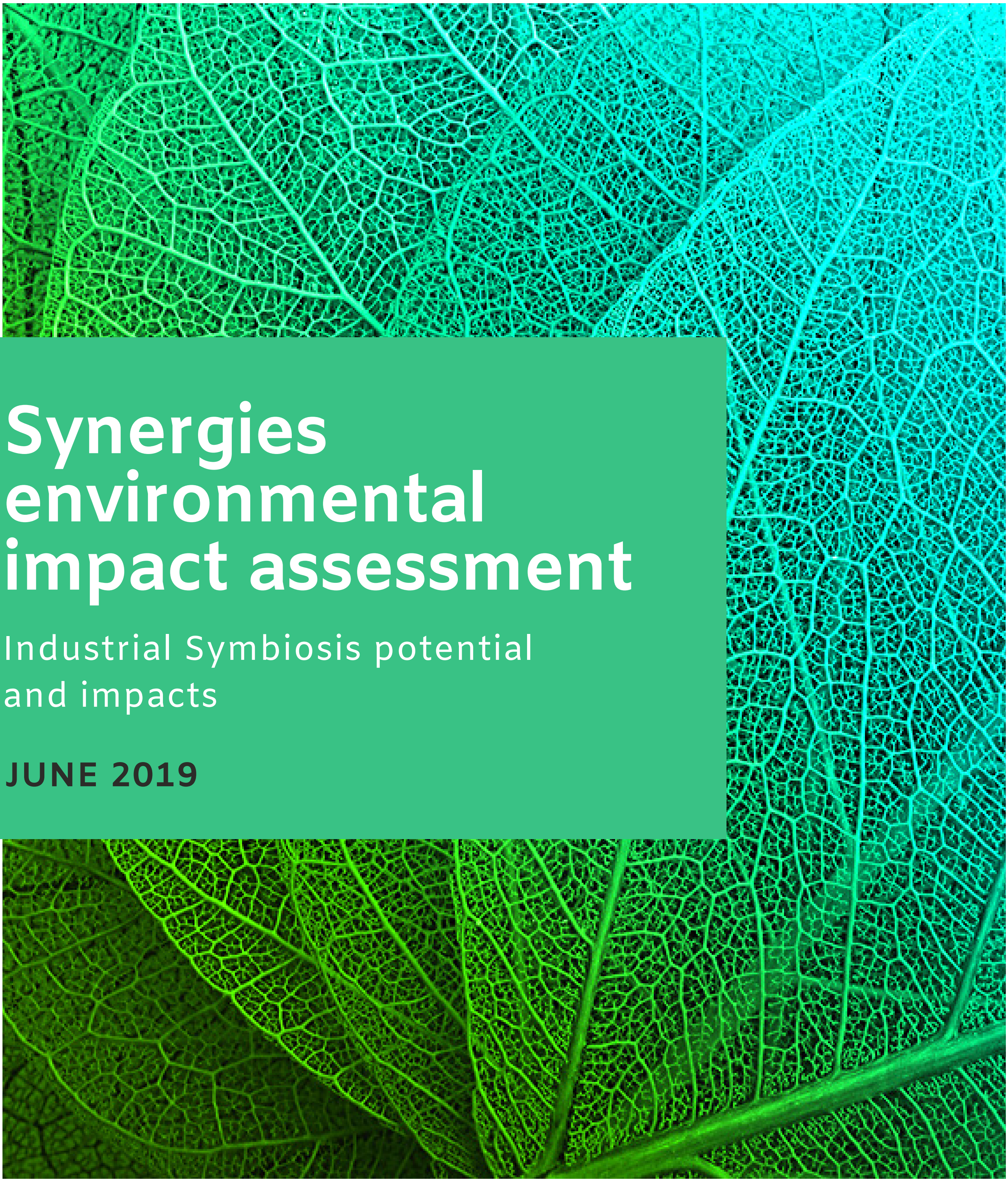

Synergies environmental impact assessment

Industrial Symbiosis potential and impacts

JUNE 2019

SCALER

SCALING EUROPEAN RESOURCES WITH INDUSTRIAL SYMBIOSIS

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Executive summary

This deliverable presents screening life cycle assessment results of the 100 synergy types which were selected in Deliverable 3.1 for assessing the potential of industrial symbiosis in Europe. The shortlist is considered representative of the diversity of synergies that may be encountered within a European context.

Of the 74 synergy types that could be modelled an estimated total climate change savings of 122 million tons CO_2-eq was calculated, equivalent to removing approximately 29 million cars off the road or 27 coal fired power plants. Other indicators confirm this environmental and human health benefits. These results clearly show the potential of industrial symbiosis in Europe from an environmental and human health perspective. Industrial symbiosis is thus a key driver to leverage the circular economy in Europe.

Major contributors to the savings mentioned above are the steel (slag and coke oven gas) and waste treatment industries (prepared fuel), identified as key sender sectors. With respect to the receiver sectors, the cement industry is key along with various sectors receiving prepared fuels from the waste treatment industry. The latter confirms the important role of intermediaries in industrial symbiosis, which is in line with the findings from Deliverable 2.1.

Other sectors present high IS potential; the highest unexploited potential lies in the glass and ceramic industries, mainly for indirect synergies.

A sensitivity analyses of some specific synergies as well as a comparison of modes and distances of transport allowed us to further investigate specific environmental impacts' and benefits' contributions. Key learnings include: (1) lorry transport is not necessarily negligible, but in general, long distances are needed for the impacts to outweigh the benefits of the synergy; (2) some procedures (including technologies) have very high energy requirements, which may outweigh the environmental benefits of the synergy; (3) in general, transport by train and/or barge should be chosen if possible, as their environmental and human health impacts are lower than that of lorry transport.

Data quality and availability was identified as one of the main challenges of this work. Despite an in-depth and extensive search for data, some synergies could not be evaluated due to a lack of data specifically needed from a life cycle assessment perspective. Primary industrial data are required to confidently model an accurate LCA. Although the scope of this work does not encompass modelling to this level of detail, secondary data allowed us to perform a screening level LCA, with a certain degree of uncertainty.

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Abbreviations

IS: Industrial symbiosis

SPIRE: European association for Sustainable Process Industry through Resource and Energy Efficiency

EAF: Electrical Arc Furnace

EAFD: Electrical Arc Furnace Dust

COG: Coke Oven Gas

BOF: Basic Oxygen Furnace

BOFG: Basic Oxygen Furnace Gas

BF: Blast Furnace

BFG: Blast Furnace Gas

LHV: Lower Heating Value

BREF: Best Available Techniques Reference Document

LCA: Life cycle assessment

TDB: Technology database

WWTP: Wastewater Treatment Plant

1. Scope

1.1 Objective

WP3 aims at quantifying the potential of industrial symbiosis in Europe. The specific objectives of the work package are to:

- Map industrial sites, identify new locations, estimate the potential reduction of operational / logistics costs from a wide implementation of IS in Europe.
- Provide an input / output flows database to enable an automatic identification of physical resource synergies
- Develop a database of technical solutions enabling the implementation of the synergies and estimate the related investment needs and related costs.
- Assess and quantify environmental and socio-economic impacts of a synergy implementation.

The aim of this deliverable is **to perform a screening level assessment of the environmental impacts of a synergy type implementation.** More specifically, the objective is to:

- Quantify the environmental impacts/benefits of the shortlisted 100 synergies types implementation
- Benchmark the identified synergies against a defined baseline scenario
- Provide input for the economic and social assessment (Task 3.5)

This deliverable builds upon the output from D3.1 “Short list of the 100 most promising synergies” and will provide input for Deliverable 3.4, the “socio-economic assessment of the synergies” implementation.

It is not the aim of this task to provide a detailed LCA for each of the 100 synergy types. A more detailed LCA of each synergy would require the collection of primary data at the operational/site level. The present report provides a hotspot analysis and preliminary recommendations for the most promising scenarios and/or configurations from a sustainability perspective based on the current status of data available.

2. Methodology

2.1 LCA approach

Heightened concern around the environmental and social sustainability of society’s consumption habits has focused attention on understanding and proactively managing the potential environmental and societal consequences of production and consumption of products and services. Nearly all major product manufacturers now consider environmental and social impacts as a key decision point in material selection, and sustainability is a recognized point of competition in many industries.

A leading tool for assessing environmental performance is life cycle assessment (LCA), a method defined by the International Organization for Standardization (ISO) 14040-14044 standards (ISO 2006a; ISO 2006b). LCA is an internationally-recognized approach that evaluates the relative potential environmental and human health impacts of products and services throughout their life cycle, beginning with raw material extraction and including all aspects of transportation, manufacturing, use, and end-of-life treatment. It is important to note that LCA does not quantify the real impacts (i.e. direct measurements have not been made at site) of a product or service due to data availability and modelling challenges. However, it allows us to estimate and understand the potential environmental impacts which a system might cause over its life cycle, by quantifying (within the current scientific limitations) the likely emissions generated and resources consumed. Hence, environmental impacts calculated through LCA should not be interpreted as absolute, but rather relative values within the framework of the study. Ultimately, this is not a limitation of the methodology, since LCA is generally used to compare different systems performing the same function, where the relative differences in environmental impacts which key for identifying the solution which performs best.

Among other uses, LCA can identify opportunities to improve the environmental performance of products, inform decision-making, and support marketing, communication, and educational efforts. The importance of the life cycle view in sustainability decision-making is sufficiently strong that over the past several decades it has become the main approach to evaluate a broad range of environmental issues, identify health and social risks and help make decisions within the complex arena of socio-environmental sustainability.

2.2 Goal and scope

2.2.1 Functional unit FU

The functional unit (FU) quantifies the performance of a product system and is used as a reference unit for which the LCA study is performed and associated results are presented. For the present study the functional unit, for each of the 100 synergy types, is the following:

FU = Waste stream to be treated/exchanged by a receiver industrial sector over a period of one year.

Note that one synergy type refers to a synergy that has been scaled up to represent all similar potential synergies of that type in Europe. The scale up is based on data collected by Strane Innovation on parameters such as number of sites and production volume per site. For example, for synergy 4, the recovery of coke from the organic chemicals sector and sent to the steel sector, is based on 39 facilities in Europe, for a total of 400’000 tons of coke per year. See Deliverable 3.1 for more information about each of the 100 synergy types and the associated data collected.

2.2.2 System boundaries

In order to assess the benefits of a potential synergy type, it is compared to a baseline scenario. The system boundaries of the baseline and synergies type scenarios are shown Figure 1. The boundaries include:

- The fate of the resource of interest if not used in the synergy type (baseline scenario)
- The stream (material, fuel) which would have been used if the synergy was not in place (raw material/fuel)

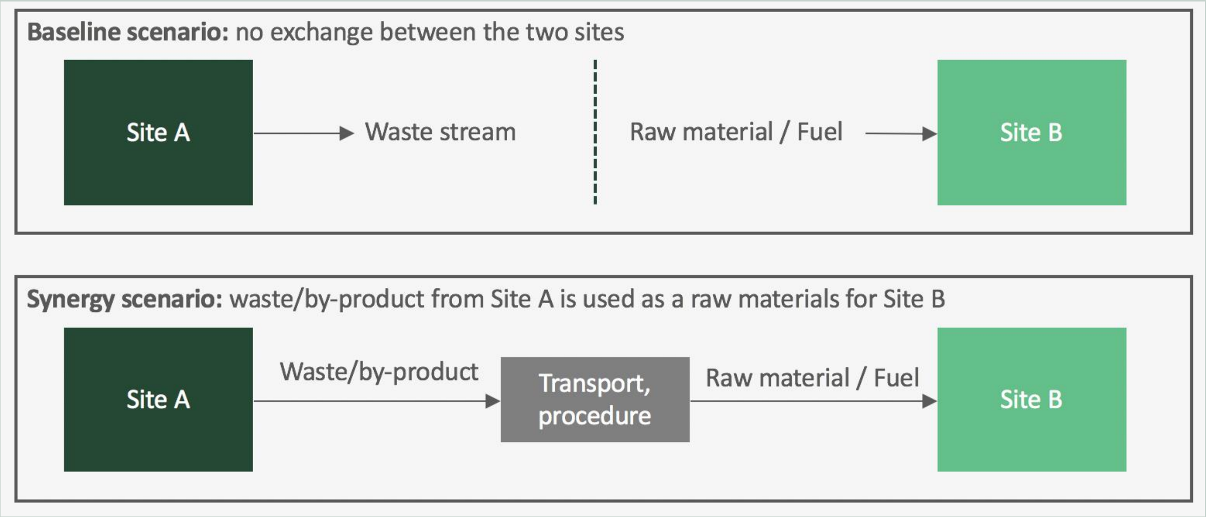

Figure 1. Schematic of baseline and synergy scenarios

It is important to note that the chosen system boundaries exclude potential operational effects of the synergy type on the sender and receiver industry such as:

- Physical and chemical raw material input quality requirements, e.g. purity requirements for a recycling process
- Product quality requirements, e.g. health and safety requirements for materials to be used in drinking water applications
- Modified emissions in receiver industry, e.g. increased SO_2 emissions from changing fuel source to pet-coke
- Additional needs for infrastructure, e.g. need for gas cleaning scrubbers or active coke filters
- Impact of market effects, e.g reduced efficiency leading to reduced sales
- Continuous availability of the flow

2.2.3 Life cycle inventory

The quality of LCA results are dependent on the quality of data used in the evaluation. Every effort has been made for this study to implement the most credible and representative information available.

