. Wood chips are more variable in size and moisture compared to pellets, but on the other hand chips require less processing and thus are cheaper. Straw can also be used in stoves and boilers for domestic heating after being pre-processed into pellets or briquettes.

Technology readiness levels

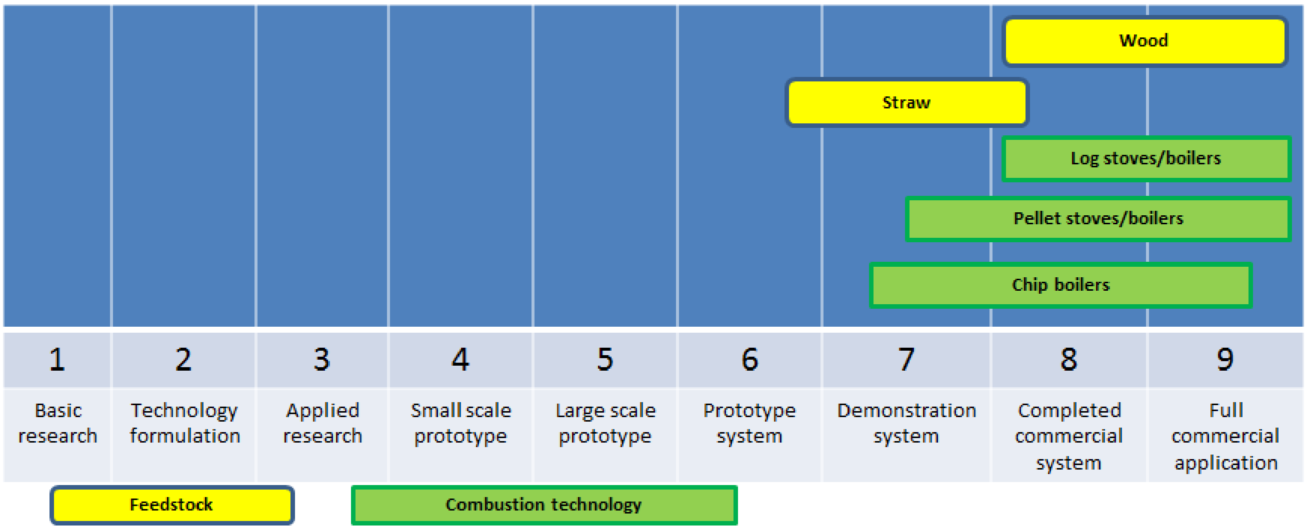


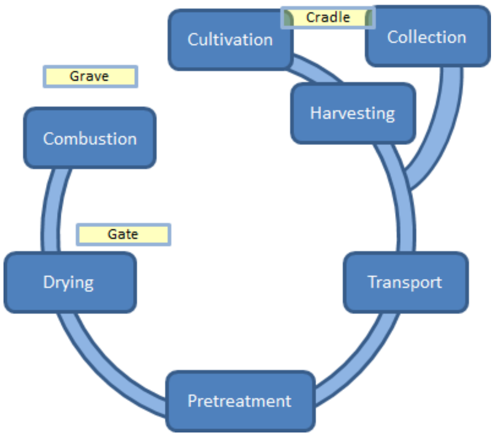
Figure 2. *Technology readiness levels for smaller-scale combustion of biomass for heating*

SWOT analysis (Strengths, Weaknesses, Opportunities, Threats)

S1. Mature technology. **S2.** Costs of primary energy obtained from fossil fuels are typically higher. **S3.** Modular equipment and easy installation. **S4.** Feedstock at commercial scale.	**W1.** Particulate emissions can be significant. **W2.** Quality and characteristics of the fuel are often variable, which prevents efficient burning. **W3.** Competition with other non-energy uses of wood (e.g. for furniture) and straw.
O1. Renewable domestic heat incentive schemes — subsidies framework. **O2.** Possible use of pure biomass ashes as fertiliser.	**T1.** High initial investment. **T2.** Some feedstocks, such as straw, are challenging and need further development.

ENVIRONMENTAL DATA AND INFORMATION

System boundaries of the environmental assessment



1. **Cradle to grave**: includes cultivation (with production of ancillary products), harvesting or collection (in case other feedstock), transport, pre-treatment (i.e. briquetting, pelletising, chipping), drying and storage and the combustion.
2. **Cradle to gate**: same boundaries as cradle to grave, excluding the combustion phase.

Figure 3*: LCA system boundaries and stages for smaller-scale heating production from biomass*

Environmental assessment: settings & impacts

Table 1. LCA results for functional unit (FU) 1 MJ			
Raw material input (feedstock)	Wood logs	Wood pellets	Wood chips
LCA boundaries	1	1	1
Allocation/substitution	A (NA – S)	S	A (NA)
Geographical coverage	Italy-Norway	Italy	Spain
Product	Heat		
References	[6],[7]	[7]	[8]
Impact categories from environmental sustainability assessment methodology			
Climate change (kg CO_2 eq)	-4.49E-2 – 3.06E-2	-5.30E-2	3.06E-2
Ozone depletion (kg CFC-11 eq)	N.A.	N.A.	7.5E-11
Freshwater eutrophication (kg P eq)	6.52E-6 – 9.06E-6	N.A.	6.97E-6
Additional impact categories			
Acidification (kg SO_2 eq)	3.89E-5 – 1.44E-4	8E-5	1.25E-4
Photochemical oxidation (kg C_2H_4 eq)	2.49E-4 – 1.53E-3	3.74E-5	3.61E-5
Freshwater ecotoxicity (1,4-DB eq)	N.A.	N.A.	8.33E-6
Terrestrial ecotoxicity (1,4-DB eq)	N.A.	N.A.	5.56E-6
Human toxicity (1,4-DB eq)	N.A.	N.A.	3.06E-4
Marine aquatic ecotoxicity (1,4-DB eq)	N.A.	N.A.	2.22
Human toxicity, cancer (kg Benzene eq)	2.08E-4 – 1.06E-3	N.A.	N.A.
Human toxicity, non-cancer (kg Toluene eq)	1.28E-1 – 3.33E-1	N.A.	N.A.

Note: All values were transformed to the functional unit (MJ).
A = allocation ($ — economic; E — energy; m — mass; NA — no allocation). S = substitution. N.A. = not available.
The normalisation presented in Figure 4 is performed using the normalisation factors described in the JRC methodology [9] and ReCiPe normalisation values (see explanatory document).

Comments and interpretation of the environmental performance

1. The highest normalised impact values are reported for human toxicity where particulate matter emissions are considered.
2. Negative impact values (i.e. environmental benefits) in climate change are reported in reference [7] because emissions avoided in comparison with fossil fuels are credited to the system.
3. The lowest impact values are reported for high-efficiency technologies such as pellet stoves and chip boilers.
4. The highest impact values in reference [7] are reported for open fireplaces, whose efficiency is around 20 %.

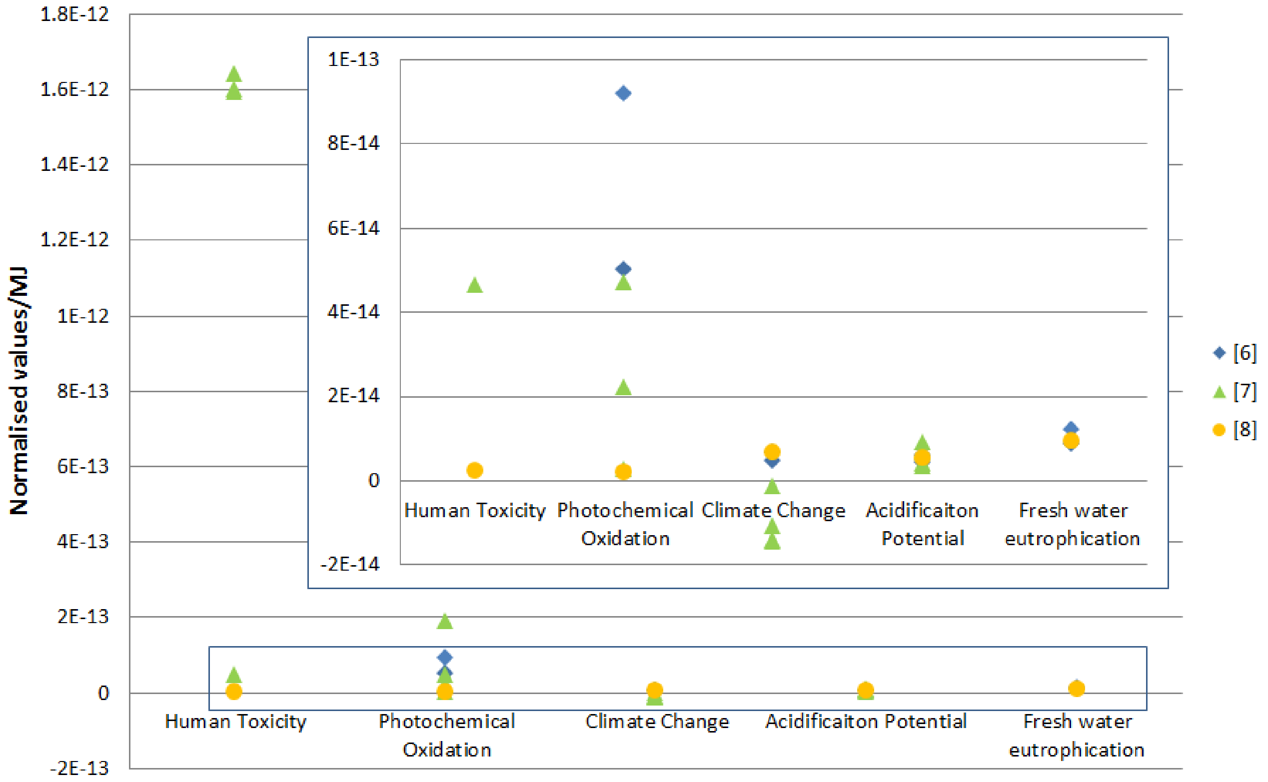


Figure 4. *Environmental performance expressed as normalised impact categories*

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FP7 project references in CORDIS (http://www.cordis.europa.eu)
POPFULL
ULTRALOWDUST
BIOCHIPFEEDING

ENVIRONMENTAL FACTSHEET: **Larger-scale heat generation via combustion**

PROCESS INFORMATION

Biomass is a feasible feedstock for large-scale heat generation. It can be used for space and water heating in commercial applications, as process heat in industrial applications (i.e. manufacturing, agriculture and other industries) or for district heating in the form of hot water/steam [1]. The main characteristics of the process (Fig. 1) are as follows:

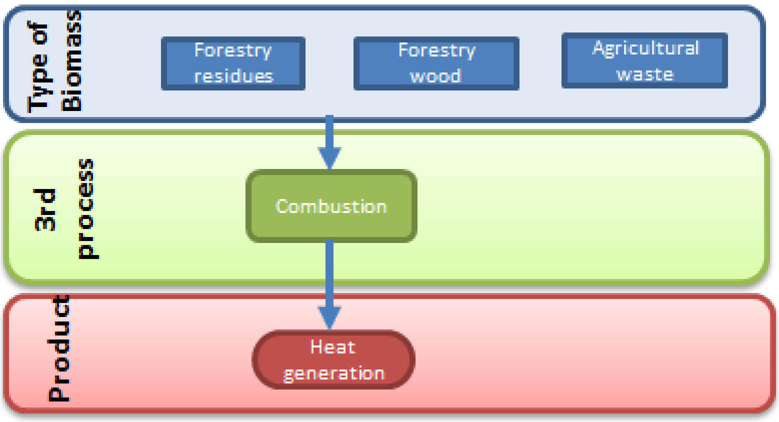


Figure 1. *Flowchart of the* ***combustion*** *process*

- Wood is the most common feedstock for large-scale heating. Others like agricultural wastes and dedicated herbaceous crops are less proven options [2].
- Different pre-processing steps can be used to reduce the particle size, such as pelletising or chipping to optimise burning (by improving the contact between the fuel and oxygen).
- The moisture content is a key challenge in the combustion process. Drying is usually needed to optimise the process. Moisture content higher than 55-60 % makes the combustion process rather inefficient.
- The main components of the heat generation system are the storage place, the fuel-feeding system, the combustion chamber and boiler, the heat exchanger and the pollution control system [3].
- Other applications of biomass combustion are smaller-scale heat production (e.g. household) (see Smaller-scale heat generation via combustion factsheet), power generation (see Electricity generation via combustion factsheet) and combined heat and power production (see CHP via combustion factsheet).
- The neat (not mixed with other types of ashes, e.g. coal ash) biomass ashes left after combustion can be used as fertilised for agriculture.

Technological overview

In large-scale heating systems manual fuel-feeding is no longer an option due to prohibitive costs and low efficiency. Fully automated operation systems are usually installed. Batch-type systems can eventually be used for straw-bale combustion [2]. There are different combustion configurations and technologies [4], as described below:

- Fixed-bed combustion is the most simple and most used technology. Biomass is burned in a fixed bed in the presence of the primary air, and the gases produced are burned, usually in a separated zone with added secondary air. Different technologies are available.
    - Grate furnaces: can be fixed, inclined, moving, travelling, rotating, vibrating and cigar burners. They are able to process various types of fuels including those with a high moisture and ash content, and also mixtures of different fuels simultaneously (e.g. woody with herbaceous). Depending on the flow directions of the fuel and the gas, they can be counter-current flow, co-current flow or cross-flow.
    - Underfeed stokers: more suitable for high-moisture, low-ash content and small-sized fuels. They provide easy control of the fuel supply. Normally installed for smaller and medium-sized systems.

  Most often, the boiler is situated above the grate.
- Fluidised bed combustion (FB) is a more recent technology concept for biomass that consists in burning the biomass in a solid-bed material that is fluidised, passing through it the primary combustion air. They can deal with various fuel mixtures (e.g. wood and straw) due to the good mixing achieved. FB is potentially interesting for large-scale applications, especially when heat generation is coupled with electricity generation. Depending on the fluidisation velocity, there are two different technologies: circulating fluidised bed (CFB) or bubbling fluidised bed (BFB). FB technologies have higher particulate emissions compared to fixed-bed combustion.

- Dust combustion is used for fuel available in the form of wood powder (diameter < 2 mm). This is burned with the primary air in a quick and efficient process while it is in suspension. The gas produced is burned with secondary air. The main drawback of this concept is that fine shredding of biomass is challenging and energy intensive, i.e. the overall energy efficiency may be disadvantageous.

For efficient heat generation, the combination between fuel properties and combustion technology ought to be optimised. In the heat exchanger, the hot flue gases produced in the combustion zone transfer the heat to another medium (typically hot water or steam) that is used for delivering the heat to the final users. Large-scale heating usually requires the installation of pollution control devices, mainly for the reduction of fly ashes and particulate matter, which can be addressed through multicyclones and bag filters.

Concerning the type of pre-processed biomass fuel (Fig. 2), less processed materials such as firewood or briquettes are less suitable because automatic systems may not handle them. Pellets and, mostly, chips are used within this application. Herbaceous biomass and straw can also be used with prior pre-treatment (such as washing to reduce polluting and corrosive elements) [5].

Technology readiness levels

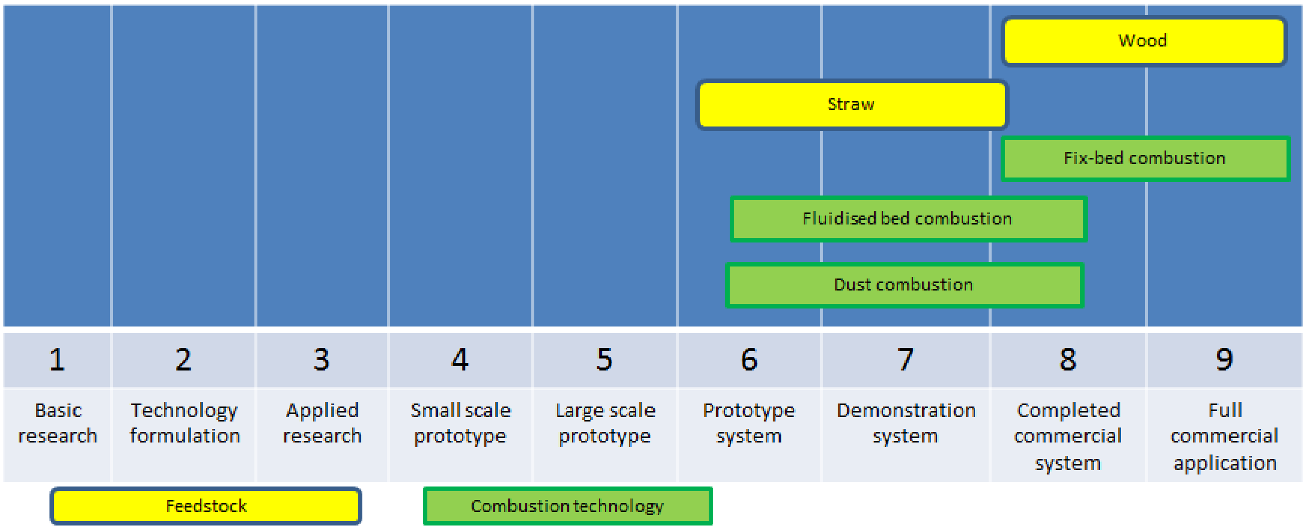


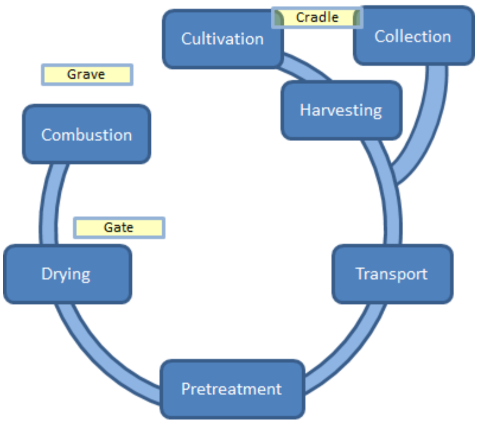
Figure 2. *Technology readiness levels for larger-scale combustion of biomass for heating*

SWOT analysis (Strengths, Weaknesses, Opportunities, Threats)

S1. Heat generation is the most efficient energy use of biomass (around 85 %). **S2.** Economies of scale. **S3.** Fuel quality is less important in large-scale applications compared to small-scale appliances.	**W1.** Heat distribution losses are typically high. **W2.** Require low-cost, locally sourced biomass in order to be cost-efficient. **W3.** Capital intensive to install.
O1. Higher concentration of heat consumers leads to lower distribution losses.	**T1.** No EU initiatives for promoting bioheating.

ENVIRONMENTAL DATA AND INFORMATION

System boundaries of the environmental assessment



1. **Cradle to grave**: includes cultivation (with production of ancillary products), harvesting or collection (in case other feedstock), transport, pre-treatment (i.e. pelletising, chipping), drying and storage, and combustion.
2. **Cradle to gate**: same boundaries as cradle to grave, excluding the combustion phase.

Figure 3*. LCA system boundaries and stages for larger-scale heat generation from biomass*

Environmental assessment: settings & impacts

Table 1. LCA results for functional unit (FU) 1 MJ		
Raw material input (feedstock)	Wood chips	Wheat straw
LCA boundaries	1	1
Allocation/substitution	A(NA)	A(NA)
Geographical coverage	France	Denmark
Product	Heat	
References	[6]	[7]
Impact categories from environmental sustainability assessment methodology		
Climate change (kg CO_2 eq)	8E-3 – 1.41E-2	-0.1
Freshwater eutrophication (kg P eq)	1.57E-5 – 4.44E-5	N.A.
Additional impact categories		
Acidification (kg SO_2 eq)	3.9E-5 – 1.1E-4	N.A.
Photochemical oxidation (kg C_2H_4 eq)	2.4E-6 – 6.8E-6	N.A.
Acidification (m^2 UES)	8E-3	N.A.
Terrestrial eutrophication (m^2 UES)	6.6E-3	N.A.
Aquatic eutrophication (kg NO_3 eq)	1E-4	N.A.
Non-renewable energy consumption (MJ eq)	7.7E-2 – 9.27E-2	8.4E-2

Note: All values were transformed to the functional unit (MJ).
A = allocation ($ — economic; E— energy; m — mass; NA — no allocation). S = substitution. N.A. = not available.
The normalisation presented in Figure 4 is performed using the normalisation factors described in the JRC methodology [8] and ReCiPe normalisation values (see explanatory document).

Comments and interpretation of the environmental performance

1. The higher reported impacts are for freshwater eutrophication, mainly due to the fertilisation step considered in the study for the short rotation coppices.
2. A negative value (i.e. environmental benefit) is reported for climate change in ref. [7] mainly due to the consideration that biogenic CO_2 emissions are not contributing.