All life cycle inventory data sources are taken from the *ecoinvent* database v3.4 cut-off by classification allocation model (Weidema et al. 2013). Ecoinvent is recognized as one of the most complete background LCI databases available, from a quantitative (number of included processes) and a qualitative (quality of the validation processes, data completeness, etc.) perspective. Historically focused on European production activities, it has reached a global coverage of thousands of commodities and industrial processes.

2.2.4 Impact assessment

Impact assessment classifies and combines the flows of materials, energy, and emissions into and out of each product system by the type of impact their use or release has on the environment. The method used here to evaluate environmental impact is the peer-reviewed and internationally-recognized life cycle impact assessment (LCIA) method IMPACT 2002+ vQ2.2 (Jolliet et al. 2003, adapted by Quantis). This method assesses 16 midpoint categories and then aggregates them into four endpoint (damage) categories. We have also included the water withdrawal indicator, which is an inventory level indicator. In total, the five indicators are the following:

- Climate change, expressed in kilograms of carbon dioxide equivalents (kg CO_2-eq);
- Human health, expressed in disability adjusted life-years (DALYs);
- Ecosystem quality, expressed in potentially disappeared fraction of species per square meter of land per year (PDF.m^2.y);
- Resources depletion, expressed in (in megajoules (MJ);
- Water withdrawal, expressed in cubic meters (m^3).

Table 1 presents the midpoints that are considered within each endpoint, as well as the corresponding units in which each indicator is expressed.

Table 1. List of endpoints and midpoints considered within each endpoint

Endpoint	Midpoint	Units
Human health	Human toxicity, carcinogens	DALY
	Human toxicity, non-carcinogens	
	Respiratory inorganics	
	Ionizing radiation	
	Ozone layer depletion	
	Respiratory organics	
Ecosystem quality	Aquatic ecotoxicity	PDF.m^2.y
	Terrestrial ecotoxicity	
	Terrestrial acidification/nutrification	
	Land occupation	
	Aquatic acidification	
	Aquatic eutrophication	
	Water turbined	
Resources	Non-renewable energy	MJ
	Mineral extraction	
Climate change	Global warming (IPCC 2013, 100a)	kg CO_2-eq
Water withdrawal	Water withdrawal	m^3

A more detailed description of each of the IMPACT 2002+ endpoint indicators is presented here.

Human health

Impact that can be caused by the release of substances that affect humans through acute toxicity, cancer-based toxicity, respiratory effects, increases in UV radiation, and other causes; an evaluation of the overall impact of a system on human health has been made following the human health end-point in the IMPACT 2002+ methodology, in which substances are weighted based on their abilities to cause each of a variety of damages to human health. These impacts are measured in units of disability-adjusted life years (DALY), which combine estimations of morbidity and mortality from a variety of causes.

Ecosystem quality

Impairment from the release of substances that cause acidification, eutrophication, toxicity to wildlife, land occupation, and a variety of other types of impact; an evaluation of the overall impact of a system on ecosystem quality has been made following the Ecosystem quality endpoint IMPACT 2002+ methodology, in which substances are weighted based on their ability to cause each of a variety of damages to wildlife species. These impacts are measured in units of potentially disappearing fractions (PDF), which relate to the likelihood of species loss.

Resources depletion

Depletion caused when non-renewable resources are used or when renewable resources are used at a rate greater than they can be renewed; various materials can be weighted more heavily based on their abundance and difficulty to obtain. An evaluation of the overall impact of a system on resource depletion has been made following the resources end-point in the IMPACT 2002+ methodology, which combines non-renewable energy use with an estimate of the increased amount of energy that will be required to obtain an additional incremental amount of that substance from the earth based on the Ecoindicator 99 method (Goedkoop and Spriensma 2000).

Climate change

Alterations in the statistical distribution of weather patterns of the planet over time that last for decades or longer; Climate change is represented based on the International Panel on Climate Change's 100-year weightings of the global warming potential of various substances (IPCC 2013). Substances known to contribute to global warming are weighted based on an identified global warming potential expressed in grams of CO_2 equivalents. Because the uptake and emission of CO_2 from biological sources can often lead to misinterpretations of results, it is not unusual to omit this biogenic CO_2 from consideration when evaluating global warming potentials. Here, the recommendation of the PAS 2050 product carbon footprinting guidance is followed in not considering either the uptake or emission of CO_2 from biological systems and correcting biogenic emissions of other gasses accordingly by subtracting the equivalent value for CO_2 based on the carbon content of the gas (BSI 2008).

Water withdrawal

Sum of all volumes of water used in the life cycle of the product, with the exception of water used in turbines (for hydropower production). This includes the water use (m3 of water needed) whether it is evaporated, consumed or released again downstream. Drinking water, irrigation water and water for and in industrialized processes (including cooling water) are all taken into account. It considers freshwater and sea water.

2.3 Methodology and assumptions

Performing a screening level LCA of the 100 synergy types identified in Deliverable 3.1 generated a number of challenges. The aim of this section is to document these challenges and explain how they were addressed.

2.3.1 Current vs non-current practice synergies

We have classified the synergy types presented in the Deliverable 3.1 shortlist as either "current practice" or "not current practice". Current practice means that these synergy types are currently practiced **to some extent** in Europe today, such as the use of Blast Furnace steel slag in cement (dedicated cement standards exist for this type of by-product: CEM III Blast furnace/slag). Synergy types which are classified as not current practice means their feasibility is yet to be evaluated and the synergy remains to be developed.

It is important to note that "current practice" does not mean that the synergy type has been fully implemented; it means that it has been partially implemented throughout Europe. This distinction is important, particularly with respect to the objective of the SCALER project, which is to assess the scale up potential of European resources through a wider implementation of industrial symbiosis. In this sense, the synergy types identified as current practice synergies may not contribute directly to the scaling up of European resources in the future, when compared to today.

One synergy type in the shortlist refers to many synergies that have been scaled up to represent all potential synergies of the same type in Europe (same sender sector and same receiving sector). The concept of current and not current is not entirely satisfying because one synergy type might contain both current and not current synergies, and more importantly, the distribution of the latter is unknown. One synergy might be current practice in one location, yet not in another, due to various reasons: operational, economic, regulatory, legal, etc.

Current practice synergies have been included in the life cycle assessment results; results are thus presented as a range, rather than a single number for each indicator so as to avoid an overestimation of the potential in Europe.

2.3.2 Baseline scenario

The quantification of the environmental and human health impacts or benefits of the synergy is carried out by comparing the synergy scenario to another system that performs the same function: **treating a certain quantity of a waste stream or resource of interest, per year** (see section 2.2.1). This baseline scenario is used as a basis of comparison for the analysed synergy type. The baseline scenarios identified for all synergy types can be found in the Appendix.

The baseline scenario is defined by answering the following two questions:

- For the symbiosis under study, what would have been the fate of the resource of interest stream had it not been used by the defined receiver sector of the synergy?
- If the receiver sector would not have used the waste stream from the sender sector, what raw material or energy flow would have been used in substitution?

Figure 2 illustrates an example of the impacts and benefits of the baseline and synergy type scenarios and how the overall benefits are calculated. The figure is not to scale and is for illustration purposes only. In the example shown, we have considered the avoided impact of a raw material, but the illustration would be similar for an energy flow.

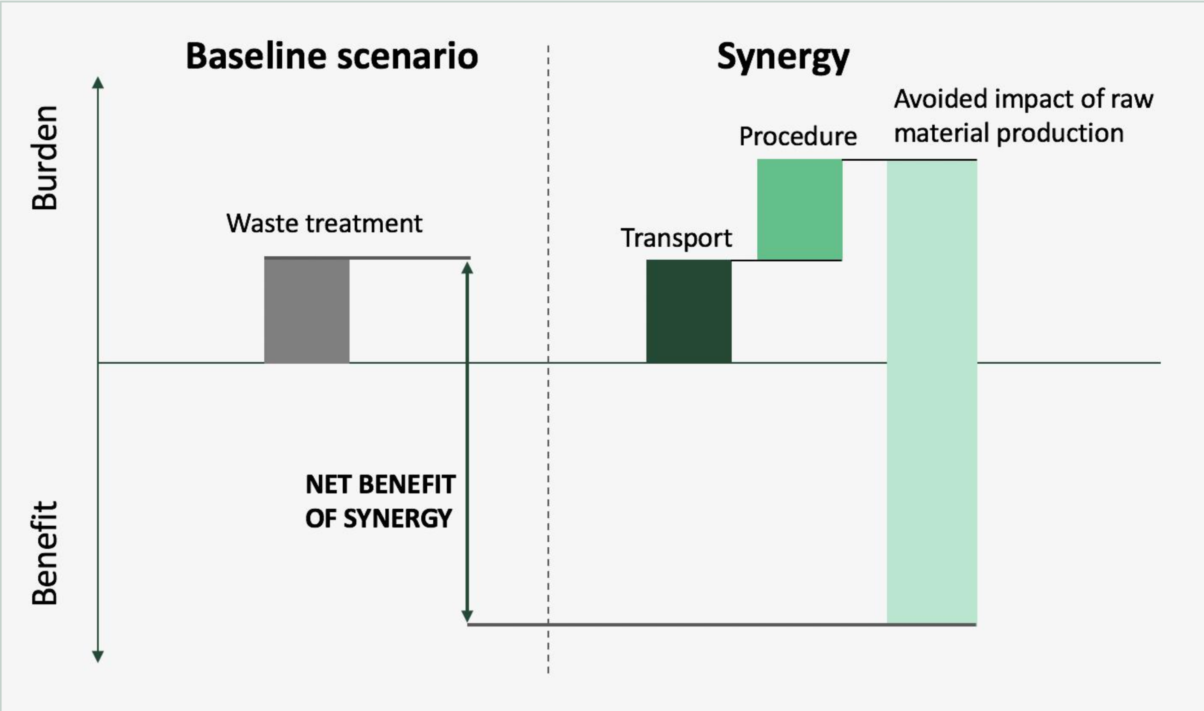

Figure 2. How benefits are accounted for between baseline and synergy scenarios

For each synergy type, different baseline scenarios may exist (Figure 3: Fate of steel slags in the European Union (source: Euroslag)). It is challenging to define current European practices for a given waste stream or synergy type, as this may depend on various operational parameters, country specific legal frameworks, economic feasibility, etc. and can therefore vary within one synergy type.

When defining the baseline scenario for the various synergy types, the key criteria is to ensure the comparability of results between synergy types. To match these requirements, we have hence selected a baseline waste treatment of landfilling (for solid waste/inert waste) or incineration (for materials with a certain energy content, e.g. calorific value LHV).

For many materials however, different valorisation routes exist. An example of this can be seen in Figure 3 which depicts the fate of steel slag in the European union.

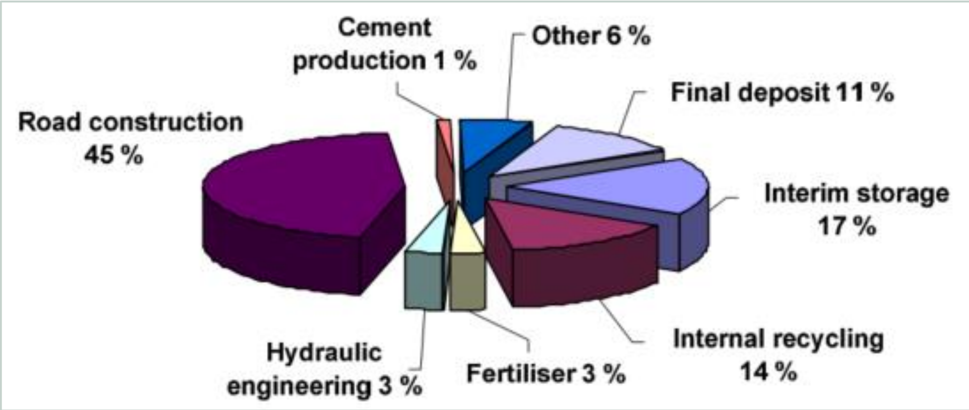

Figure 3: Fate of steel slags in the European Union (source: Euroslag)

This level of modelling detail could not be included in present deliverable because for most synergy types, this distribution is not detailed enough, and data are difficult to access. Direct contact with industries would be needed in order to collect primary data which better reflects the state of industrial symbiosis in Europe; this beyond the scope of the present deliverable.

Generic information on the fate of the waste stream is available in literature; nevertheless, data were often not accurate enough for LCA modelling (industrial primary data required) and it was impossible to generate these data for all synergy types. The modelling of all waste stream fates was outside the scope of this project, thus generic scenarios were therefore chosen (landfilling or incinerated).

The limitations described above may have led to an overestimation of the calculated environmental and human health benefits; results should be interpreted with caution.

2.3.3 Indirect synergies

In addition to classifying each synergy according to whether it is current practice or not, each synergy was also defined as either direct or indirect (see Deliverable 3.1). A synergy type is considered **direct** if the stream is directly used, or with basic technology (e.g. crusher, packaging, transport, storage, collection/distribution), as a substitute for another raw material or energy flow (substitution). A synergy type is considered **indirect** if the stream requires a transformation or a procedure[1]. This procedure can take place by an involved stakeholder or a third party. For details on indirect synergies and their associated procedure, please refer to the technology database in Deliverable D3.2.

For indirect synergy types the data needed for the modelling of the procedure includes heat, energy and water use per tonne of material and ideally emission data of the studied technologies. A substantial effort by ISQ resulted in the collection of this data, mostly from literature, and is available

[1] Technology Database definition of PROCEDURE (P) = PRETREATMENT (PT) + TECHNOLOGY (T) + POST TREATMENT (POT)

in the technology database TDB (Task 3.2) Despite ISQ's efforts, data could not be provided for all indirect synergies. Sensitivity analyses of some synergy types are presented in section 3.7, which explore the procedure impacts.

Generally speaking, the calculated benefits of the indirect synergies may be overestimated. However, results still allow us to evaluate the maximum impacts before the synergy is no longer considered interesting, from an environmental and human health perspective.

2.3.4 Transport

Each synergy type in the shortlist database is a scale-up of many synergies across many sites; distances and modes of transport may vary significantly from one potential synergy to the next. Putting a synergy in place may result in a longer or shorter transport distance compared to the baseline scenario, as well as potentially a different mode of transport, e.g. train rather than lorry. Rather than attempt to model transport consistently for each synergy type, this is addressed in a sensitivity analysis (section 3.7.5).

2.3.5 Avoided impacts

When a waste stream is used to replace a raw material or energy flow (see Figure 2), the avoided raw material/energy flow is selected from the ecoinvent v3.4 database, based on average European production or a suitable proxy. It is complex to identify the material/energy flow which is avoided. Because of the scale up of the synergies, the avoided material/energy flow may differ from one operation setting to another. For example, for one synergy type, a resource of interest with energy content might replace heavy oil, coal, coke or other fuels. The chosen avoided raw material/energy flow may have a considerable influence on the calculated benefits. Efforts were made to select the material/energy flow which is the most realistic as possible. For replaced materials/energy flow for which a European dataset does not exist in the ecoinvent database, a suitable proxy was chosen based on the practitioners' expertise, in collaboration with the consortium partners from WP3, and using literature research.

2.3.6 Data availability

The main data source for this deliverable is the shortlist of the 100 synergy types presented in Deliverable 3.1. Each synergy type described in Deliverable 3.1 is already presented as a scale up of similar synergies across many sites. For a synergy type to be modelled from a life cycle assessment perspective, the data requirements are the resource volume demand of the receiving sector (or resource of interest stream volume from sender sector) and the type of material substituted (for avoided impacts modelling). For a material of interest that are contained in another material (for example hydrogen content in coke oven), the concentration of the material of interest must be known. If these data are not available, the synergy type cannot be modelled (see list in Appendix).

Much of the data needed was collected in Deliverable 3.1 mainly from BREF documents. The data collection methodology has been documented in this same deliverable.

When working on the current deliverable it became clear, that the data granularity was in many cases not sufficient to calculate a meaningful screening LCA; about 60 synergy types could be modelled. Additional efforts were made by WP3 partners ISQ, Strane and Quantis, in order to improve the data quality of the 100 synergy types shortlist. This resulted in an increase from 60 to 74 synergy types that could be modelled. The remaining 26 were classified as "cannot be modelled"; including these in this deliverable would entail reaching out to industry to collect primary data, which is beyond the scope of this work.

No correlation was observed between the synergy types in specific sectors or certain materials with a lack of data.

For four synergy types a zoom was performed, where more detailed data could be collected, and the LCA was conducted at a higher level of detail. They are presented separately in section 3.7).

2.3.7 Various (prepared fuel) and waste treatment industry

The waste treatment industry is identified as an important sender sector in the synergies' shortlist, sending prepared liquid and gaseous fuels to a number of different industries, referred to as "Various (prepared fuel)". Various industries buy prepared fuels as a product from the waste treatment industry. Note that the synergy types considered here are not double counted with other synergy types. Although included in the 100 synergy types shortlist, these synergy types are actually the core activities of these industries.

It is important to understand, that

- the materials exchanged here are not actually waste streams of an industrial process, but among the main products of the waste treatment industry in the form of residue derived fuel (RDF), traded as a commodity
- To adequately model the environmental and human health benefits of these synergy types, the impacts of preparing that fuel from the original waste delivered to or collected by the waste treatment industries would need to be considered. This would imply knowing the applied transformation technology, its energy demand and emissions, as well as the nature and characteristic of the original waste from which the residue derived fuel was made from. In this sense the waste management industry can be seen as a pre-treatment.

2.3.8 Volumes

Volumes of waste sent (sender sector) and/or receiver sector demand volumes were estimated by Strane (Task 3.2). These values are dependent on data availability and for some synergy types the uncertainty may be high. When a range is reported in the 100 synergy types shortlist (Deliverable 3.1), the average value was used. The preferred volume used for the LCA modelling is the receiving sector demand volume, unless it is higher than the resource of interest volume sent, in which case the latter is used. If the sector demand volume is unknown, the volume of waste sent is used.

It is interesting to note that resource of interest volumes are correlated with the production volume of an industry; the steel industry (slag) is thus at the forefront of the sender sectors in terms of volume.

2.3.9 Synergy types 91 to 96

Synergies types 91 to 96 represent the **waste heat, steam and fuel feedstock** produced by various sender industries and received by various receiving industries. No total volumes are provided for these synergy types and they are modelled per GJ of heat recovered (synergy types 91 and 92), GJ of steam recovered (synergies 93 and 94) and tonne of waste fuel feedstock (synergy types 95 and 96). Results are presented separately in section 3.6.

2.3.10 Summary of challenges and assumptions

Table 2 summarises the challenges discussed above so as to give the reader an overview, particularly when interpreting the results section.

Table 2. Summary of LCA modelling challenges and assumptions

Topic	Challenge	Approach
Current vs non-current synergy types	Roughly half of the 100 synergy types identified in D3.1 are already currently practiced to some extent; the breakdown is unknown. How was this included in the assessment?	Results are presented as a range. "Current practice" synergies are presented compared to baseline scenarios (incineration or landfill). Results reflect to some extent potential that has already been exploited in the past.
Baseline scenario	Different synergies can have different baseline scenarios but at the same time consistency and comparability needs to be ensured	Baseline waste treatment scenarios of incineration or landfilling are considered
Direct and indirect synergy types	Required procedure inputs and emissions are not available for all indirect synergies	A focus on synergies for which data is available has been presented. For other synergy types, results are to be interpreted as a maximum impact for which procedure impacts are acceptable (for the synergy type to remain interesting).
Avoided impacts	The raw material/energy flow that the synergy resource of interest is substituting is not known or the avoided impact dataset is not available in ecoinvent	Best possible proxy is used according to practitioners' experience and discussion with consortium partners.
Data availability	For 26 synergies, lack of data does not allow LCA modelling.	Recommendations for future work to address this issue.
Waste stream volumes	Volumes present a high uncertainty range	Average value is used.
Waste stream volumes	Waste stream volumes data is not available	Sector demand is used as a proxy
Generic synergy types	The synergy types 91-96 are synergies involving waste heat, steam and fuel feedstock with no estimated total volumes	LCA calculation was done in a generic way, calculating savings per GJ of heat or steam recovered, or tonne of waste fuel feedstock.

3. Results

3.1 Overall results

Of the 74 synergy types that could be modelled an estimated total climate change savings of 122 million tonnes CO_2-eq is calculated. This is equivalent to approximately 29 million cars or 27 coal fired powerplants.

Table 3 presents the overall life cycle assessment results of the synergy types modelled, with corresponding benchmarks, in order to have an idea of the order of magnitude of the potential.

Table 3. Total savings calculated from synergy types modelling

Indicator	Potential savings (max)	Units	Benchmark
Climate change	122	million t CO_2-eq	29 million cars not driven[1]
Human health	138’000	DALYs	6.6 billion cigarettes not smoked[2]
Ecosystem quality	26	Billion PDF.m^2.y	3.6 million ha of forest saved from conversion to concrete[3]
Resources	$2.1x10^{12}$	MJ	350 million barrels of oil not extracted[4]
Water withdrawal	2.9	Billion m^3	1.1 million Olympic size swimming pools[5]

[1] *Assumption one car travels 20'000 km/year*
[2] *2.09E-05 DALY / cigarette*
[3] *10’000 PDF.m^2.y / ha forest converted to concrete*
[4] *5’858 MJ primary energy / barrel of oil*
[5] *2’500 m3 water/Olympic size swimming pool*

The results clearly show the potential of industrial symbiosis in Europe, from an environmental and human health benefits perspective. Industrial symbiosis is thus a key driver to leverage the circular economy in Europe.

The savings presented above include current and non-current practice synergy types. As explained in section 2.3.1 the concept of current and non-current synergy types is not entirely satisfying; it is difficult to estimate the share of a synergy type which is widely practiced (current practice) vs not. The calculated savings are thus to be interpreted as a range, from 0 to 105 Mio t CO_2-eq savings for synergy types classified as current practice. The total range carbon savings range is thus 17 to 122 Mio t CO_2-eq.

Of the 74 synergy types that could be modelled, 43 are classified as “current practice” and 31 are classified as “not current practice”. Again, the definition given to “current practice” means that these synergy types are practiced **to some extent and in place at some sites** (see section 2.3.1).

The savings listed in Table 3 result from a comparison to a baseline scenario such as incineration or landfill. The savings include the benefits of not having to dispose of the waste, but also the avoided impacts from the production of raw material used in the receiver sector, based on the synergy type definition. Excluded from these calculations are procedure and transport impacts.

3.2 Flows between sender and receiver sector

Below the climate change result (thousand tonnes CO_2-eq) are expressed as a Sankey figure from sender sectors (left) to receiver sectors (right), for all modelled synergy types.

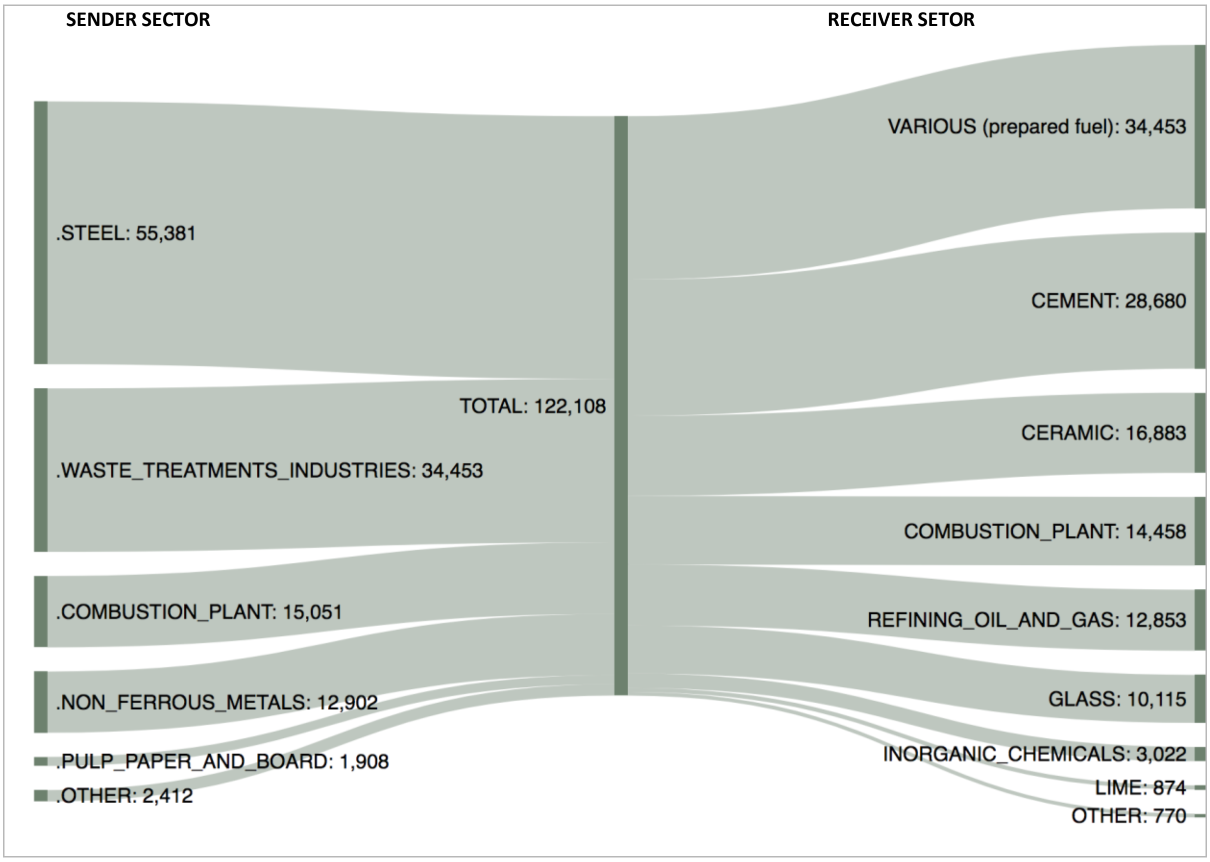

Figure 4. Climate change results (thousand tonnes CO_2-eq), expressed as a Sankey figure from sender sectors (left) to receiver sectors (right), for all modelled synergies

The main climate change savings contributors from the sender sectors are steel industry and waste treatment industries, about ¾ of the climate change savings.