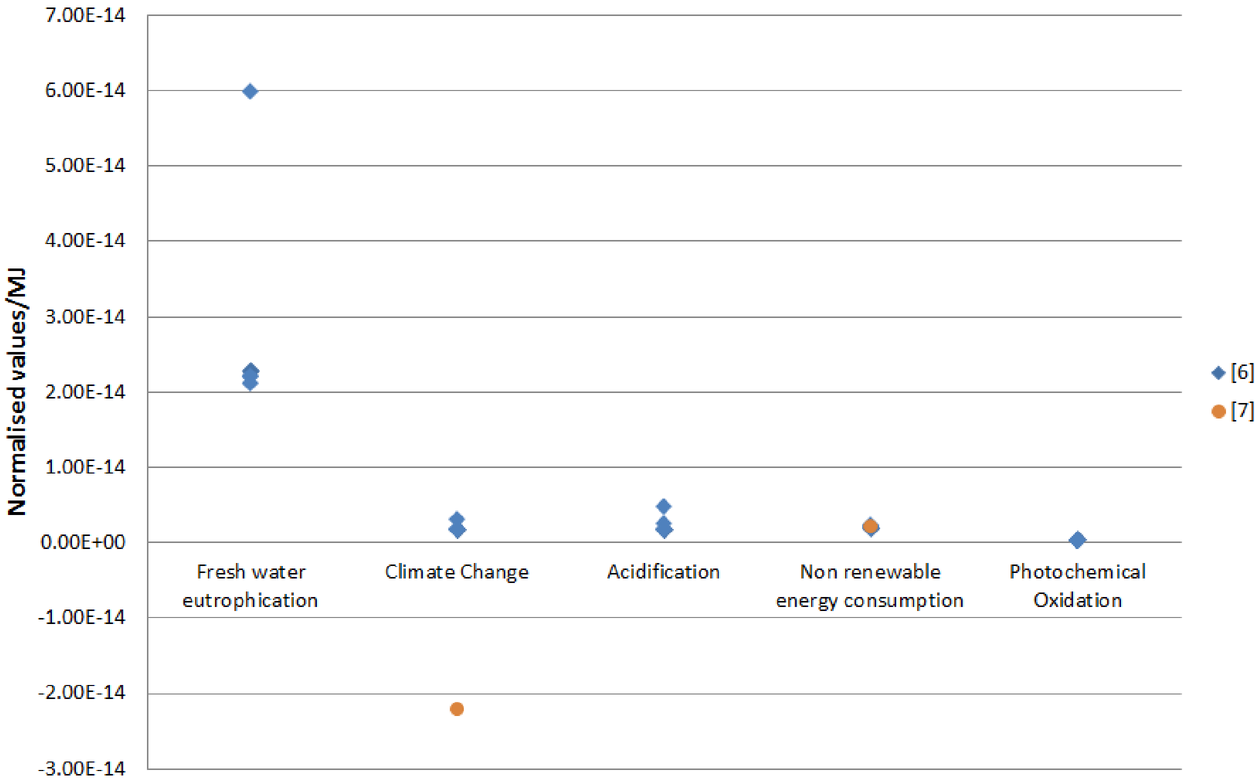


Figure 4. *Environmental performance expressed as normalised impact categories*

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FP7 project references in CORDIS (http://www.cordis.europa.eu)
POPFULL
ULTRALOWDUST
BIOCHIPFEEDING

ENVIRONMENTAL FACTSHEET: *Electricity generation via combustion*

PROCESS INFORMATION

In the electricity sector, biomass is commonly used for power generation. Most of today's plants are direct-fired facilities that combust biomass exclusively. Another option is co-fired power plants that mix biomass with coal or natural gas (see Electricity generation via co-combustion factsheet). The main characteristics of the direct-fired process (Fig. 1) are as follows:

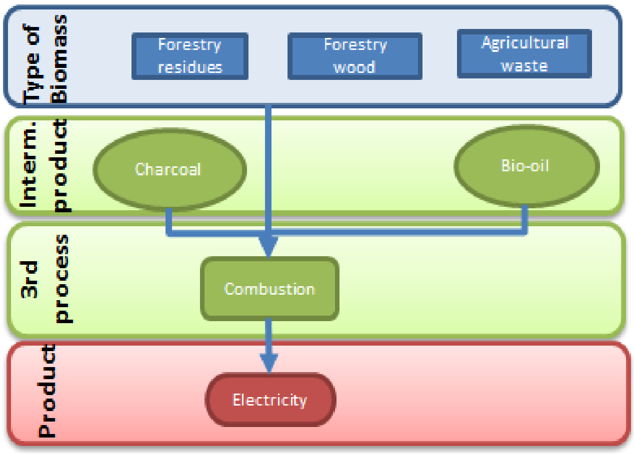


Figure 1. *Flowsheet of the combustion process*

- Wood is the most common feedstock. Others, like agricultural waste and intermediate products from other value chains such as bio-oil and biochar, can also be used.
- The pre-processing phases (i.e. drying and sizing) are important for optimising the combustion process.
- The main elements of a biomass electric generation system include: fuel storage equipment, combustor (furnace), heat generator (boiler), heat engine (turbine or motor), electricity generator and emission control devices [1].
- All heat engines produce only electricity and don't co-generate heat (see CHP via combustion factsheet).
- The biomass is burned in a furnace to generate hot gas, which is fed into a boiler to generate steam (see Larger-scale heat generation via combustion factsheet). This steam is expanded through a turbine or an engine connected to an electric generator. The heat content in the steam leaving the turbine is transferred to the atmosphere via a cooling tower system.
- Other applications of biomass combustion are smaller-scale heat generation (e.g. household) (see Smaller-scale heat generation via combustion factsheet), larger-scale heat generation (see Larger-scale heat generation via combustion factsheet) and combined heat and power generation (see CHP via combustion factsheet).
- The pure bio-ashes collected after the combustion process can be used as natural fertilisers in agriculture or forestry.

Technological overview

Electricity can be generated through either closed thermal cycles or open processes [2]. The former requires heat transfer between the fuel combustion and the power generation cycle, so the hot flue gases are not in contact with the engine, i.e. less damage is caused to the engine. Different closed-cycle technologies include the following:

- Steam turbine (Rankine cycle) — applied in medium- and large-scale power plants (from 5 to above 50 MWe) using water as a medium. A super-heater can be installed to increase the efficiency.
- Steam engines (Rankine cycle) — suitable for capacities within the range of 50 kWe to 1.2 MWe. Efficiencies can be comparable to those of steam turbines, with the advantage that steam engines require less sophisticated management of boiler water than turbines since engines are less sensitive to contaminants. The disadvantage, apart from noise and vibrations, is the need of oil injection for lubrication.
- Steam screw engine — this is a technology under development for small-scale power generation. It uses expansion instead of compression and is operated with a closed oil cycle. The advantage is the flexibility for different steam conditions.
- Steam turbines (organic Rankine cycle (ORC)) — the difference from the Rankine cycle is the use of organic oil instead of water, enabling lower operation temperatures. The power output ranges from 0.5 MWe to 10 MWe [3].
- Stirling engines are closed gas engines that theoretically present a high efficiency (Carnot process). They use air, helium or hydrogen as medium. This is an interesting option under development for small-scale power production.

- Closed gas turbines — the heat is supplied to a compressed gas with a high-temperature heat exchanger. Thus it needs a combination of a compressor and a turbine with helium, hydrogen or air as the working medium. The concept is still in the research phase.

Open cycles include directly fired gas turbines that are in the early stage of development for solid biomass, since particles and metals have to be separated from the flue gases (i.e. they are more suitable for gaseous and liquid fuels) due to there being no division between the fuel and thermal cycles.

Concerning the feedstock, woody biomass is mostly used in direct-fired power plants. Pre-processed products such as pellets, chips and sawdust are the only option for this application. Agricultural waste and herbaceous biomass are mainly used in industrial processes or co-firing plants [4], and only recently in power plants as a stand-alone fuel [5].

Technology readiness levels

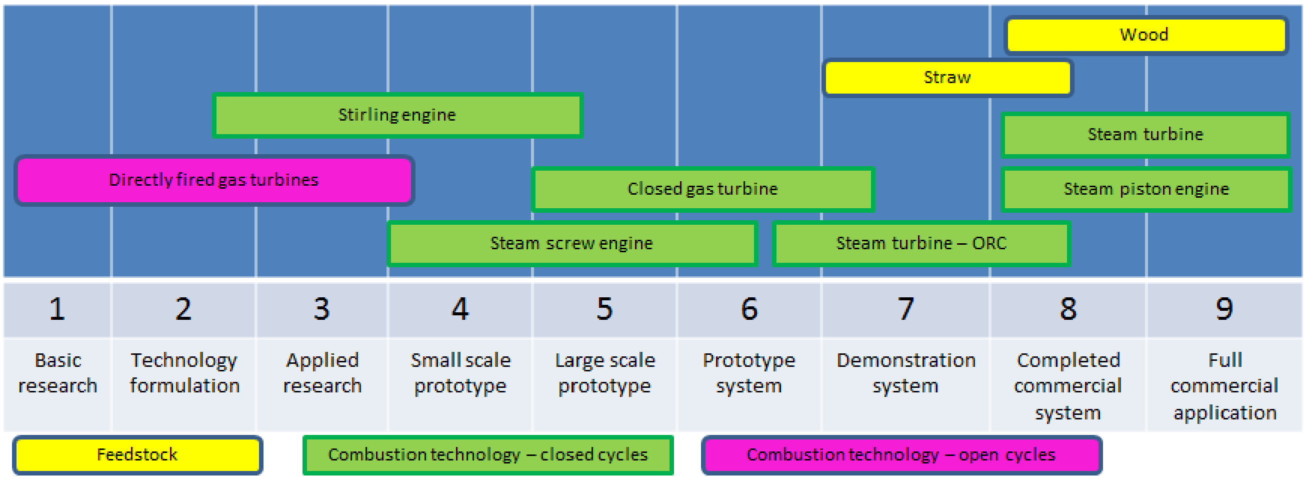


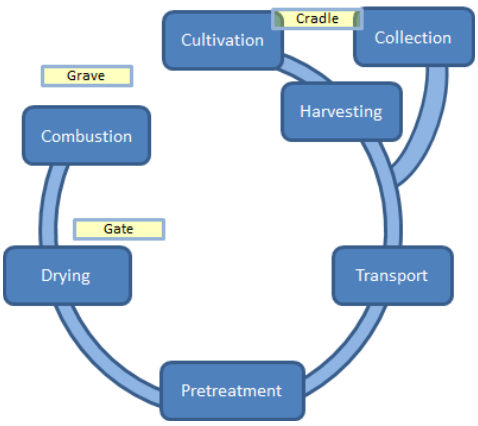
Figure 2. *Technology readiness levels for direct-fired combustion of biomass*

SWOT analysis (Strengths, Weaknesses, Opportunities, Threats)

S1. Existing mature and proven technology. **S2**. Broad range of power technologies and outputs available.	**W1**. The electric efficiency is relatively low (between 20 % and 40 %). **W2**. High investment costs.
O1. High sensitivity to economies of scale. **O2**. Combined heat and power systems greatly increase the overall energy efficiency.	**T1**. Transportation and logistics costs for biomass fuel can be significant. **T2**. The costly handling and pre-processing of biomass fuel can make the process economically not viable.

ENVIRONMENTAL DATA AND INFORMATION

System boundaries of the environmental assessment



1. **Cradle to grave**: includes cultivation (with production of ancillary products), harvesting or collection, transport, pre-treatment (i.e. pelletising, chipping), drying and storage, and combustion.
2. **Cradle to gate**: same boundaries as cradle to grave, excluding the combustion phase.