For steel the savings mainly reflect the slag used in the cement industry, as well as coke oven gases (COG) used in combustion plants. The contribution of savings from the steel industry can be explained by the large quantities of steel, and thus large quantities of resources of interest (slag and coke oven gas), produced in Europe. For some types of steel slags such as blast furnace (BF) slag, this synergy type is current practiced and exploited to some extent. However, for basic oxygen furnace (BOF) slag, this synergy is less exploited, mainly for economic reasons, and thus still presents a large potential.

Given the share of environmental savings from the steel industry resources of interest, these synergy types should be further explored at a higher level of operational and geographical detail in order to ensure this potential is further exploited.

The special case of waste management industry was discussed in section 2.3.7. The large quantity (about 9 Mio tons) of high calorific resources of interest (oil, bitumen, methanol and gas oil, synergies 97 to 100) produce high calorific value fuels highlights the correlation between mass and environmental savings. This result illustrates the important role played by business-driven intermediaries in encouraging industrial symbiosis. This observation is aligned with Deliverable 2.2, where classic intermediaries were identified as having an important role in replicating IS.

The graph below shows the same Sankey diagram as above, removing the steel industry resources od interest sent to the cement sector (but keeping those sent to other industries) and waste management industry send to prepared fuels, in order to focus on the potential of the other industries. The steel sector still presents a large advantage for industries other than the cement sector; the steel industry resources of interest can be potentially recovered in many other industries such as ceramic, combustion plant, glass, refining oil and gas.

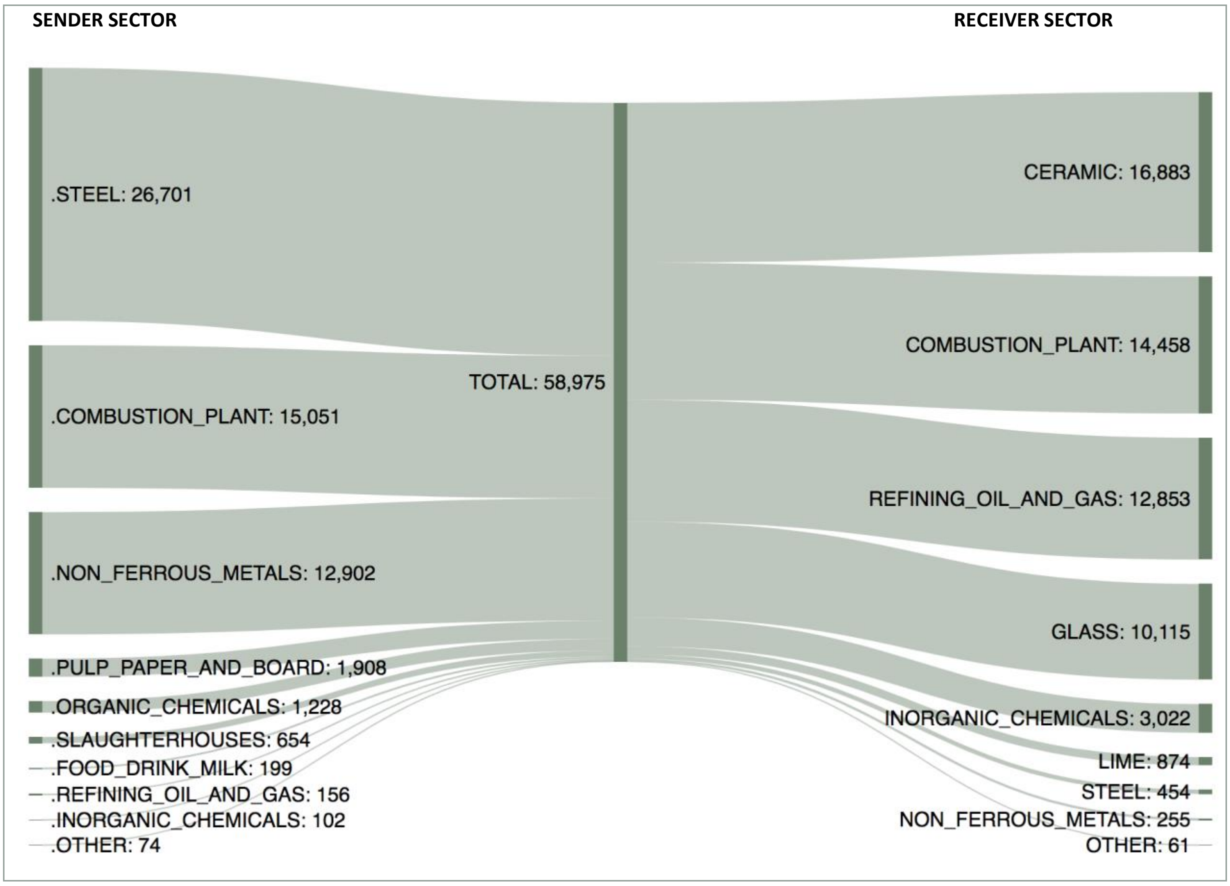

Figure 5. Climate change results (thousand tonnes CO_2-eq), expressed as a Sankey figure from sender sectors (left) to receiver sectors (right), excluding (1) waste treatment to various (prepared fuels) and (2) steel to cement

3.3 Receiver sector and origin of resources of interest

More detailed results are presented in this chapter for the climate change indicator. The trends for the other LCA indicators are similar and results can be found in the Appendix.

Figure 6 shows climate change results for the top receiver sectors, illustrating which sender sectors are the main contributors. As previously discussed, the waste treatment industries which deliver residue derived fuel to various receiver sectors have an important climate change savings contribution; note that care was taken to ensure that there is no double counting with other synergy types modelled.

For cement, a large share of the carbon savings is from the steel industry, which reflects the use of slag; some synergy potential is also seen with the non-ferrous metal industries.

For the ceramic industry the main synergy driver is the use of blast furnace and converter slag and basic oxygen furnace slag as raw material.

Combustion plant and refining mineral oil and gas industry are receivers of coke oven gas from the steel industry for its calorific value.

For the glass industry, the results reflect the benefit of using aluminium oxides (indirect), slag and refractory products (direct) as raw materials in glass manufacturing.

For inorganic chemicals, the main contribution comes from the use of sulphuric acid (indirect) as raw material. This is mainly due to the high impact of the production of virgin sulphuric acid. This results however probably presents a high uncertainty range as the concentration and purity of the sulphuric acid is not a known parameter. The remaining part comes from using lime and silica.

The synergies with the refining mineral oil and gas is mainly from coke oven gas from the steel industry.

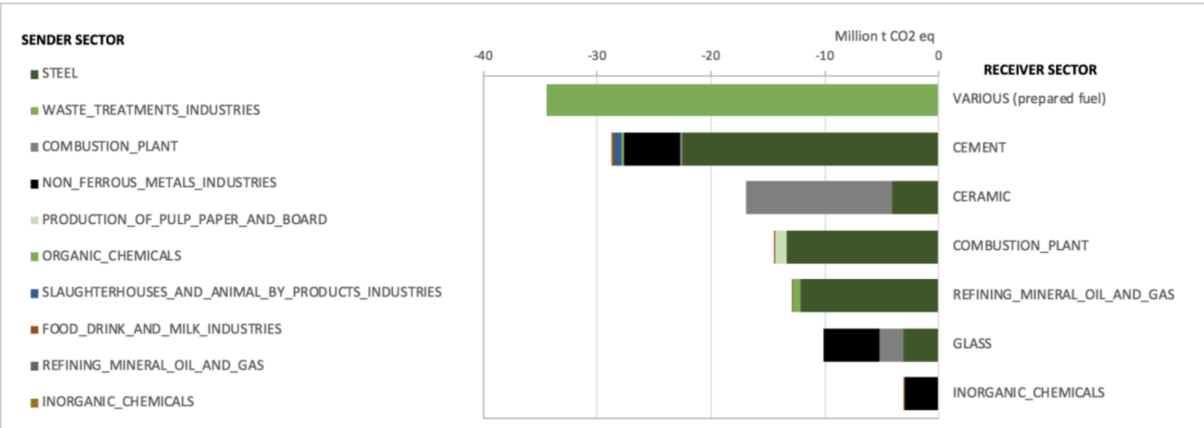

Figure 6. Climate change results for the receiver sector, by sender sector, for all modelled synergies

3.4 Receiver sector | Direct and indirect synergy types

Figure 7 and Figure 8 show climate change savings for the receiver industries for the top 7 (Figure 7) and remaining industries (Figure 8, change of scale). The top 7 industries represent 99% of climate change savings while the remaining represent 1%. The breakdown of direct and indirect synergies can be seen in the figures, and we can see that direct synergy types are important in terms of potential. Many indirect synergies indicate a remaining potential to be tapped and intermediaries play an important role here in facilitating and encouraging synergies. The main high potential receiver industries are various prepared fuels, cement, ceramic, combustion plant, oil and gas refining, glass and inorganic chemicals.

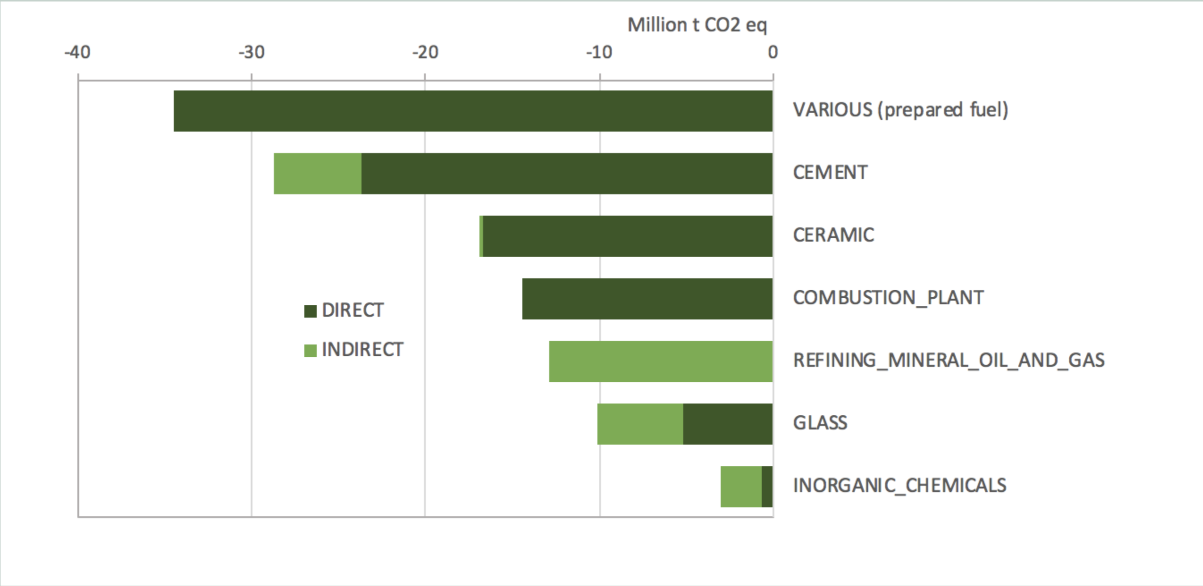

Figure 7. Climate change results for the receiver sector, illustrating direct and indirect breakdown, for top 7 industries

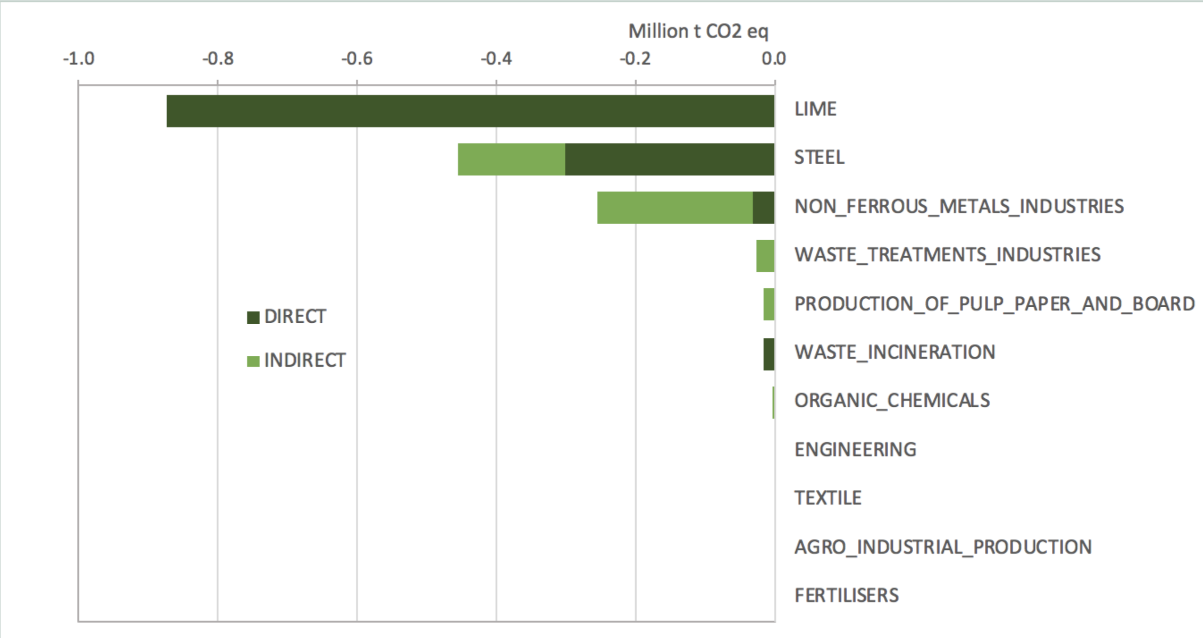

Figure 8. Climate change results for the receiver sector, illustrating direct and indirect breakdown, for other industries excluded from the top 7 in above figure.