Figure 3. *LCA system boundaries and stages for direct-fired combustion of biomass*

Environmental assessment: settings & impacts

Table 1. LCA results for functional unit (FU) 1 MWh			
Raw material input (feedstock)	Sugar cane bagasse	Herbaceous — Wheat straw	Wood — Wood residues
LCA boundaries	1	1	1
Allocation/substitution	A ($,E)	A ($,NA)	A (NA)
Geographical coverage	Brazil, Mauritius	Spain	Canada, southern Europe
Product	Electricity		
References	[6],[8]	[9]	[7],[10]
Impact categories from environmental sustainability assessment methodology			
Climate change (kg CO_2eq)	1.17E-4 – 3.56E1	1.17E1 – 2.13E1	7.3E1 – 2.89E2
Ozone depletion (kg CFC-11 eq)	2E-5	N.A.	N.A.
Freshwater eutrophication (kg P eq)	4.92E-6 – 1.44E-1	N.A.	8.02E-2 – 2.24E-1
Marine eutrophication (kg N eq)	2.19E-3	N.A.	N.A.
Resource depletion — water (m^3)	2.24E5	N.A.	N.A.
Resource depletion — mineral (kg Sb eq)	N.A.	N.A.	3.31E-1 – 7.45E-1
Additional impact categories			
Acidification (kg SO_2 eq)	9.52E-7 – 3.56E-1	N.A.	1.5 – 3.44
Photochemical oxidation (kg C_2H_4 eq)	4.45E-3 – 2.38E-2	N.A.	5.63E-2 – 9.19E-2
Human toxicity (1,4-DB eq)	4.49E-1	N.A.	N.A.
Ecotoxicity — water (m^3)	2.15E1	N.A.	N.A.
Ecotoxicity — soil (m^3)	7.6E5	N.A.	N.A.
Ecotoxicity — air (m^3)	1.39E8	N.A.	N.A.
Human toxicity (m^3)	3.02	N.A.	N.A.
Human toxicity (m^3)	1.33E4	N.A.	N.A.
Non-renewable energy consumption (MJ eq)	N.A.	N.A.	7.6E2 – 1.72E3

Note: All values were transformed to the functional unit (MWh).
A = allocation ($ — economic; E — energy; m — mass; NA — no allocation). S = substitution. N.A.= not available.
The normalisation presented in Figure 4 is performed using the normalisation factors described in the JRC methodology [11] and ReCiPe normalisation values (see explanatory document).

Comments and interpretation of the environmental performance

1. The highest normalised impact values are reported for freshwater eutrophication and resource depletion, mainly due to the contributions from agricultural activities (e.g. fertiliser application and production) and biomass transport [7].
2. Impact values reported in refs [6] and [8] tend to be lower, mainly due to the allocation method applied (i.e. based on economic or energetic criteria), which assigns low allocation values to the electricity surplus production using sugarcane bagasse in ethanol industrial processes.

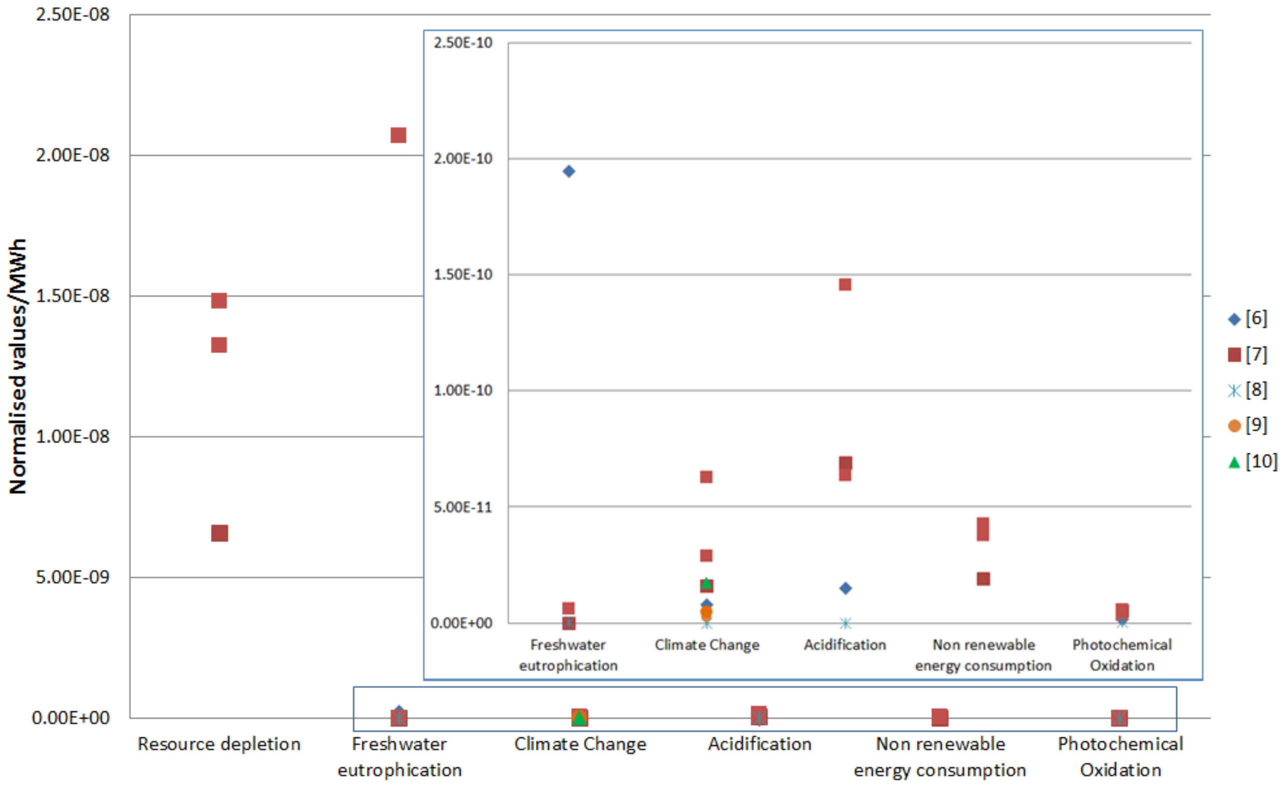


Figure 4. *Environmental performance expressed as normalised impact categories*

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FP7 project references in CORDIS (http://www.cordis.europa.eu)
BIOMAXEFF
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ENVIRONMENTAL FACTSHEET: ***Electricity generation via co-combustion***

PROCESS INFORMATION

In the electricity sector, biomass is commonly used for power generation, mostly in direct-fired combustion plants that exclusively use biomass as fuel (see Electricity generation via combustion factsheet). However, co-fired power plants that mix biomass with coal or natural gas are becoming a more popular option. The main characteristics of the co-combustion process (Figure 1) are as follows:

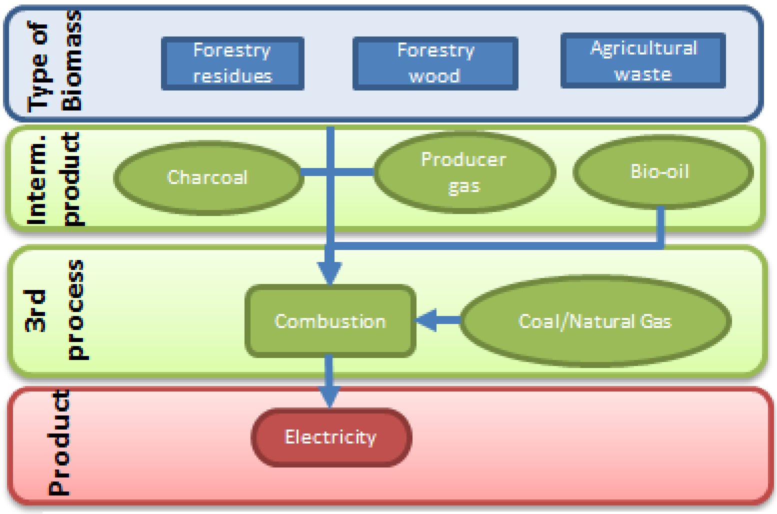


Figure 1. *Flowsheet of the* ***co-combustion*** *process*

- The most common option is co-combustion of solid biomass (wood and/or agricultural wastes) or intermediate products with coal. Also, co-combustion with natural gas is possible with previous gasification of the biomass (i.e. the so called producer gas) [1] (see CHP via gasification factsheet).
- The fuel preparation is important, including the phases of handling and storage, cleaning, drying and sizing (max. size 1-2 mm for pulverised coal plants).
- Biomass can only replace coal up to 30 % of the energy input in pulverised coal plants [2] due to declining efficiency, slagging, fouling and corrosion issues.
- All heat engines only produce electricity and don't co-generate heat (see CHP via combustion factsheet).
- When proper choices of biomass, coal and boiler design are made, co-firing can reduce the NO_x, CO_2 and SO_2 emissions compared to neat coal combustion (e.g. SO_2 reduction due to synergetic reactions between alkalis in biomass and sulphur in coal) [3].
- There is a significant reduction in the produced fly ash in co-firing compare to neat coal combustion. Concerning the quality and use of fly ashes from co-firing, current standards preclude their application as concrete additive [ASTM standard (C-618) only allows the use of fly ash completely originated from coal]. This limitation may need revision, considering that the EN450 standard allows their use (up to 20 % biomass) as pozzolanic addition in concrete and cement [2].
- Other applications of biomass combustion are smaller-scale heat generation (e.g. household) (see Smaller-scale heat generation via combustion factsheet), larger-scale heat generation (see Larger-scale heat generation via combustion factsheet) and combined heat and power generation (see CHP via combustion factsheet).

Technological overview

There are three different concepts for co-firing biomass with coal in pulverised coal-fired power plants [4].

- Direct co-firing: biomass is fed into the boiler furnace and burned with coal. The simplest and most economical option is to pre-mix biomass with coal and then co-mill the mixture. Another option is to handle and comminute biomass separately from coal and then mix directly in the firing system. The selection of the approach depends on fuel- and site-specific factors. The use of straw is possible but more challenging due to size and homogeneity issues.
- Indirect co-firing: the biomass is gasified and the resulting gas is combusted in the coal-fired boiler furnace. In this option the pre-processing equipment is substituted by a gasifier that mostly operates with air-blown, atmospheric pressure and circulating fluidised bed. The combustion technology is well known but the gasification technology is still under development.
- Parallel combustion: the biomass goes to a separate pre-treatment, feeding and combustion installation and the steam produced is utilised with the coal-fired steam for the power generation.

Both indirect and parallel co-firing require higher capital costs. On the other hand they interfere less with the operation of burners, allow the possibility of ashes separation for further uses and allow the use of a wider range of fuels, for example by size (less pre-processed fuels such as bales and chips) or quality (contaminated biofuels could be used).

For co-firing gasified biomass with natural gas, different technologies are available, including: gas turbines, furnaces and boilers [5]. In natural gas-fired combined-cycle power plants it can be done through separate gasification or by separate combustion with steam-side integration.

Concerning the feedstock, it ranges from woody to grassy and straw-derived materials. The most common application is the co-combustion of wood in pulverised coal boilers, where fine sawdust is basically the only option. If another technology is used, such as stokers or fluidised bed boilers, a wider range of fuel sizes is accepted (e.g. pellets, chips). Other forms of biomass, such as straw and energy crops, have been less investigated but are already at demonstration and even commercial scale [6].