For each synergy type, the baseline waste treatment before the synergy is in place is assumed to be incineration, landfilling or wastewater treatment (WWTP). Figure 9 presents climate change savings results for the receiver sector, for all synergies, classified by baseline waste treatment scenario. Results show that waste that is both landfilled and incinerated has a potential to participate in a synergy and depends on the receiving industry. The various (prepared fuels), combustion plant and refining mineral oil and gas sectors receive flows that would be incinerated if no synergy is in place. The cement, glass and ceramic sectors receive flows which would be landfilled if no synergy is in place.

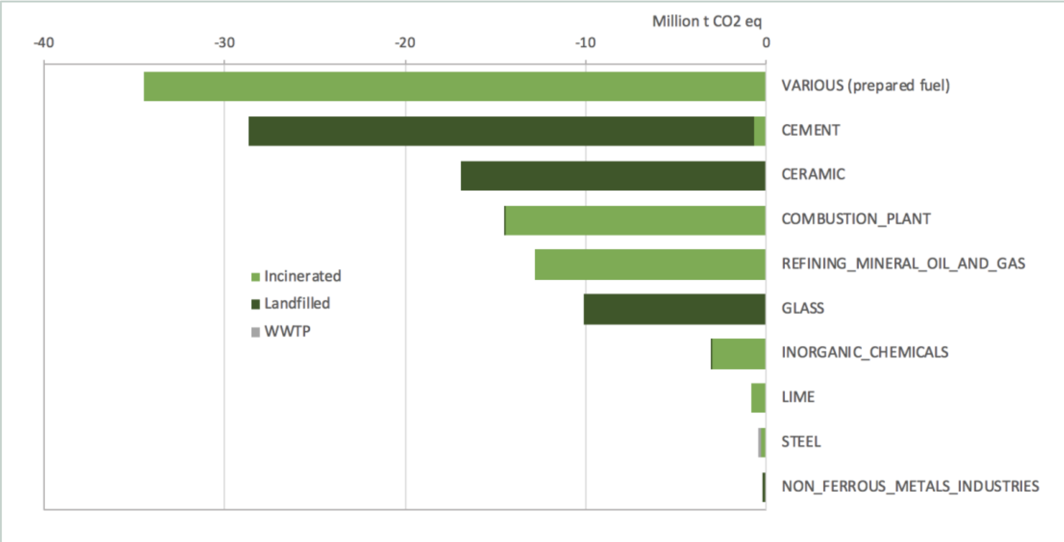

Figure 9. Climate change results for the receiver sector, by baseline waste treatment scenario, all synergies

3.5 Sender sector | Direct and indirect synergy types

Figure 10 and Figure 11 show climate change savings for the sender industries for the top 6 (Figure 10) and remaining industries (Figure 11, change of scale). The top 6 industries represent 99% of climate change savings while the remaining represent 1%. As mentioned in section 3.4, the direct synergy types are important in terms of potential, yet many indirect synergies indicate a remaining potential to be tapped. The main high potential sender industries are various: steel, waste treatment, combustion plant, non-ferrous metals, pulp and paper and organic chemicals.

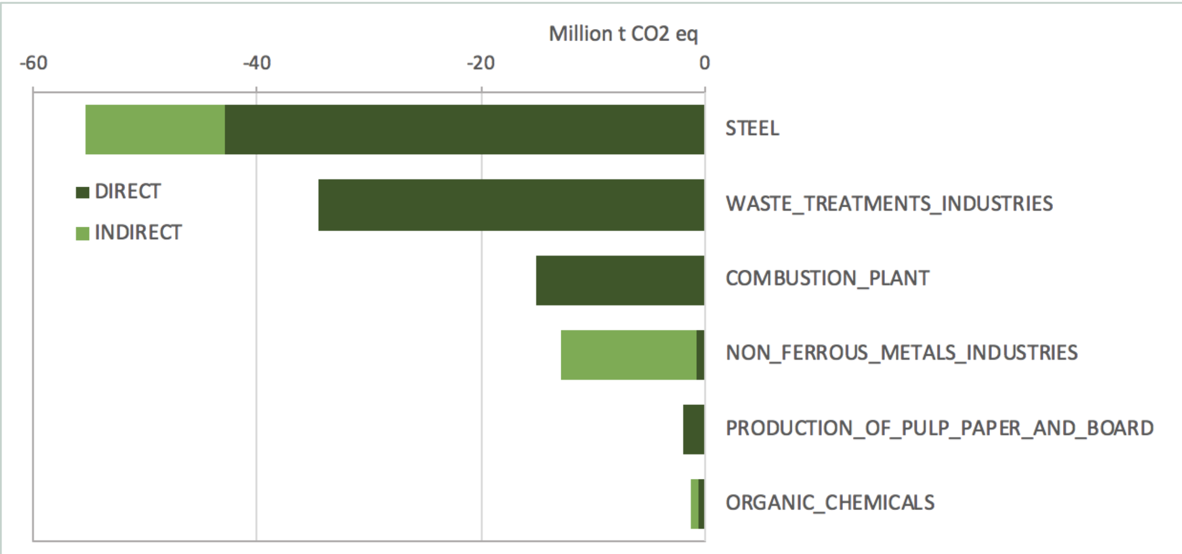

Figure 10. Climate change results for the sender sector, illustrating direct and indirect breakdown, for top 6 industries

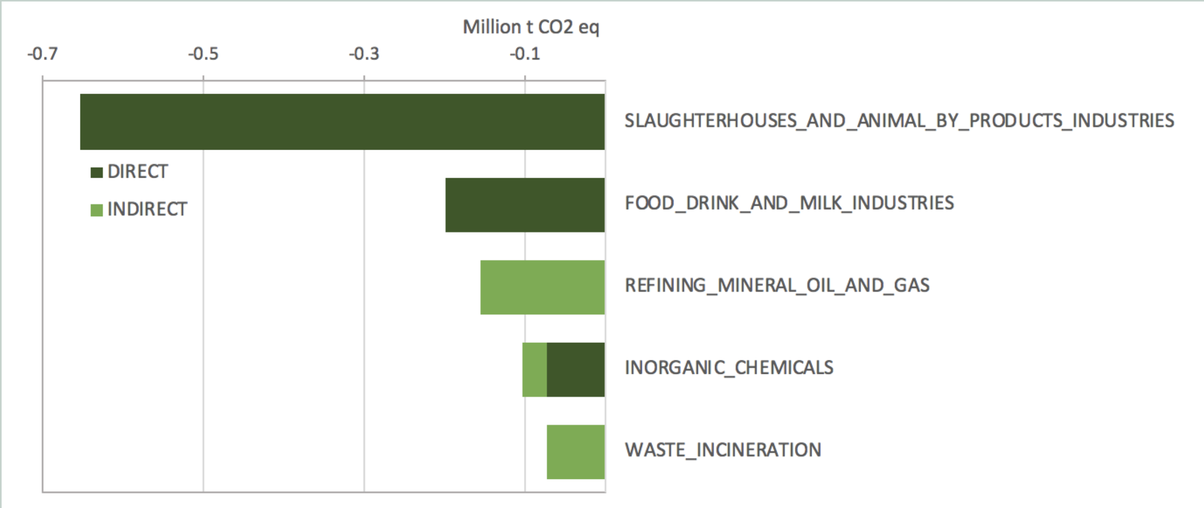

Figure 11. Climate change results for the sender sector, illustrating direct and indirect breakdown, for other industries excluded from the top 7 in above figure.

3.6 Synergy types 91 to 96

Synergy types 91 to 96 are explored separately because these represent generic synergies and results are presented per GJ of waste heat recovered (synergy type 91 and 92), per GJ of heat from steam (synergy type 93 and 94), and per tonne of generic residue derived fuel (synergy type 95 and 96). Table 4 presents life cycle results for the generic synergy types, synergy types 91 to 96. The results show the potential, per GJ of energy recovered or per ton of waste recovered for fuel feedstock.

Table 4. Generic life cycle assessment results for synergies 91 to 96

Synergy type description	**Climate change** (kg CO_2-eq)	**Human health** (DALY)	**Ecosystem quality** (PDF.m^2.y)	**Resources** (MJ)	**Water withdrawal** (m^3)
Synergy 91, 92: waste heat recovery (results per GJ heat recovered)	-96	-5.78E-05	-11	-1'464	-0.5
Synergy 93, 94: steam recovery (results per GJ steam recovered)	-103	-3.13E-05	-9	-1'568	-1.1
Synergy 95, 96: waste recovered for fuel feedstock (results per ton waste recovered)	-3'121	-1.61E-03	-592	-67'188	-64

3.7 Focus on some synergies

As explained in section 2.3.6 data availability and quality has been a challenge for the life cycle assessment modelling and the environmental impacts of the technologies needed for indirect synergy types has not been systemically included in all modelled synergy types. In order to determine whether these impacts would have a large influence on results, some synergies were selected for which a more detailed assessment was performed; this assessment includes the benefits of the synergy type (e.g. avoided impacts of waste treatment and production of virgin raw material, as well as transport and procedure impacts). The detailed assessment was possible due to a collective effort from Strane, Quantis and ISQ to collect more detailed data.

The technology "procedure" refers to:

PROCEDURE (P) = PRE-TREATMENT (PT) + TECHNOLOGY (T) + POST-TREATMENT (POT)

and is explained in more detail in the technology database Deliverable 3.2. The synergy types assessed in more detail in the following sections are for technologies which were given a "GO" (as opposed to "NO GO"); see Deliverable 3.2 for more details about the GO / NO GO selection criteria.

3.7.1 Synergy type 18 | Hydrogen recovery from inorganic chemicals

Synergy 18 is an indirect synergy, where hydrogen is recovered from sodium chlorate production, from the inorganic chemicals industry to be used in the hydrocracking process of the oil and gas refining industry. The baseline waste treatment scenario for this synergy is incineration; we have considered the impacts for the incineration of hydrogen to be negligible. The procedure to recover the hydrogen involves electrolysis and purification (see Deliverable 3.2 for more details), procedures with a very high electricity demand. The electricity requirements are from 4700 (synergy 18b) to 5200 (synergy 18c) kWh per tonne of sodium chlorate processed, which yields 60 kg of hydrogen. Pipeline transport is modelled for the recovered hydrogen.

Table 5 presents the four scenarios studied for the sensitivity analysis.

Table 5. Synergy 18, hydrogen (H_2) recovery from inorganic chemicals industry

Scenario	Description (all scenarios include the benefits of the synergy type, avoided hydrogen production)
Synergy 18a	No procedure or transport
Synergy 18b	4700 kWh electricity/t $NaClO_3$, 0.060 t H_2/t $NaClO_3$, 50 km pipeline transport
Synergy 18c	5200 kWh electricity/t $NaClO_3$, 0.060 t H_2/t $NaClO_3$, 50 km pipeline transport
Synergy 18d	No procedure, 2500 km pipeline transport

$NaClO_3$: sodium chlorate

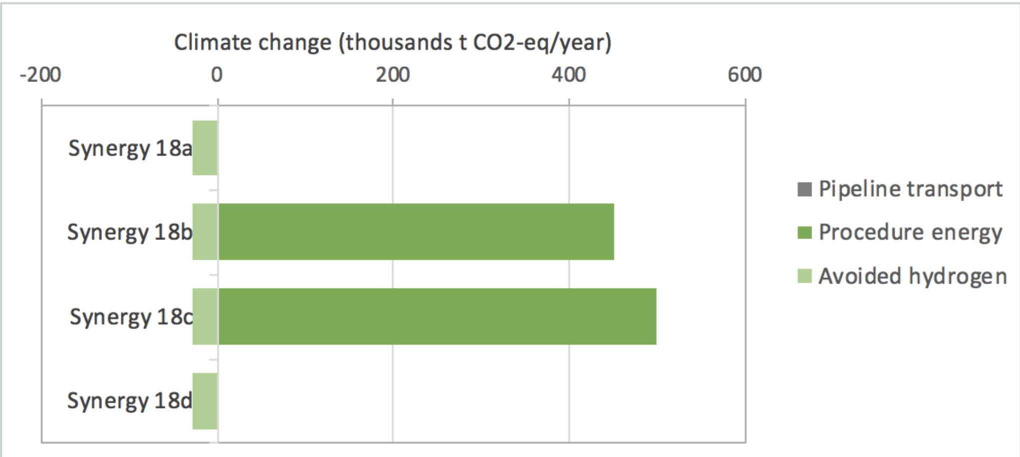

Figure 12. Synergy 18, hydrogen recovery from inorganic chemicals industry, sensitivity analyses

Figure 12 shows results for the different scenarios presented in Table 5. For the scenario synergy 18a, no procedure is considered, only the avoided impacts of hydrogen recovery and 50 km of transport by pipeline. The transport impacts are negligible compared to the savings. Even in synergy 18d, where 2500 km of transport is considered, the impacts are negligible compared to the savings.

However, when considering the procedure, both the low and high electricity consumption estimates, synergy 18b and 18c respectively, result in a very high climate change result, which outweighs the avoided impacts of hydrogen recovery; procedure impacts are roughly 16 to 17 times higher than climate change savings. In other words, the benefits of the synergy are cancelled out by the use of the technology. This technology could thus potentially be re-classified as a NO GO but would need further study.

3.7.2 Synergy type 21 | Sulphur recovery from steel industry

Synergy 21 is an indirect synergy, where sulphur is recovered from coke oven plants in the steel industry to be treated and compliant for recycling in the sulphite pulping process, in the pulp and paper industry. The baseline waste treatment scenario for this synergy is landfill. The procedure required to put this synergy in place is combustion to produce sulphur dioxide and a catalytic step for the unburned H_2S to react with SO_2 to produce sulphur and water for cooling and condensation. The heat and electricity requirements for the procedure vary from 1000 to 1600 MJ and 60 to 75 kWh, respectively, per ton of resource treated. Cooling water is also used, from 0 to 20 m^3 per t of resource of interest.

Table 6 presents the four scenarios studied for the sensitivity analysis.

Table 6. Synergy 21, sulphur recovery from steel industry

Scenario	Description (all scenarios include the benefits of the synergy type, avoided sulphur production and landfilling)
Synergy 21a	No procedure or transport
Synergy 21b	1000 MJ natural gas/t slag, 60 kWh/t electricity, 50 km truck transport
Synergy 21c	1600 MJ natural gas/t slag, 75 kWh/t electricity, 20 m^3 water, 50 km truck transport
Synergy 21d	No procedure, 2500 km truck transport

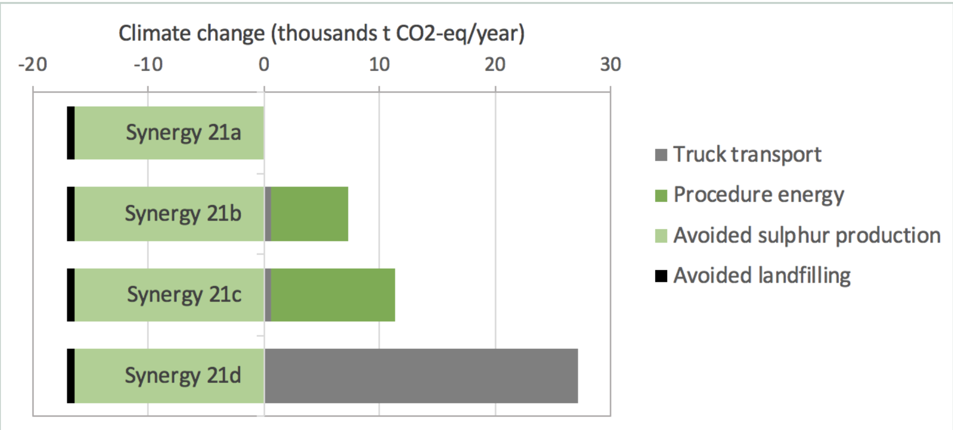

Figure 13. Synergy 21, sulphur recovery from steel industry, sensitivity analyses

Figure 13 shows results for the different scenarios presented in Table 7. The main savings are from the avoided impact of not producing sulphur; the avoided impact of landfilling the resource of interest has negligible savings.

The impacts of the procedure vary, depending on the quantity of energy (1000 MJ natural gas and 60 kWh to 1600 MJ natural gas to 75 kWh per t of resource processed). For climate change, procedure impacts reduce the climate change savings from 17 to 10 (scenario 21b, best case) and to 6 (scenario 21c, worst case) thousand t CO_2-eq. In other words, climate change savings thus decrease by 42% to 66%, compared to scenario 21a, where no procedure is considered. It can be concluded here that procedure impacts do not have negligible impacts, but that the synergy is still interesting to implement because the impacts of the procedure do not outweigh the benefits.

When 50 km of lorry transport is considered, the influence on results is negligible; when 2500 km is considered, the impacts of the transport outweigh the benefits of the synergy. The break-even point, when the impacts of transport are equivalent to the benefits of the synergy, is around 1500 km, which is a very large distance, in a European geographical context.

3.7.3 Synergy type 31 | Aluminium oxide recovery

Synergy 31 is an indirect synergy, where aluminium oxides (Al_2O_3) are recovered from salt slag of the non-ferrous metals industry and are used in the cement sector. The baseline resource of interest treatment scenario for this synergy is landfill. The procedure required to recycle the salt slag involves crushing and sieving followed by leaching, filtering, centrifuging and drying (see Deliverable 3.2 for more details). Energy and water use data for the technology procedure were collected. The energy use (electricity and fuel, detailed breakdown unknown) is estimated to be between 1900 to 3845 MJ/tonne of salt slag processed. Water is used for the procedure, but the amount is unknown, and it is a closed loop recirculation system, therefore it is assumed to have a negligible impact on results.

Several scenarios were modelled (Table 7) in order to understand the potential impacts of procedure energy use and transport.

Table 7. Synergy 31, aluminium oxides recovery from salt slag, sensitivity analyses

Scenario	Description (all scenarios include the benefits of the synergy type, avoided Al_2O_3 production and landfilling)
Synergy 31a	No procedure or transport
Synergy 31b	1900 MJ (electricity)/t slag, 50 km truck transport
Synergy 31c	1900 MJ (light fuel oil)/t slag, 50 km truck transport
Synergy 31d	3845 MJ (electricity)/t slag, 50 km truck transport
Synergy 31e	No procedure, 2500 km truck transport

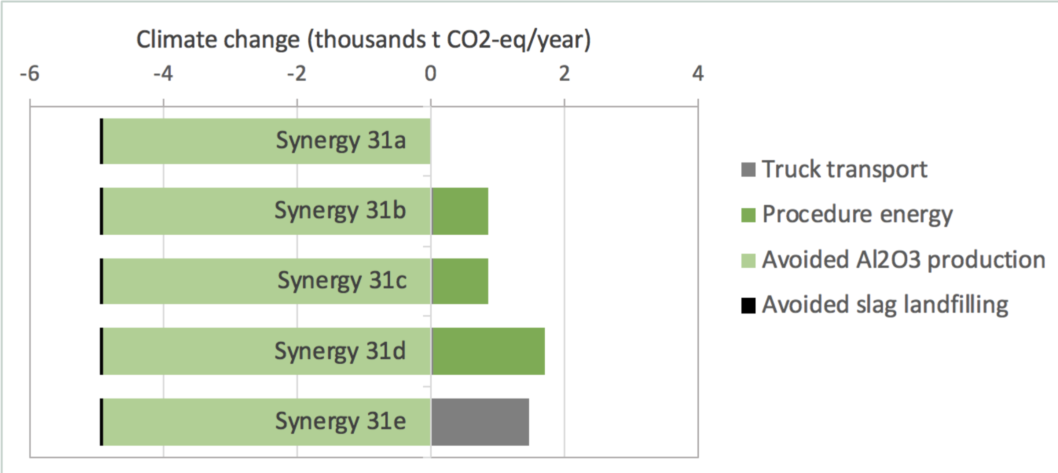

Figure 14. Synergy 31, aluminium oxides recovery from salt slag, sensitivity analyses

Figure 14 shows results for the different scenarios presented in Table 7. What is important to note is that the main savings are from the avoided impact of producing aluminium oxide; the avoided impact of landfilling has negligible savings.

The impacts of the procedure vary, depending on the quantity of energy (1900 to 3845 MJ/t salt slag processed). The impacts do not vary depending on electricity or light fuel oil as an energy source. For climate change, procedure impacts reduce the climate change savings from 5 to 4.1 (scenario b and c) and 3.2 (scenario d) thousand t CO_2-eq. In other words, climate change savings thus decrease by 17 to 34%, compared to the scenario a, where no procedure is considered. It can be concluded here that procedure impacts do not have negligible impacts, but that the synergy is still interesting to implement because the impacts of the procedure do not outweigh the benefits.

When 50 km of lorry transport is considered, the influence on results is negligible; when 2500 km is considered, there is a non-negligible contribution to the overall impacts. The impacts of 2500 km lorry transport reduce the climate change savings from 5 to 3.5 thousand t CO_2-eq, but the synergy is still interesting to implement because the impacts of the transport do not outweigh the benefits, for climate change. The break-even point, when the impacts of transport are equivalent to the benefits of the synergy, is over 8000 km, meaning the transport is most likely not a factor that influences the benefits of the synergy.

3.7.4 Synergy type 59 | Non-ferrous metals recovery from slag ash

Synergy 59 is an indirect synergy, where non-ferrous metal oxides (Al_2O_3, SiO_2, MgO and CaO) are recovered from slag ash and used in the non-ferrous metals industry. The baseline waste treatment scenario for this synergy is landfill. The procedure required to recycle the slag ash involves grinding and crushing to reduce the particle size and magnetic separation for the removal of the non-ferrous metals (see Deliverable 3.2 for more details). Electricity use for the procedure is estimated to be 10 kWh per tonne of slag ash treated (Deliverable 3.2).

Table 8. Synergy 59, non-ferrous metals recovery from slag ash

Scenario	Description (all scenarios include the benefits of the synergy type, non-ferrous metals production and landfilling)
Synergy 59a	No procedure or transport
Synergy 59b	10 kWh electricity, 50 km truck transport
Synergy 59c	No procedure, 2500 km truck transport

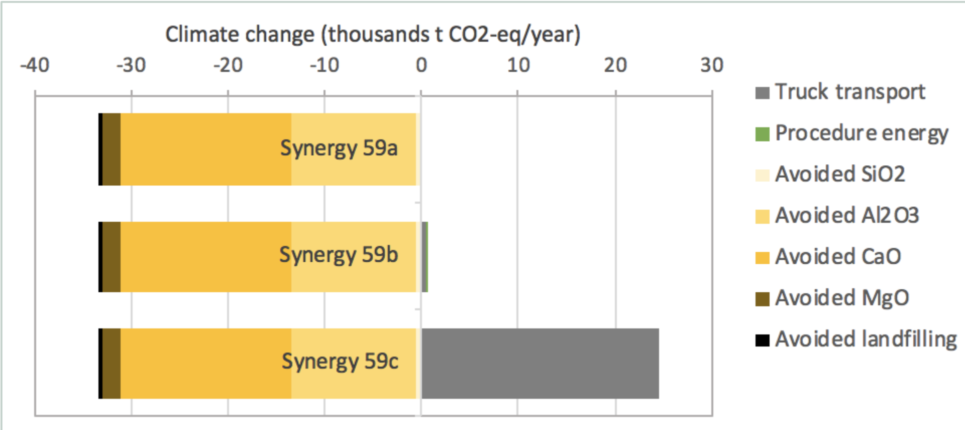

Figure 15. Synergy 59, non-ferrous metals recovery from slag ash, sensitivity analyses

Figure 15 shows results for the different scenarios presented in Table 8. The main savings are from the avoided impact of producing aluminium oxide (Al_2O_3) and calcium oxide (CaO); the avoided impact of landfilling has negligible savings, as well as the savings from the avoided impacts of producing silicon dioxide (SiO_2) and magnesium oxide (MgO).

The impacts of the procedure are related to the electricity use (10 kWh/t slag ash treated) and has negligible influence on the climate change result.

Likewise, when 50 km of lorry transport is considered, the influence on results is negligible; when 2500 km is considered, there is a non-negligible contribution to the overall impacts. The impacts of 2500 km lorry transport reduce the climate change savings from 33 to 9 thousand t CO_2-eq, but the synergy is still interesting to implement because the impacts of the transport do not outweigh the benefits, for climate change. The break-even point, when the impacts of transport are equivalent to the benefits of the synergy, is about 3400 km, meaning the transport is most likely not a factor that influences the benefits of the synergy.

3.7.5 Comparison of different modes of transport

Various different modes of transport can facilitate the implementation of a synergy, lorry, train, barge, pipeline, etc. The different modes of transport depend on the resource to be transported and available infrastructure, among other factors. Figure 16 presents climate change results for different modes of transport, when transporting 1 tonne of resource a distance of 1 km (1 tkm). Generally, lorry is the least favourable option and transport by train and/or barge should be chosen if possible. The same conclusion holds for the indicators: human health, ecosystem quality, resources.