Technology readiness levels

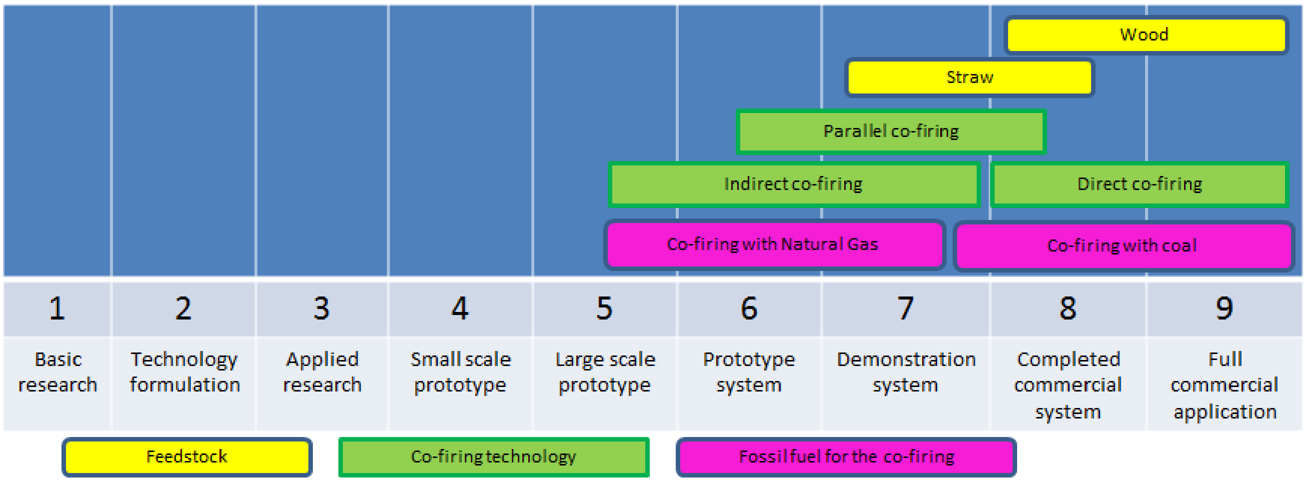


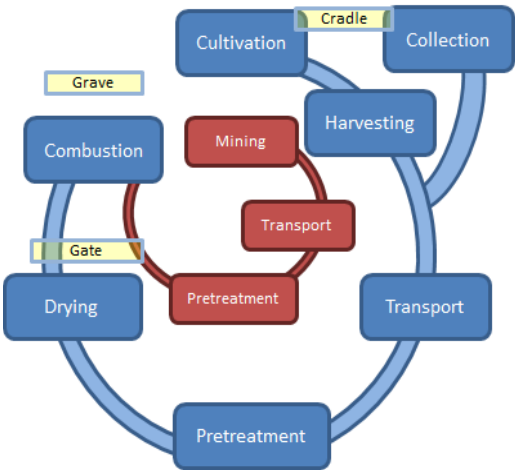
Figure 2. *Technology readiness levels for co-combustion of biomass*

SWOT analysis (Strengths, Weaknesses, Opportunities, Threats)

S1. Low investment costs since retrofitting is feasible for existing mature coal power plants. **S2.** Co-firing with coal can result in lower nitrogen oxide and sulphur oxide emissions.	**W1**. Higher costs for fuel handling and equipment maintenance. **W2**. No acceptance of mixed coal/biomass ashes as cement additive under certain standards. **W3**. Security of sufficient biomass supply with guaranteed and stable quality.
O1. Co-firing earns higher electric efficiency potential compared to direct-fired neat biomass. **O2**. Large operational experience gathered in the last ten years.	**T1**. The choice of improper fuel and technology design can significantly reduce the advantages of co-firing and may severely damage the equipment. **T2**. Introduction of co-firing requires revising a plant's operation authorisation.

ENVIRONMENTAL DATA AND INFORMATION

System boundaries of the environmental assessment



1. **Cradle to grave**: includes cultivation (with production of ancillary products), harvesting or collection, transport, pre-treatment (e.g. cleaning, sizing), drying and storage, and combustion with a fossil fuel.
2. **Cradle to gate**: same boundaries as cradle to grave, excluding the combustion phase.

Note: In the case of co-firing, the LCA studies can report either impacts resulting from the fossil fuel combustion along with the biomass (in this case mining, transport and pre-treatment of the fossil fuel are also included in the system boundaries) or just the impacts from the biomass combustion.

Figure 3. *LCA system boundaries and stages for co-combustion of biomass*

Environmental assessment: settings & impacts

Table 1. LCA results for functional unit (FU) 1 MWh				
Raw material input (feedstock)	Wood		Herbaceous/Straw	
LCA boundaries	1 (including coal)	1 (excluding coal)	1 (including coal)	1 (excluding coal)
Allocation/substitution	A ($, NA)	A (NA)	A ($, NA)	A ($, NA)
Geographical coverage	Canada, Spain, the Netherlands	Canada	Canada, Spain	Canada, Spain
Product	Electricity			
References	[7],[8],[10],[11]	[7]	[7],[8],[9]	[7],[9]
Impact categories from environmental sustainability assessment methodology				
Climate change (kg CO2 eq)	6.57E2 – 1.09E3	2.1E2 – 3.02E2	6.62E2 – 1.08E3	2.37E1 – 1.65E2
Ozone depletion (kg CFC-11 eq)	8E-6 – 8.51E-6	N.A.	8.33E-6 – 8.85E-6	N.A.
Particulate matter (kg PM_{10} eq)	5.41E-1 – 6E-1	N.A.	5.58E-1 – 6.15E-1	N.A.
Ionising radiation (kg U^{235} eq)	2.91E1 – 2.99E1	N.A.	3.22E1 – 3.29E1	N.A.
Photochemical ozone formation (kg NMVOC eq)	1.4 – 1.47	N.A.	1.42 – 1.5	N.A.
Freshwater eutrophication (kg P eq)	2.97E-1 – 2.98E-1	N.A.	3.01E-1 – 3.02E-1	N.A.
Marine water eutrophication (kg N eq)	5.38E-1 – 5.6E-1	N.A.	5.49E-1 – 5.72E-1	N.A.
Resource depletion — water (m^3)	7.51E-1 – 8.15E-1	N.A.	7.78E-1 – 8.43E-1	N.A.
Additional impact categories				
Acidification (kg SO_2 eq)	1.52 – 1.21E2	1.28 – 1.57	1.57 – 5.93	1.86 – 2.62
Photochemical oxidation (kg C_2H_4 eq)	8.64E-1 – 1.39	N.A.	N.A.	N.A.
Freshwater ecotoxicity (1,4-DB eq)	4.28	N.A.	4.33 – 4.34	N.A.
Terrestrial ecotoxicity (1,4-DB eq)	8.03E-3 – 9.05E-3	N.A.	8.35E-3 – 9.3E-3	N.A.
Human toxicity (1,4-DB eq)	1.87E2	N.A.	1.89E2 – 1.9E2	N.A.
Marine aquatic ecotoxicity (1,4-DB eq)	4.27 – 4.28	N.A.	4.33 – 4.34	N.A.
Metal depletion (kg Fe eq)	5.85 – 6.03	N.A.	5.8 – 5.98	N.A.
Fossil depletion (kg oil eq)	1.66E2	N.A.	1.68E2	N.A.
Net energy ratio (MJ eq)	N.A.	3.9E2 – 4E2	N.A.	3.7E2
Agricultural land occupation (m^2year)	7.64E1 – 7.68E1	N.A.	4.38E1 – 4.4E1	N.A.
Urban land occupation (m^2year)	4.8 – 4.81	N.A.	4.12	N.A.

Note: All values were transformed to the functional unit (MWh).
A = allocation ($ — economic; E — energy; m — mass; NA — no allocation). S = substitution. N.A. = not available.
The normalisation presented in Figure 4 is performed using the normalisation factors described in the JRC methodology [12] and ReCiPe normalisation values (see explanatory document).

Comments and interpretation of the environmental performance

1. The highest normalised impact values are reported for freshwater eutrophication in ref. [8], mainly due to the coal mining and transportation stages of the co-firing value chain.
2. Acidification impact values in ref. [7] are also higher due to the contribution of the coal value chain to the co-firing process. The biomass combustion stage also adds significantly, especially in the case of using baled agricultural residues (e.g. straw).
3. The lowest values in climate change reported in ref. [8] consider 30 % of biomass co-firing (on energy content basis) while the highest values in ref. [11] consider 10 %. Intermediate values (i.e. ref. [10] and ref. [11]) consider 20 % of biomass co-firing on energy content basis.

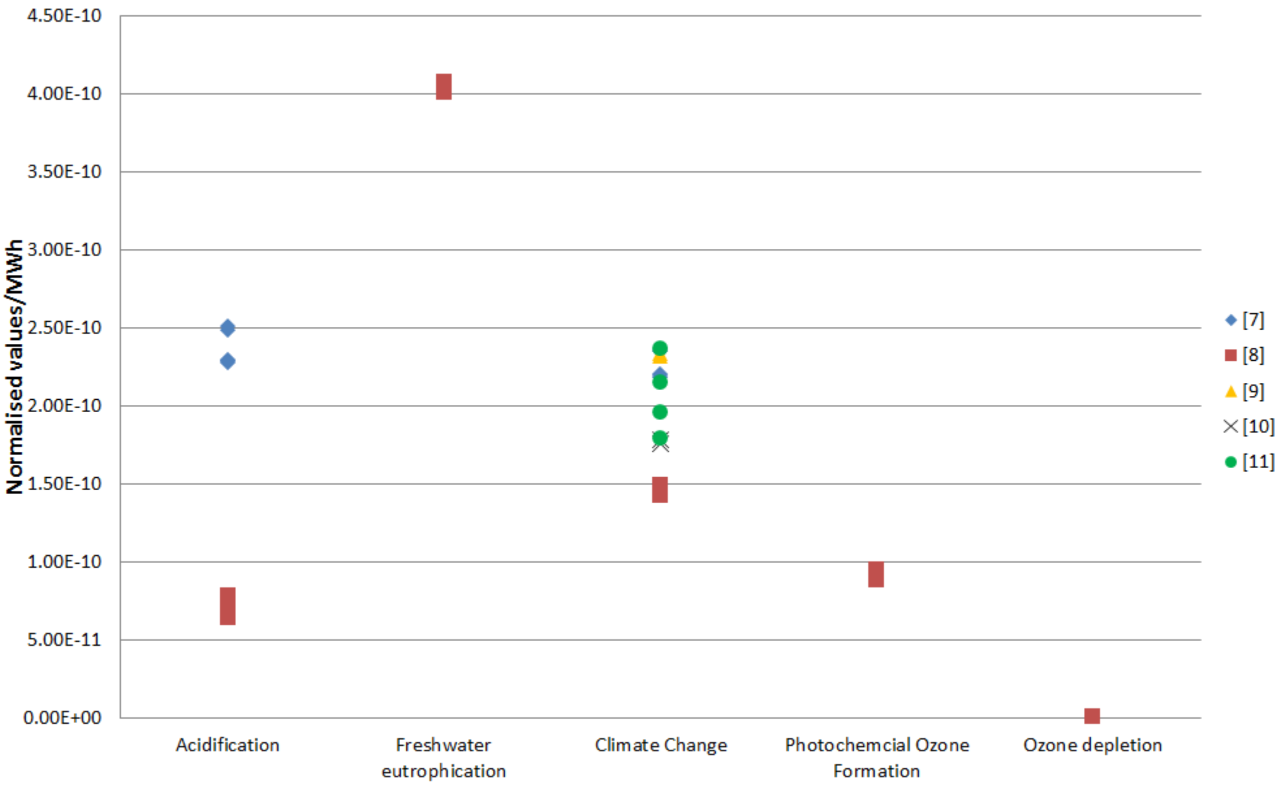


Figure 4. *Environmental performance expressed as normalised impact categories. Note: only the values for the co-firing value chains including coal are depicted.*

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ENVIRONMENTAL FACTSHEET: *Combined heat and power via combustion*

PROCESS INFORMATION

Combined heat and power (CHP), or co-generation, is the simultaneous conversion of primary energy into electrical energy and useful heat. The main characteristics of the CHP generation process (Figure 1) are as follows:

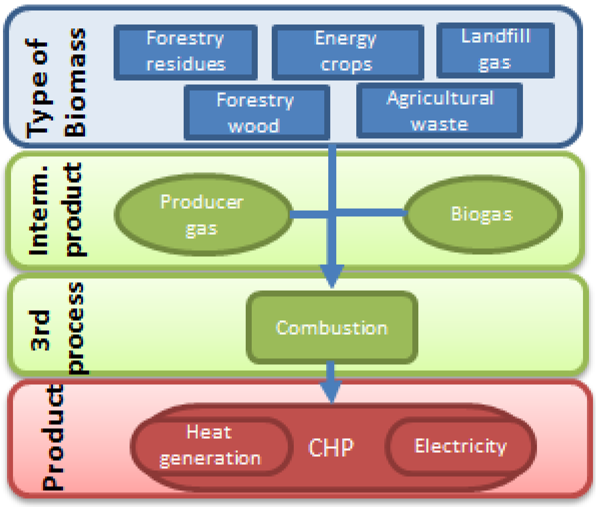


Figure 1. Flowsheet of the **CHP generation** process

- Solid biomass can be gasified before combustion [1] (see CHP via gasification factsheet). Landfill gas and biogas can also be used for co-generation (see CHP via anaerobic digestion factsheet).
- Fossil fuel stations can be retrofitted into co-firing plants (see also Electricity generation via co-combustion factsheet).
- The pre-processing of the feedstock includes receiving, drying, grinding and storage.
- CHP is an energy system that integrates two main components: the **energy conversion system** that converts the biomass into steam (through boilers, largely explained in the Larger-scale heat generation via combustion factsheet) or producer gas (through gasifiers, explained in the CHP via gasification factsheet) and the **power and heat production system** that converts the steam or gas into electric power and useful heat. The second system integrates several individual components: the prime mover (generally a heat engine), the generator, the heat recovery system and the electrical interconnection.
- The prime mover generates mechanical energy that is usually transformed into electricity, but it can also be used to drive rotating equipment such as pumps and fans [1]. The thermal energy can also be used for space heating, hot water, drying, etc.
- Biomass CHP is commonly used in the industrial sector to cover on-site needs. Extra power can be fed into the grid. Plant capacities range from several kWe up to 350 MWe [2].
- The ashes remaining after combustion can be utilised for fertilising and soil-improving purposes.

Technological overview

The prime movers are the pieces of equipment that drive and identify the overall CHP system. They include the following:

- Steam turbine — Well-known technology that requires steam (produced by combusting, for example, biomass in a boiler) to generate electricity. It works on a closed-circuit process (i.e. it requires a separate heat source to convert fuel to steam and then steam to electricity) enabling the use of a wide range of fuel flexibility. In the Rankine cycle, water is converted to high-pressure steam that causes the rotation of the turbine, creating power that is then converted to electricity with a generator. For the CHP, steam is extracted from the turbine and used for heating. Depending on the configuration there are different types of turbines [3]: back-pressure, extraction back-pressure, uncontrolled extraction and extraction condensing. Typical capacities range between a few and several hundred MWe.

The rest of the prime movers require gas to operate (i.e. the feedstock can be biogas/landfill gas or other gasified solid biomass):

- Gas turbine (combustion turbine) — Internal combustion engine that operates with rotational motion using the Brayton cycle. It can operate as: simple cycle to produce electricity only (see Electricity generation via combustion factsheet); co-generation of electricity with heat recovery from the turbine exhaust and its conversion into useful thermal energy through a heat exchanger; and combined cycle, which uses a steam turbine to create additional power from the high-pressure steam, obtained from the exhaust heat. Since it is a thermodynamically open process, the gas fuel must be carefully cleaned to avoid damaging the turbine blades. Typical capacities range from 0.5 MWe up to 300 MWe.
- Reciprocating internal combustion engine (ICE) — Well–known technology that includes both spark-ignition (SI) (Otto cycle) and compression ignition (CI) (diesel cycle) configurations. SI can work with gaseous fuels and CI can be set up to run in a dual-fuel biogas-diesel configuration (see

CHP via anaerobic digestion factsheet). As in gas turbines, the fuel must be sufficiently purified to avoid engine damage. The heat recovery is more complex and flexible in ICE engines since it can be done from the exhaust, the cooling water and the engine oil. Sizes range from several kW to more than 5 MW for power generation.

- Microturbine — Small gas turbine with capacities from 30 kW to 250 kW. It presents lower efficiencies than ICE and large gas turbines. On the other hand it is simpler (does not require cooling) and presents lower maintenance costs.
- Fuel cell — This is an emerging smaller-scale technology (up to 2 MW) that converts the energy in the fuel to electricity electrochemically without combustion (i.e. it is not a heat engine). It requires hydrogen to operate so a reformer is needed to increase its concentration. It presents high electric efficiencies with the major challenges of cost and durability.

Another prime mover that can operate either with solid or gaseous biomass is the Stirling engine. It is an externally heated reciprocating engine that transfers the heat to a working fluid in a closed-circuit process. Forced cooling of the medium is required. Despite many years of research, it is still at an early stage of development due to challenges with cost and performance. Other technologies under research [4] are: the organic Rankine cycle, the air bottoming cycle, the evaporative gas turbine, the externally fired gas turbine and the pulverised wood-fired gas turbine. Concerning the feedstock, wood is the most commonly used biomass fuel for CHP, but straw can also be used, alone or in combination with other feedstock [5].

Technology readiness levels

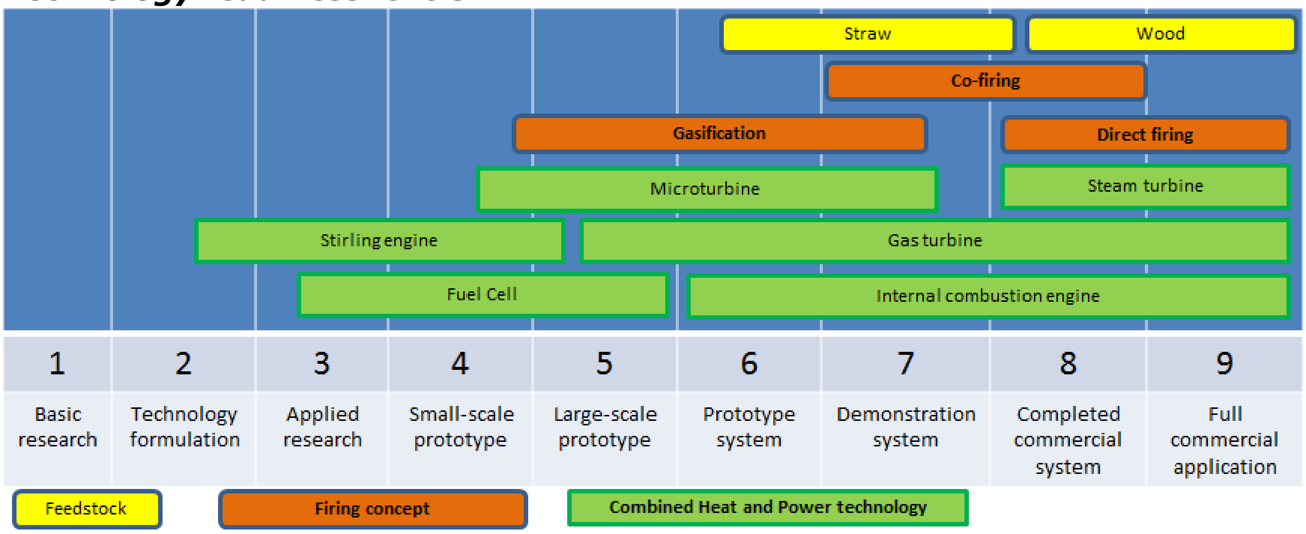


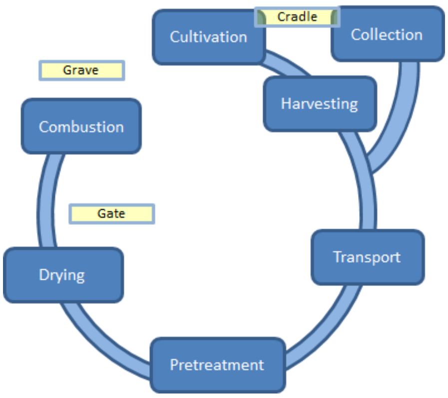
Figure 2. *Technology readiness levels for CHP generation from biomass*

SWOT analysis (Strengths, Weaknesses, Opportunities, Threats)

S1. Higher total efficiency due to waste-heat recovery. **S2**. Lower emissions rates compared to separate heat and power systems per energy unit output.	**W1**. Lower electrical efficiency compared to stand-alone power plants.
O1. Potential for reaching higher efficiencies. **O2**. Lower demand for cooling water (i.e. it allows decentralisation).	**T1**. The utilisation of the by-product heat limits the dimension of the CHP plant compared to power plants, due to the large heat transmission losses and costs.

ENVIRONMENTAL DATA AND INFORMATION

System boundaries of the environmental assessment



1. **Cradle to grave**: includes cultivation, harvesting (with production of ancillary products) or collection (in case of by-products / wastes), transport, pre-treatment (e.g. cleaning, sizing), drying and storage, and the combustion phase.
2. **Cradle to gate**: same boundaries as cradle to grave, excluding the combustion phase.
3. **Gate to grave**: considers only the combustion phase.

Figure 3. *LCA system boundaries and stages for CHP generation from biomass*

Environmental assessment: settings & impacts

Table 1. LCA results for functional unit (FU) 1 MJ

Raw material input (feedstock)	Wood			Herbaceous/straw
LCA boundaries	1		3	1
Allocation/substitution	S, A (E, NA)	A (E)	A (NA)	S
Geographical coverage	Sweden		Europe	Denmark
Product	Heat	Electricity	Heat	Heat
References	[6],[8],[10],[11]	[8],[10]	[11]	[7],[9]
Impact categories from environmental sustainability assessment methodology				
Climate change (kg CO_2 eq)	-7E-2 – 2.1E-1	1.41E-2 – 1.1E-1	2.94E-3 – 1.12E-2	-7.1E-2 – -1.6E-1
Ozone depletion (kg CFC-11 eq)	6.74E-10	N.A.	1.75E-10 – 5.97E-10	N.A.
Human toxicity — non-cancer effects (CTUh)	8.78E-9	N.A.	7.71E-9 – 3.25E-8	N.A.
Acidification (mol H^+ eq)	1.45E-4	N.A.	1.2E-4 – 1.36E-4	N.A.
Photochemical ozone formation (kg NMVOC eq)	1.3E-4	N.A.	1.26E-4 – 1.79E-4	N.A.
Terrestrial eutrophication (mol N eq)	5.3E-4	N.A.	5.17E-4 – 6.99E-4	N.A.
Freshwater eutrophication (kg P eq)	1.1E-5 – 1.17E-5	2.32E-5	4.57E-7 – 9.26E-6	N.A.
Marine water eutrophication (kg N eq)	1.65E-2	N.A.	6.6E-3 – 2.23E-2	N.A.
Resource depletion — water (m^3)	1.44E-5	N.A.	2.16E-6 – 1.34E-5	N.A.
Additional impact categories				
Acidification (kg SO_2 eq)	3.1E-4	1.6E-4	N.A.	N.A.
Photochemical oxidation (kg C_2H_4 eq)	1.8E-4	9E-5	N.A.	N.A.
Freshwater ecotoxicity (1,4-DB eq)	6.3E-4	3.2E-4	N.A.	N.A.
Acidification (m^2 UES)	N.A.	N.A.	N.A.	1E-2
Terrestrial eutrophication (m^2 UES)	N.A.	N.A.	N.A.	8E-3
Cumulative energy demand (MJ eq)	N.A.	N.A.	1.34 – 1.52	N.A.
Primary energy use — non-renewable (MJ eq)	-4E-1 – -7.5E-1	1.65E-4	N.A.	-1.4E-1 – -7.67E-1
Primary energy use — renewable (MJ eq)	4E-1 – 9E-1	N.A.	N.A.	N.A.
Land use (m^2year)	N.A.	N.A.	N.A.	9E-2
Land required (ha)	N.A.	5.69E-5	N.A.	N.A.