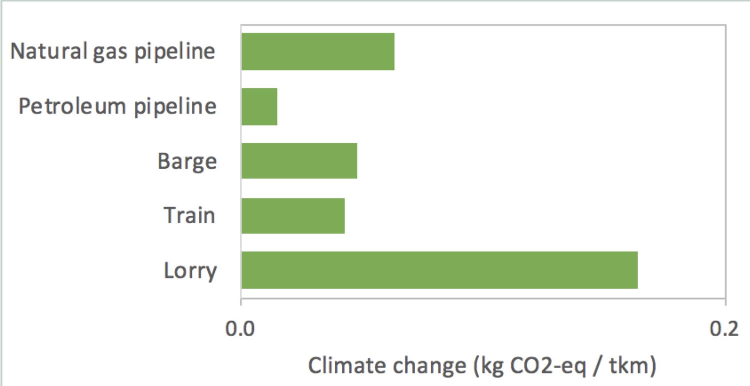

Figure 16. Climate change results for different modes of transport, per tkm

Figure 17 presents water withdrawal results or different modes of transport, when transporting 1 tonne of resource a distance of 1 km (1 tkm). Unlike climate change results, for this indicator, freight transport by rail has a higher result compared to barge or lorry. This is due to cooling water use for electricity production, used to power the train.

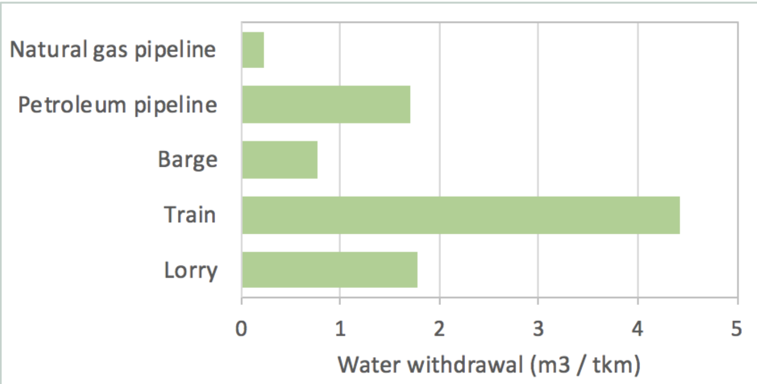

Figure 17. Water withdrawal results for different modes of transport, per tkm

Table 9. Life cycle assessment results for different modes of transport, per tkm

Indicator (results per tkm)	Lorry	Train	Barge	Petroleum pipeline	Natural gas pipeline
Climate change (kg CO_2-eq)	0.16	0.04	0.05	0.01	0.06
Human health (DALY)	1.81E-07	4.74E-08	6.83E-08	1.74E-08	3.55E-08
Ecosystem quality (PDF.m^2.y)	0.12	0.014	0.010	0.0042	0.0036
Resources (MJ)	2.69	0.71	0.67	0.26	1.02
Water withdrawal (l)	1.78	4.43	0.77	1.71	0.23

4. Discussion and conclusion

4.1 Key learnings

The results and conclusions of this deliverable are applicable within the context of a screening life cycle assessment. The study is meant to provide a hotspot analysis and preliminary recommendations for the most promising scenarios and/or configurations from a sustainability perspective based on the current status of data available.

Of the 74 synergy types that could be modelled an **estimated total climate change savings of 122 million tons CO2-eq was calculated**. This is equivalent to removing approximately 29 million cars off the road. Other indicators confirm this environmental and human health benefits. These results clearly show the potential of industrial symbiosis in Europe from an environmental and human health perspective. **Industrial symbiosis is thus a key driver to leverage the circular economy in Europe.**

Major contributors to the savings mentioned above are the steel (slag and coke oven gas) and waste treatment industries (prepared fuel), identified as key sender sectors. With respect to the receiver sectors, the cement industry is key along with various sectors receiving prepared fuels from the waste treatment industry. The latter confirms the **important role of intermediaries in industrial symbiosis**, which is in line with the findings from Deliverable 2.1.

Other sectors present high IS potential; the highest unexploited potential lies in the glass and ceramic industries, mainly for indirect synergies that require technology implementation.

The sensitivity analyses of synergies 18, 21, 31 and 59, as well as the comparison of modes and distances of transport (see section 3.7) allowed us to further investigate specific environmental impacts' and benefits' contributions. There may be large variations between different synergy types with respect to savings and technology procedure impacts; nevertheless, the sensitivity analyses led to some key learnings. Lorry transport is not necessarily negligible, **but in general, long distances are needed for the impacts to outweigh the benefits of the synergy**. Some technology procedures have very high energy requirements, which may outweigh the environmental benefits of the synergy. In general transport by train and/or barge should be chosen if possible, as their environmental and human health impacts are lower than that of lorry transport. Pipeline transport is also interesting, depending on the resource to transport, as well as the technological and economical barriers.

Data availability was indeed one of the main challenges of this work. Despite an in-depth and extensive search for data, some synergies could not be evaluated due to a **lack of data** specifically needed from a life cycle assessment perspective. It is important to note that the lack of data we mention here refers specifically to **data needed for the LCA modelling**.

4.2 Future work and recommendations

While the following study provides a good first indication of potential environmental and human health benefits from industrial symbiosis in Europe, a more detailed assessment of some key sectors and resources/wastes would provide additional value, particularly for the waste treatment industries sector as well as steel and cement synergies. This would require additional effort to collect and fill data gaps related to waste flows (quantity, description) based on primary data from industry.

A direct contact with industry may lead to improved granularity of the results. Specific points to address may include:

- Refining baseline scenarios for a given synergy type
- Quantifying the distribution of synergies already in place within a synergy type in order to distinguish the practices already in place vs potential future synergies. This would assist in linking the environmental results to key enablers, incentives or barriers, ultimately contributing to defining the boundary conditions needed to produce the savings potential of these untapped synergies.
- Including more detailed transport and technology procedure data
- Considering more operational factors/issues

Appendices

Synergy #	Baseline	Current practice?	ANNUAL VOLUME	RECEIVER SECTOR DEMAND	Can be modelled?	Climate change [kg CO2-eq]	Human health [DALY]	Ecosystem quality [PDF.m2.y]	Resources [MJ]	Water withdrawal [m3]
4	Incinerated	N	400 000 t/y	5 070 000 - 8 320 000 t/y	Y	-267'634'600	-737	-63'436'589	-14'065'594'000	-4'443'907
6	Landfilled	Y	10 478 800 - 20 241 200 t/y	Gypsum : 100 000 t/y Limestone and lime marn and chalk : 185 260 000 t/y Chalk composition : CaCO3 06%, MgO 20-55% (I can procide the full composition) Lime Marn : 96% CaCO3, 0-50% SiO2, 0-4% N2O Limestone : 96% CaCO3, 0-20% Al203, 0-10 CaO, 20-55 MgO, 0-50 SiO2	Y	-10'010'534'000	-5'119	-3'014'204'400	-72'080'234'000	-97'873'247
8	Landfilled	Y	UNKNOWN	7 850 000 t/y	Y	-126'775'460	-641	-153'481'360	-2'546'866'600	-3'487'883
11	Landfilled	Y	1 002 000 t/y	2 099 500 t/y	Y	-44'467'283	-55	-24'095'060	-651'766'320	-4'376'506
12	Incinerated	N	620 000 - 1 705 000 t of salt	377 000 t/y	Y	-654'785'280	-299	-105'422'790	-3'396'080'800	-16'664'554
13	Landfilled	N	68 127 t/y	377 000 t/y	Y	-13'309'202	-27	-10'784'602	-208'030'610	-1'710'605
14	Incinerated	N	829 - 1658 t/y	41 744 520 t of coke/y	Y	-821'991	-1	-144'249	-43'395'390	-13'273
15	Landfilled	Y	252 000 - 504 000 t/y	2 068 250 t/y - 11 582 000 t/y	Y	-16'775'083	-21	-9'089'753	-245'875'920	-1'651'017

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement no

Synergy #	Baseline	Current practice?	ANNUAL VOLUME	RECEIVER SECTOR DEMAND	Can be modelled?	Climate change [kg CO2-eq]	Human health [DALY]	Ecosystem quality [PDF.m2.y]	Resources [MJ]	Water withdrawal [m3]
22	Landfilled	N	132 368 - 1 886 244 t/y	107 945 - 215 890 t/y (ave: 161'918 t/y)	Y	-336'269'680	-280	-62'051'898	-3'269'935'800	-6'369'779
23	Landfilled	N	1 000 0000 t/y	Demand range calculated from mineral wool composition - SiO2 : 1 388 647 - 2 558 033 t/y - Alkaline oxides : 18 272 - 657 780 t/y - Earth alkaline oxides : 292 347 - 1 644 450 t/y - B203 : 0 - 438,520 - Iron oxides : 0 - 438 520 (18 272 - 438 520 in case of stone wool) t/y - Al203 : 0 - 840 497 (182 716 - 584 693 in case of slag wool) t/y - TiO2 : 0 - 146 173 (18 272 - 146 173 in case of stone slag) t/y - P2O5 : 0 - 54 815 t/y	Y	-1'393'841'600	-1'789	-398'934'180	-17'114'936'000	-45'377'228
24	Landfilled	N	40 302 648 - 52 326 000 t/y	Demand range calculated from mineral wool composition - SiO2 : 1 388 647 - 2 558 033 t/y - Alkaline oxides : 18 272 - 657 780 t/y - Earth alkaline oxides : 292 347 - 1 644 450 t/y - B203 : 0 - 438,520 - Iron oxides : 0 - 438 520 (18 272 - 438 520 in case of stone wool) t/y - Al203 : 0 - 840 497 (182 716 - 584 693 in case of slag wool) t/y - TiO2 : 0 - 146 173 (18 272 - 146 173 in case of stone slag) t/y - P2O5 : 0 - 54 815 t/y	Y	-2'750'523'300	-3'530	-787'232'770	-33'773'588'000	-89'544'699

Synergy #	Baseline	Current practice?	ANNUAL VOLUME	RECEIVER SECTOR DEMAND	Can be modelled?	Climate change [kg CO2-eq]	Human health [DALY]	Ecosystem quality [PDF.m2.y]	Resources [MJ]	Water withdrawal [m3]
25	Landfilled	Y	1 002 000 t/y	187 260 000 t/y of limestone, clay, shale, marl, and other Ca sources. For information, 2 450 000 tons of wastes were used Ca source in 2004	Y	-44'467'283	-55	-24'095'060	-651'766'320	-4'376'506
26	Landfilled	Y	418 000 - 836 000 t/y	185 260 000 t/y of limestone, clay, shale, marl, and other Ca sources. $CaCO_3$ volume : 177 849 600 t/y CaO volume : 0 - 18 526 000 t/y For information, 2 450 000 tons of wastes were used Ca source in 2004	Y	-27'825'336	-35	-15'077'447	-407'841'800	-2'738'592
27	Landfilled	N	61 360 - 583 983 t/y	185 260 000 t/y of limestone, clay, shale, marl, and other Ca sources. $CaCO_3$ volume : 177 849 600 t/y CaO volume : 0 - 18 526 000 t/y For information, 2 450 000 tons of wastes were used Ca source in 2004	Y	-9'011'407	-56	-13'607'333	-432'058'750	-379'918
28	Landfilled	Y	16 587 - 77 406 t/y	187 260 000 t/y of limestone, clay, shale, marl, and other Si sources. Si volume : 0 - 92 630 000 t/y For information, 1 500 000 tons of spent sand were used Si source in 2004	Y	-1'086'107	-7	-1'062'191	-21'332'963	-103'126
29	Landfilled	N	3 720 000 - 9 300 000 t/y	185 260 000 t/y of limestone, clay, shale, marl, and other Al_2O_3 sources. Al_2O_3 volume : 0 - 37 052 000 t/y Fe_2O_3 volume : 0 - 11 115 600 t/y For information 690 000 tons of wastes were used Al source in 2004 3 780 000 tons of wastes were used as	Y	-4'297'805	-140	-30'942'968	-82'922'322	-124'140

Synergy #	Baseline	Current practice?	ANNUAL VOLUME	RECEIVER SECTOR DEMAND	Can be modelled?	Climate change [kg CO2-eq]	Human health [DALY]	Ecosystem quality [PDF.m2.y]	Resources [MJ]	Water withdrawal [m3]
				Si-Al-Ca-Fe source in 2004 3 370 000 tons of wastes were used as Fe source in 2004.						
30	Landfilled	Y	40 302 648 - 52 326 000 t/y	185 024 000 tons/y of limestone, clay, shale ; 7 198 000 tons/y of gypsum and anhydrite ; and 20 296 000 tons of mineral additions are used for raw meal preparation.	Y	-7'496'613'500	-12'315	-8'138'684'400	-119'967'390'000	-241'540'440
34	Landfilled	N	4 052 000 tons/y EU-15 in 2010 16 000 tons of bottom ash for 1 000 000 tons of coal fired	Iron ore : 25 245 000 - 26 055 000 t/y	Y	-16'556'957	-245	-59'764'167	-367'852'000	-629'174
35	Landfilled	Y	4 963 800 - 22 337 100 t/y	Clinker : 125 600 000 t/y Gyspum : 7 850 000 t/y Mineral additions : 21 980 000 t/y	Y	-5'041'695'900	-2'991	-1'467'892'500	-41'413'106'000	-59'605'356
36	Landfilled	Y	252 000 - 504 000 t/y	UNKNOW	Y	-16'775'083	-21	-9'089'753	-245'875'920	-1'651'017
40	Landfilled	N	40 302 648 - 52 326 000 t/y	50 000 - 70 000 t/y of slag	Y	-28'333'812	-24	-10'349'157	-278'076'030	-1'607'133
44	Landfilled	Y	16 587 - 77 406 t/y	0 to 1,5 kg of fluxes /t	Y	-1'767'716	-7	-1'272'860	-28'721'048	-130'910
47	Incinerated	Y	18 122 400 000 - 26 076 120 000 Nm3/y	Equivalent natural gas volume for the same Energy content : 8 104 427 329 - 11 661 370 435 Nm3/y (average: 9'882'899'000 Nm3)	Y	-13'201'569'000	-15'059	-2'936'777'200	-63'603'778'000	-191'136'960

Synergy #	Baseline	Current practice?	ANNUAL VOLUME	RECEIVER SECTOR DEMAND	Can be modelled?	Climate change [kg CO2-eq]	Human health [DALY]	Ecosystem quality [PDF.m2.y]	Resources [MJ]	Water withdrawal [m3]
48	Incinerated	Y	139 536 000 000 - 232 560 000 000 Nm3/y	Equivalent natural gas volume for the same Energy content : 9 013 505 590 - 23 111 552 795 Nm3/y average: 6062529193	Y	-96'388'848	-40	-8'288'040	-3'446'385'900	-6'837'333
49	Incinerated	Y	43 148 000 000 - 64 722 000 000 MJ/y	Equivalent natural gas volume for the same Energy content : 7 611 200 000 - 16 240 800 000 Nm3/y 6062529193	Y	-78'722'417	-33	-6'768'984	-2'814'722'200	-5'584'167
50	Landfilled	Y	450 000 - 2 475 000 t/y	UNKNOW	Y	-12'276'932	-33	-22'313'367	-295'621'090	-722'749
60	Incinerated	Y	UNKNOW	UNKNOW	N	0	0	0	0	0
64	Landfilled	Y	23 t/y/site	UNKNOW	N	0	0	0	0	0
65	Landfilled	Y	UNKNOW	UNKNOW	N	0	0	0	0	0
66	Landfilled	N	40 302 648 - 52 326 000 t/y Real case : 1 275 000 t/y	19 250 000 t/y	Y	-3'902'277'400	-1'107	-314'565'040	-19'913'455'000	-17'178'820
67	WWTP	Y	UNKNOWN	e.g. 3 - 5 m3 of used cooling water per ton of atmospheric residues	N	0	0	0	0	0
68	Landfilled	Y	38 000 t/y/ site for a coal power plan	1 240 000 - 22 200 00 t/y	Y	-680'707'140	-1'019	-178'148'130	-9'870'443'200	-19'247'897
69	Landfilled	Y	32 616 000 t/y	UNKNOW	Y	-12'833'494'000	-19'219	-3'358'658'500	- 186'089'230'00 0	-362'884'040
78	Landfilled	Y	1 110 - 3 415 t/y (ave: 2'262 t/y)	0,1 - 10 % of waste complement	Y	-1'659'705	-2	-325'321	-86'941'270	-27'507
79	Landfilled	Y	327 200 t/y		Y	-240'077'530	-239	-47'057'992	-12'576'120'000	-3'978'960
80	Incinerated	Y	580 - 17 415 t/y (ave: 8998 t/y)		Y	-4'594'285	-1	-656'495	-268'674'970	-48'734

Synergy #	Baseline	Current practice?	ANNUAL VOLUME	RECEIVER SECTOR DEMAND	Can be modelled?	Climate change [kg CO2-eq]	Human health [DALY]	Ecosystem quality [PDF.m2.y]	Resources [MJ]	Water withdrawal [m3]
82	Incinerated	Y	5 350 400 - 6 186 400 t/y		Y	-972'684'440	-2'233	-1'847'710'400	-18'170'066'000	-95'861'919
83	Incinerated	Y	16700000 T beet/yr, 230 kg/t beet	0,1 - 10 % of waste complement	Y	-107'372'510	-109	-17'870'066	-39'056'128'000	-18'224'047
84	Incinerated	Y	Sludge volume: 581- 17 415 t/y	0,1 - 10 % of waste complement	Y	-9'536	0	-1'135	-144'908	-50
86	Incinerated	Y	3 906 899 t carcass/y		Y	-640'694'670	-1'544	-1'271'831'800	-11'743'284'000	-62'523'224
87	Incinerated	Y	5 350 400 - 6 186 400 t wood waste/y		Y	-873'509'180	-1'959	-1'769'317'200	-17'025'142'000	-90'804'325
89	WWTP	Y	UNKNOWN	e.g. 3 - 5 m3 of used cooling water per ton of atmospheric residues	N	0	0	0	0	0
90	Incinerated	Y	UNKNOW	274 045 m3/y	N	0	0	0	0	0
97	Incinerated	Y	4 475 965 t/y	See table 7.7	Y	-17'850'755'000	-4'620	-1'526'884'300	-274'610'380'000	-107'598'850
98	Incinerated	Y	201 286 t/y	See table 7.7	Y	-847'467'290	-508	-100'833'340	-12'877'988'000	-4'469'289
99	Incinerated	Y	270 147 t/y	See table 7.7	Y	-774'547'240	-95	-15'531'131	-14'564'805'000	-15'407'852
100	Incinerated	Y	3 739 682 t/y	See table 7.7	Y	-14'980'281'000	-29'515	-2'337'009'600	-229'767'160'000	-101'192'520
7	Landfilled	Y	2 543 550 t/y	7 850 000 t/y	Y	-61'604'124	-3'810	-149'551'700	-1'211'772'600	-2'386'463
1	Incinerated	Y	850'610 t H2/y	260 and 400 t of h2/t of feed	Y	-1'892'599'900	-785	-162'736'080	-67'669'960'000	-134'251'380
2	Incinerated	Y	15'251'000 t methanol/y 206'990'000 MJ nat gas avoided/y	UNKNOW	Y	-10'224'519'000	-9'452	-1'195'999'900	-553'951'520'000	-464'334'270
3	Incinerated	Y	2400 t/y	UNKNOW	Y	-4'998'582	-2	-334'880	-49'503'758	-8'979

Synergy #	Baseline	Current practice?	ANNUAL VOLUME	RECEIVER SECTOR DEMAND	Can be modelled?	Climate change [kg CO2-eq]	Human health [DALY]	Ecosystem quality [PDF.m2.y]	Resources [MJ]	Water withdrawal [m3]
5	Landfilled	Y	16 600 - 1 985 520 t/y	603 000 t/y	Y	-38'688	0	-155'602	-436'826	-1'945
9	Incinerated	N	1 018 000 t/y	1 129 950 - 2 043 210 t/y.	Y	-110'097'770	-805	-81'044'672	-7'526'784'100	-72'587'192
10	Incinerated	N	Around 3 300 000 t/y	1 129 950 - 2 043 210 t/y	Y	-171'590'290	-1'254	-126'310'270	-11'730'693'000	-113'129'060
16	Incinerated	N	211 420 - 453 060 t/y	8 800 t/y	Y	-9'342	0	-651	-44'804	-379
17	Incinerated	N	156 500 t/y	6460,5 Nm3/y	Y	-17'410'557	-7	-1'497'055	-622'514'940	-1'235'016
18	Incinerated	Y	6 183 - 19 236 t/y	260 - 400 t of h2/t of feed	Y	-28'279'639	-12	-2'431'638	-1'011'139'300	-2'006'013
19	Incinerated	Y	271'619 - 349'225 t H2/y		Y	-690'686'250	-286	-59'388'980	-24'695'506'000	-48'993'758
20	Landfilled	N	70 - 8156 t/y	UNKNOW	Y	-1'550	0	-4'409	-20'309	-105
21	Landfilled	N	45 306 - 100 680 t/y	61 600 - 70 400 t/y	Y	-17'086'973	-44	-6'548'108	-2'075'919'200	-333'161
31	Landfilled	Y	2 976 000 - 4 216 000 t/y	UNKNOW	Y	-4'953'541'300	-7'682	-2'002'798'500	-78'071'597'000	-145'000'010
32	Landfilled	N	2 976 000 - 4 216 000 t/y	UNKNOW	Y	-4'953'541'300	-7'682	-2'002'798'500	-78'071'597'000	-145'000'010
33	Landfilled	N	225 760 - 669 120 t/y	UNKNOW	Y	3'323'338	9	2'677'039	45'002'321	216'971
37	Incinerated	N	16 600 - 1 985 520 t/year	UNKNOW	Y	-104'955	-2	-405'782	-977'788	-3'831
38	Incinerated	N	266 802 - 704 760 t/y	4 448 955 - 4 515 538 t/y	Y	-55'547	0	-779	-734'456	-901
39	Incinerated	N	100 000 t/y	198 000 t/y	Y	-2'027'589'200	-434	-76'283'168	-3'530'963'400	-22'081'641
41	Landfilled	N	87 040 - 284 240 t/y	50 000 - 70 000 t/y	Y	-43'295'843	-34	-9'028'623	-400'383'890	-622'136
42	Incinerated	N	253 000 - 730 000 t/y	50 000 - 70 000 t/y	N	0	0	0	0	0

Synergy #	Baseline	Current practice?	ANNUAL VOLUME	RECEIVER SECTOR DEMAND	Can be modelled?	Climate change [kg CO2-eq]	Human health [DALY]	Ecosystem quality [PDF.m2.y]	Resources [MJ]	Water withdrawal [m3]
43	Incinerated	N	61 360 - 322 672 t/y	50 000 - 70 000 t/y	N	0	0	0	0	0
45	Incinerated	N	69 - 687 t/y	UNKNOW	N	0	0	0	0	0
46	Incinerated	N	61 360 - 583 983 t/y	UNKNOW	N	0	0	0	0	0
51	Incinerated	N	Part of 675 214 - 1 576 000 t/y (include slurry)	1 326 000 t/y	N	0	0	0	0	0
52	Incinerated	N	UNKNOW	9 603 t/y	Y	-26'732'411	-13	-4'009'303	-168'421'970	-1'311'848
53	WWTP	N	UNKNOW	UNKNOW	N	0	0	0	0	0
54	WWTP	N	UNKNOW	UNKNOW	N	0	0	0	0	0
55	WWTP	N	UNKNOW	4 484 403 - 5 813 115 t/y	N	0	0	0	0	0
56	Incinerated	N	UNKNOW	UNKNOW	N	0	0	0	0	0
57	Landfilled	N	207 - 72450 t/y	UNKNOW	N	0	0	0	0	0
58	Incinerated	N	UNKNOW	UNKNOW	N	0	0	0	0	0
59	Landfilled	N	9 002 860 - 15 755 005 t/y	50 000 - 70 000 t/y	Y	-33'642'159	-30	-5'836'166	-316'450'340	-562'579
61	Incinerated	N	UNKNOW	ELEMENT MATCHING	N	0	0	0	0	0
62	Incinerated	N	UNKNOW	ELEMENT MATCHING	N	0	0	0	0	0
63	Incinerated	N	UNKNOW	ELEMENT MATCHING	N	0	0	0	0	0
70	Incinerated	N	10 565,5 t/y including Sodium Hydroxide/Hydrochloric Acid/Sodium Silicate	UNKNOW	N	0	0	0	0	0

Synergy #	Baseline	Current practice?	ANNUAL VOLUME	RECEIVER SECTOR DEMAND	Can be modelled?	Climate change [kg CO2-eq]	Human health [DALY]	Ecosystem quality [PDF.m2.y]	Resources [MJ]	Water withdrawal [m3]
71	Landfilled	N	4 430 t/y	0,4 - 2,5 kg /t	N	0	0	0	0	0
72	Landfilled	N	19 - 21 t/y	1 909 000 - 30 129 000 tons of high alloy	Y	-43	0	-20	-669	-3
73	Landfilled	Y	7.2-12 t Pt/y	0,4 and 2,5 kg of catalysts	N	0	0	0	0	0
74	Landfilled	N	4 430 t/y	0,4 and 2,5 kg of catalysts	N	0	0	0	0	0
75	Landfilled	N	448 kg/y	UNKNOW	Y	-1	0	-6	-7	0
76	Landfilled	N	209 576 - 2 644 356 t/y		Y	-147'424'950	-229	-59'606'340	-2'323'529'900	-4'315'422
77	Landfilled	N	209 576 - 2 644 356 t/y		Y	-147'424'950	-229	-59'606'340	-2'323'529'900	-4'315'422
81	WWTP	N	327 200 t/y	3 500 028 t/y	Y	-155'645'560	-202	-86'813'580	-18'344'617'000	-5'516'107
85	WWTP	N		2 160 m3/y	N	0	0	0	0	0
88	WWTP	N			N	0	0	0	0	0
91		Y	See D3.1, table 7.1	See table 7.1	Y	-96	-5.78E-05	-11	-1'464	-0.5
92		Y	See D3.1, table 7.2	See table 7.2	Y					
93		Y	See D3.1, table 7.3	See table 7.3	Y	-103	-3.13E-05	-9	-1'568	-1.1
94		Y	See D3.1, table 7.4	See table 7.4	Y					
95	Incinerated	Y	See D3.1, table 7.5	N/A	Y	-3'121	-1.61E-03	-592	-67'188	-64
96	Incinerated	Y	See D3.1, table 7.6	N/A	Y					