Note: All values were transformed to the functional unit 1 MJ (MJe if the product is electricity, MJh if the product is heat).
A = allocation ($ — economic; E — energy; m — mass; NA — no allocation). S = substitution. N.A. = not available.
The normalisation presented in Figure 4 is performed using the normalisation factors described in the JRC methodology [12] and ReCiPe normalisation values (see explanatory document).

Comments and interpretation of the environmental performance

1. The highest normalised impact value is reported for climate change in ref. [10], where the allocation method based on the energy content is used when producing electricity and heat.
2. Negative values for climate change (i.e. environmental benefits) are reported in refs [6], [7] and [9] that use substitution as allocation method. In refs [7] and [9], co-produced electricity from straw and miscanthus displaces the Danish electricity mix.
3. Higher impact values reported for freshwater eutrophication in refs [8] and [11] are mainly due to the combustion phase of the biomass and the waste water treatment, when included.

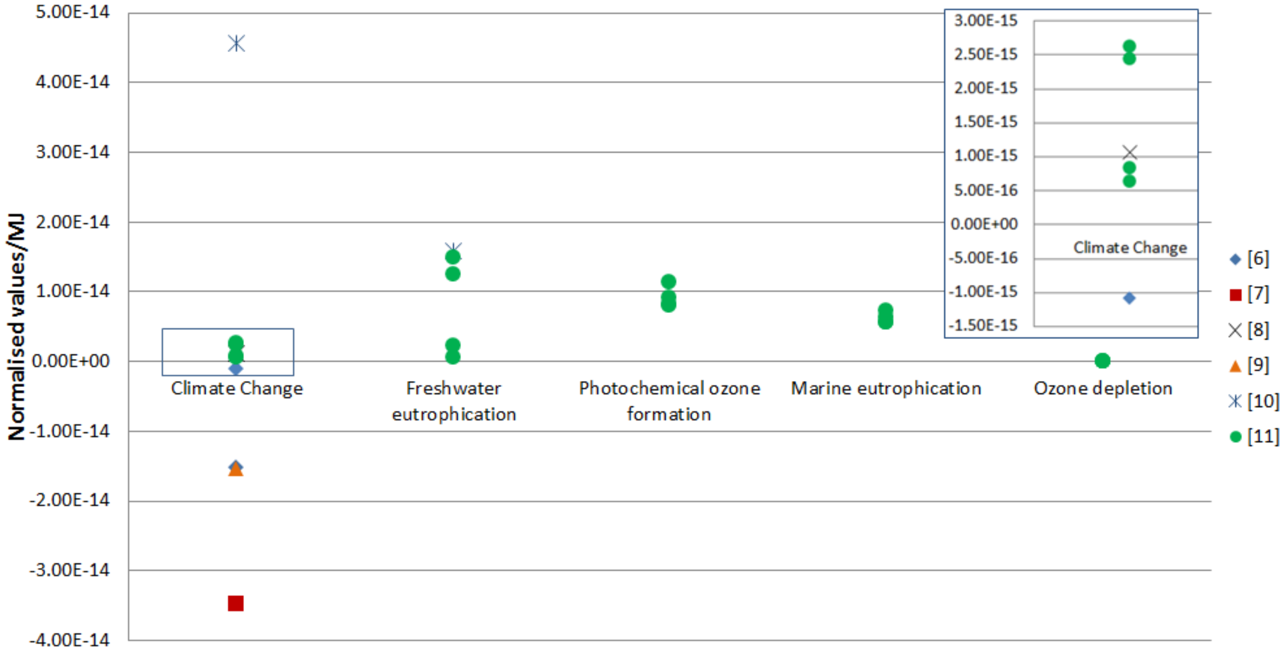


Figure 4. *Environmental performance expressed as normalised impact categories. Note: only the values for the heat product are depicted.*

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ENVIRONMENTAL FACTSHEET: ***Heat and power via anaerobic digestion***

PROCESS INFORMATION

Anaerobic digestion is a biochemical pathway able to convert almost all sources of biomass (including wet materials such as organic wastes and animal manure) to a highly energetic energy carrier referred to as biogas. Only strongly lignified organic substances such as wood are not suitable for digestion. The main characteristics (Figure 1) of the process are as follows:

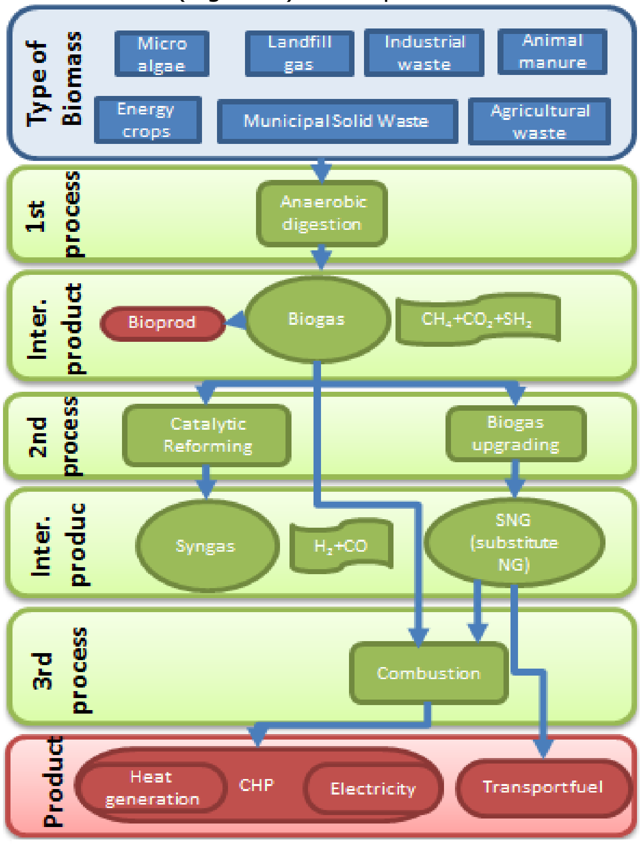


Figure 1. *Flowsheet of the* ***anaerobic digestion*** *process*

- Anaerobic digestion consists of four phases (hydrolysis, acidogenesis, acetogenesis, methanogenesis) where microorganisms sequentially transform the different molecules (i.e. carbohydrates, proteins and lipids) into biogas that consists mainly of methane (CH_4) (around 50-70 %), but also carbon dioxide (CO_2) (around 30-50 %) and traces of hydrogen sulphide (H_2S) and water vapour.
- Depending on the technology, a pre-processing phase of drying and dewatering can increase biogas yield.
- Landfill gas has a similar composition to biogas and hence it can be used in the same way.
- The most common application for biogas is combustion to produce electricity or heat, or both combined heat and power (CHP) (see CHP via combustion factsheet).
- Another use is upgrading to produce a substitute for natural gas (SNG), known as biomethane, which can be injected into the grid (to be combusted) or utilised as vehicle fuel. For that use, contaminants must be removed, the methane content typically being greater than 97 %.
- Another option to utilise the energy contained in the biogas, albeit mostly theoretical at present, is catalytic reforming to generate Syngas (H_2+CO) (see Biofuels via gasification factsheet).
- A by-product of biogas production is the digestate, which can be composted to enhance its characteristics or used directly as fertiliser [1].

Technological overview

There are multiple configurations and designs for digesters, depending on the following:

- Total solids content: wet digesters that operate with less than 15 % total solids in the reactor and dry digesters that operate with around 25-30 % total solids.
- Operating temperatures: thermophilic digesters that operate in a temperature range of 50-65 °C and mesophilic digesters that operate at around 35-40 °C.
- Number of reactors used: two-phase digesters that separate (in different reactors) the phases of methanogenesis from the hydrolysis/acidogenesis and thereby allow for optimisation of the operation conditions. Conversely, the one-phase digesters present only one reactor where all reactions take place under average operating conditions that suit all reactions.
- Feeding methods: batch digesters that are loaded at once and the reactions take place over a certain period of time; and continuous flow digesters that are fed and discharged in continuous manner.

Biogas produced can be combusted for CHP generation in internal combustion engines (either spark ignition or compress ignition, with dual fuel configuration in the second case), achieving total efficiencies of up to 77-80 %. It is also common to use it in gas and micro-gas turbines (with total efficiencies between 63-71 %). Its use in fuel cells (overall efficiency up to 80 %) is in the early stages of research and development [mainly solid oxide fuel cell (SOFC) and molten carbonate fuel cells (MCFC)] [2,3].
Concerning gas upgrading technologies, there are different types: absorption (either physical or chemical), pressure swing adsorption (PSA), cryogenic technology and membrane separation [4,5]. The most

commonly applied method to decrease the CO_2 content in biogas is physical absorption using water scrubbing. This is due to the larger solubility (and hence easier separation) of CO_2 and H_2S in water compared to the solubility of CH_4.
For catalytic reforming (i.e. converting CH_4 and CO_2 into H_2 and CO) there are two main methods [6]: dry reforming, which is endothermic; and auto-thermal reforming (ATR), where heat and co-reactants should be provided to drive the endothermic reaction.
Concerning the feedstock, anaerobic digestion of municipal organic wastes and manure is a well-known and mature technology. The use of energy crops in digesters is applied to a lesser extent but it is growing in interest and development. A common practice is to operate digesters with co-digestion of two or more types of feedstock (i.e. animal manure as primary feedstock, plus silage to increase gas production). Another concept, microalgae digestion, is at the early stage of development [7].

Technology readiness levels

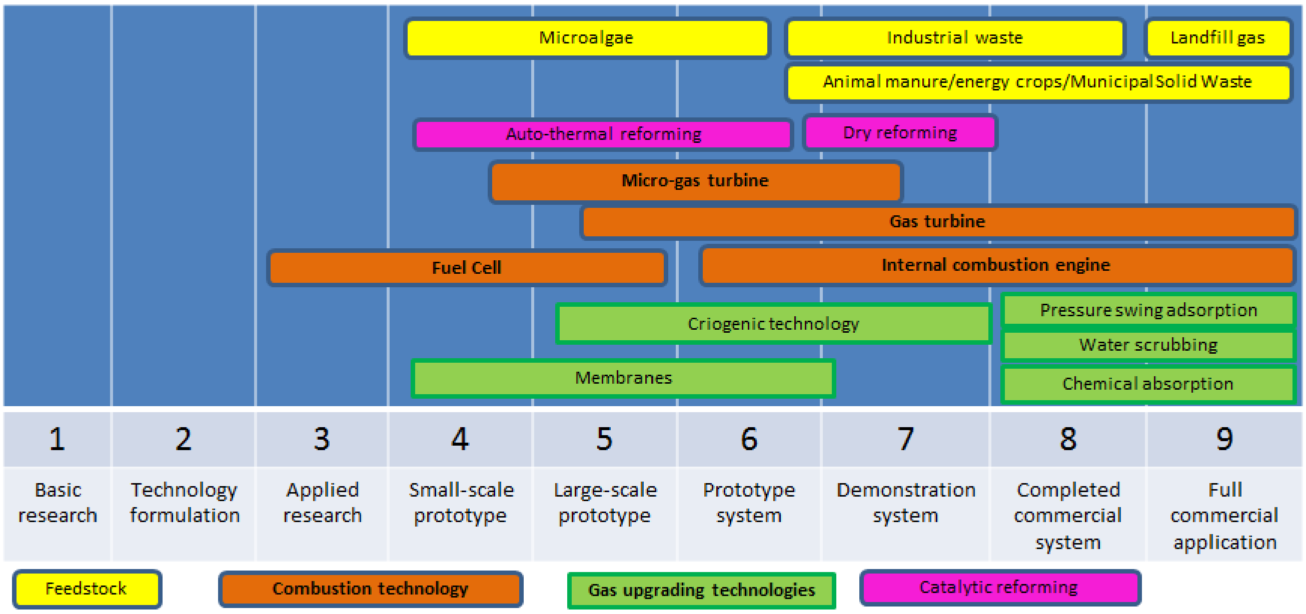


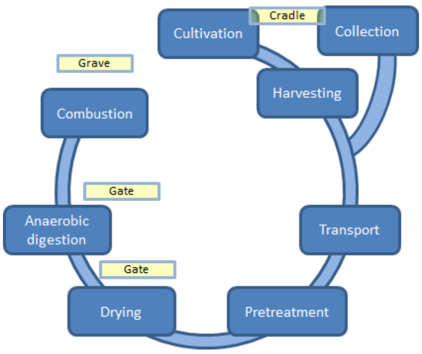
Figure 2. *Technology readiness levels for the anaerobic digestion process*

SWOT analysis (Strengths, Weaknesses, Opportunities, Threats)

S1. Able to treat wet biomass (difficult for other technologies). **S2.** Better conversion efficiencies of biomass to biogas compared to other biofuel production alternatives. **S3.** Broad applicability and relatively simple set-up.	**W1.** Investments are quite large, while energy and digestate prices are relatively low. **W2.** Biogas is a severe greenhouse gas itself (escapes and leakages). **W3.** As a transportation fuel application, further development is still needed.
O1. Use in landfill can reduce vented methane emissions. **O2.** The existing natural gas infrastructure can be used.	**T1.** May compete against food, feed and fibre production under land-availability constraints. **T2.** Consumers are not used to biogas as fuel. **T3.** No common quality standard exists for biogas.

ENVIRONMENTAL DATA AND INFORMATION

System boundaries of the environmental assessment



1. **Cradle to grave**: includes cultivation, harvesting (with production of ancillary products) or collection (in case of by-products/waste), transport, pre-treatment (e.g. cleaning, sizing), drying (if needed), anaerobic digestion and the combustion of the biogas produced.
2. **Cradle to gate**: same boundaries as cradle to grave, excluding the combustion phase.
3. **Gate to grave**: only consider the anaerobic digestion and combustion phases.

Figure 3. *Life Cycle Assessment system boundaries and stages for anaerobic digestion*

Environmental assessment: settings & impacts

Table 1. LCA results for functional unit (FU) 1 MJ							
Raw material input (feedstock)	Energy crop — manure (co-digestion)		Agricultural residue — manure (co-digestion)	Energy crops			Manure
LCA boundaries	1	2	1	1	2	3	1
Allocation/substitution	A (E,m,$,NA), S	S	S	S	S	S	S
Geographical coverage	Italy, Germany, United Kingdom	Germany	United Kingdom	Germany, United Kingdom, Luxembourg	Luxembourg	Germany	Germany
Product	Heat and electricity	Biogas	Heat and electricity	Heat and Electricity	Biogas	Heat and electricity	Heat and electricity
References	[8],[11],[13-15]	[12]	[15]	[10],[13],[15]	[10]	[9]	[13]
Impact categories from environmental sustainability assessment methodology							
Climate change (kgCO_2 eq)	-8E-2 – 1.26E-1	1E-3 – 1.1E-2	6.17E-2	-8.2E-2 – 6.3E-2	3E-3	1.61E-2 – 4.97E-2	-2E-1
Ozone depletion (kg CFC-11 eq)	-2.1E-9 – 2.78E-11	N.A.	4.72E-10	3.33E-10	N.A.	N.A.	N.A.
Freshwater eutrophication (kg P eq)	6.07E-5 – 1.73E-4	4.24E-5 – 4.37E-5	9.06E-5	6.85E-5	N.A.	2.99E-5 – 7.25E-5	-1.24E-4
Resource depletion — mineral (kg Sb eq)	-5E-9 – -4.4E-5	N.A.	1.08E-8	3.86E-9.	N.A.	N.A.	N.A.
Additional impact categories							
Acidification (kg SO_2 eq)	-4.31E-4 – 1.94E-3	6.9E-4 – 7.2E-4	9.86E-4	4E-4	N.A.	4.5E-4 – 6.06E-4	-2E-3
Photochemical oxidation (kg C_2H_4 eq)	1.5E-5 – 7E-5	N.A.	2.33E-5	1.39E-5	N.A.	N.A.	N.A.
Freshwater ecotoxicity (1,4-DB eq)	8.06E-4	N.A.	2.28E-3	2.54E-3	N.A.	N.A.	N.A.
Terrestrial ecotoxicity (1,4-DB eq)	4.44E-5	N.A.	4.56E-4	7.86E-4	N.A.	N.A.	N.A.
Human toxicity (1,4-DB eq)	1.14E-3	N.A.	3.08E-3	1.88E-3	N.A.	N.A.	N.A.
Marine aquatic ecotoxicity (1,4-DB eq)	8.33E-1	N.A.	2.78	2.31	N.A.	N.A.	N.A.
Cumulative non-renewable energy demand (MJ eq)	6.79E-2	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Primary energy demand (MJ eq)	-8.66E-1 – 4.56E-1	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Total fossil energy demand (MJ eq)	5.56E-4	N.A.	5.28E-3	3.28E-3	N.A.	-2.74E-1 – 1.75E-1	N.A.
Energy-related primary energy balance (MJ eq)	N.A.	-1.25 – -1.07	N.A.	N.A.	N.A.	N.A.	N.A.

Note: All values were transformed to the functional unit 1 MJ (1 MJe or 1 MJth depending on which is the main product, electricity or heat respectively — if biogas is the final product, the functional unit 1 MJ refers to the energy contained in the biogas).
A = allocation ($ — economic; E — energy; m — mass; NA — no allocation). S = substitution. N.A. = not available.
The normalisation presented in Figure 4 is performed using the normalisation factors described in the JRC methodology [16] and ReCiPe normalisation values (see explanatory document).

Comments and interpretation of the environmental performance

1. The highest and lowest normalised impact values are reported for freshwater eutrophication. The highest values in ref. [8], where energy crops are used as feedstock and the emissions during the storage phase contribute the most. On the other hand, the lowest values in ref. [13], where liquid manure is used in mono-digestion and emissions of the avoided manure storage and the fertiliser use replaced by the digestate are credited to the system.
2. Negative impact values (i.e. environmental benefits) are reported for freshwater eutrophication, acidification and climate change when a credit approach is used to solve multi-functionality.
   Note: Not all studies that use a substitution approach report negative values (this depends mainly on the stages included and the system of reference).
3. Lower positive values are reported mainly because, instead of considering the whole life cycle (i.e. cradle to grave), ref. [9] selected gate to grave and refs [10] and [12] cradle to gate as system boundaries.

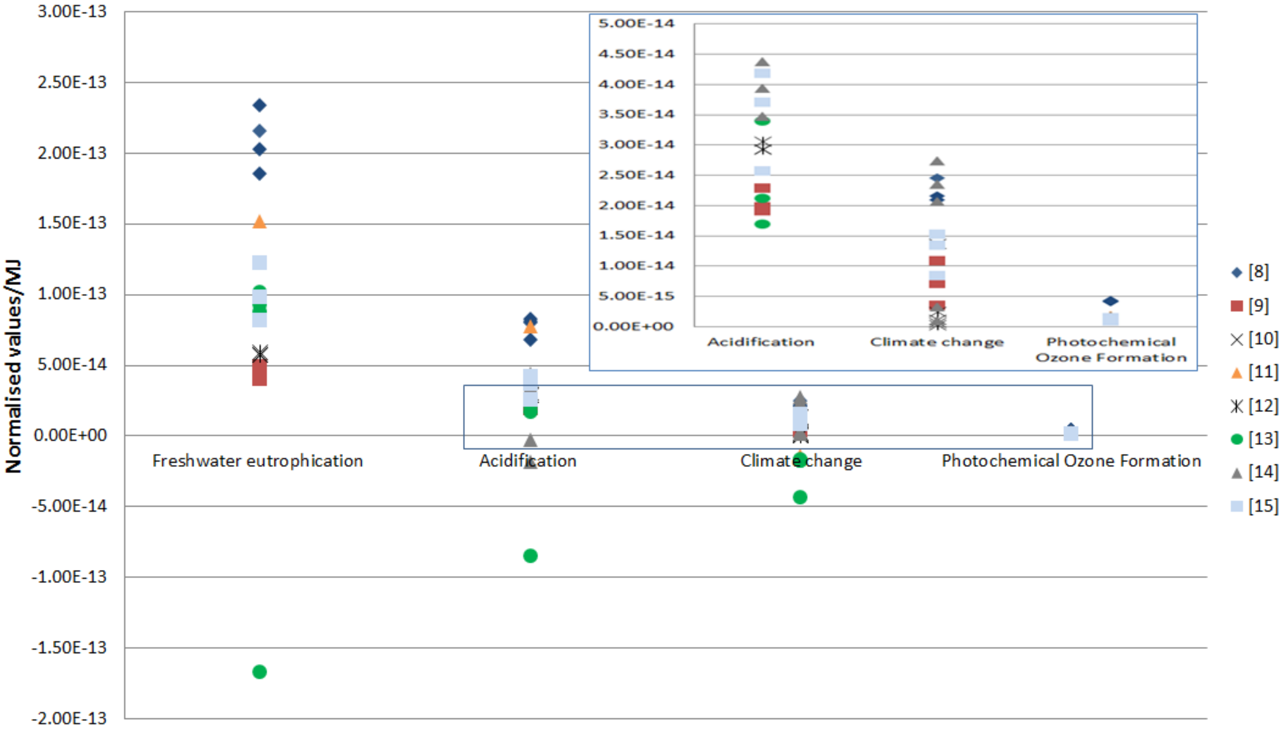


Figure 4. *Environmental performance expressed as normalised impact categories.*

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