European Commission – DG Environment

Wider environmental impacts of industry decarbonisation

Final Report

Wood E&IS GmbH – February 2021

Report for

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Document revisions

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1	Draft interim report	29 May 2020
2	Draft final report	18 December 2020
3	Final report v1	25 January 2021
4	Final report v2	11 February 2021

Abstract

Industry faces major challenges to handle the transition towards an economy with net-zero greenhouse gas (GHG) emissions by 2050. Whilst there is a growing literature seeking to understand how this transition will unfold, there is currently limited understanding of what the wider environmental impacts could be from the transformation. Furthermore, there is little knowledge on the possible untapped potential of installations within sectors covered by the Industrial Emissions Directive (IED) to contribute to the circular economy. The objective of the study was to provide a first overview of the potential wider environmental impacts of the transition of industry under the scope of the IED to a low carbon economy, and to get a better understanding of the potential of IED plants to contribute to a circular economy. The study compiled information from both literature and stakeholder consultations.

The results illustrate the variety in the type of technologies and their potential impact on GHG emission reductions, covering both innovative and more established technologies. There are significant uncertainties in terms of direct and indirect environmental impacts, often related to the maturity of the decarbonisation technologies. The study concludes that many IED installations have made considerable progress in resource efficiency and circular economy. There is, however, no "magic bullet" in the application of IED to further improve circular material use by IED installations.

Executive summary

The European Environment Agency (2019)[1], indicates that greenhouse gas (GHG) emissions in the EU decreased in the majority of sectors between 1990 and 2017[2]. Emission reductions for manufacturing industries (particularly iron and steel production), and for electricity and heat production are amongst the largest at aggregate level. However, the current reduction rate will not be sufficient to deliver the savings needed to achieve the EU's 2030 reduction target (reducing GHG emissions to at least 55% below 1990 levels). Achieving the 2030 targets will require a focused effort across the EU and achieving the long-term goals of even greater levels of decarbonisation (net-zero by 2050) will require faster rates of reduction than those currently projected. Major changes will need to be made in the way industry consumes energy and produces its products.

A portfolio of options to decarbonise industry is described in the literature, presenting a range of choices to industry to reduce GHG emission (combinations of increased material and energy efficiency, greater material recirculation, new production processes and carbon capture technologies). Changes can be expected in processes or technologies and these changes will eventually require increased R&D, economic incentives, transformation of value chains and development of infrastructure. Any such radical changes in industry require careful examination of the wider environmental impacts, identifying any potential new environmental challenges or opportunities for a successful transition.

To ensure the best pathways to decarbonisation are adopted, it is important to assess wider environmental impact of available options. Some studies are available, such as LCA studies for a specific industrial process or technology, or more general studies on the benefits of energy efficiency measures. There is, however, a gap in knowledge of the expected impact when different decarbonisation pathways across different sectors are combined. Limited information is also available on the wider environmental impacts of the available options. Addressing this gap was a major focus of this study.

Installations under the scope of the Industrial Emissions Directive (Directive 2010/75/EU, IED) are considered as important potential contributors to the circular economy. Some operate within the material flows of a linear economy – consuming materials, producing products and waste. Reducing consumption and waste is important ("resource efficiency"). However, other installations operate a circular model, where materials are reused within the installation, or where they use secondary materials from other sources and produce by-products instead of waste. Some of these material flows are in the control of the installation (e.g. technical decisions), while some flows are dependent on other factors (market, legal, etc.). Linked to the issue of circularity of resources is the concept of resource efficiency – using fewer materials and less energy in production. However, while resource efficiency is essential for a greener economy, being resource efficient alone does not necessarily deliver a circular economy – it could simply deliver a more efficient linear economy. The relative emphasis on efficiency and circularity is important when considering the obligations in implementing the IED and what operators and regulators should do and what they could do. There is little knowledge on the possible untapped potential of IED installations to contribute to the circular economy.

The aim of the study was twofold:

[1] EEA Annual European Union greenhouse gas inventory 1990–2017 and inventory report 2019. https://www.eea.europa.eu/publications/european-union-greenhouse-gas-inventory-2019

[2] With the notable exception of transport, including international transport, and refrigeration and air conditioning.

- to provide an overview of the potential wider environmental impacts of the transition of the industry under the scope of the IED to a low carbon, circular economy, based upon a review of relevant literature; and
- to get a better understanding of the potential of IED plants to contribute to a circular economy.

The work was delivered through four project tasks:

- Task 1: Identification of relevant literature and summary of decarbonisation options.
- Task 2: Identification and assessment of the wider environmental impacts of the identified technology pathways.
- Task 3: Delivery of stakeholder workshops.
- Task 4: Assessment of the potential contribution of IED installations to the circular economy.

Wider environmental impacts of industry decarbonisation

In order to identify and review existing literature that includes or generates data or information on the transition pathways to effectively zero GHG emissions for industry sectors within the scope of the IED, the following research questions were defined and addressed in the study:

- What are the decarbonisation pathways and technologies for each IED sector?
- What are the wider environmental impacts of the technologies? In particular:
  - What are the direct non-GHG emission-related impacts (emissions to air, water, soil, energy and resource use, and waste generation)?
  - Are there any indirect environmental impacts associated with the decarbonisation technologies (linked to the energy source, or other stages of the entire value chain)?
- Are technologies ready for deployment?
- What is the level of decarbonisation achieved?
- Are decarbonisation pathways technologically feasible?
- What are the barriers to the deployment of technologies?

The induced risks of accident were not included in the scope of the assessment of the environmental impacts. It is generally assumed that the decarbonisation options have been or will be deployed following a risk analysis.

The information was identified through (i) literature review, (ii) interviews with industry experts, and (iii) stakeholder workshops.

Within the data compiled and assessed, several information gaps were expected and identified, related to the decarbonisation options applied in IED sectors/activities and to the wider environmental impacts of these options (both direct and indirect). Efforts have been made to fill these gaps via consultation of experts in interviews, expert judgement by the project team and through the delivery of the workshops. Three online webinars were delivered in October 2020, each focussed on a specific sector or group of industrial activities (Production and processing of metals; Mineral industry; and Chemical industry). The discussions with the experts informed the assessment and conclusions drawn, and focussed on:

(i) the identification of decarbonisation options, and

(ii) their wider environmental impacts.

The webinars brought together experts from the European Commission, industry, NGOs, governments and academic experts. Around 25-45 experts participated in each webinar.

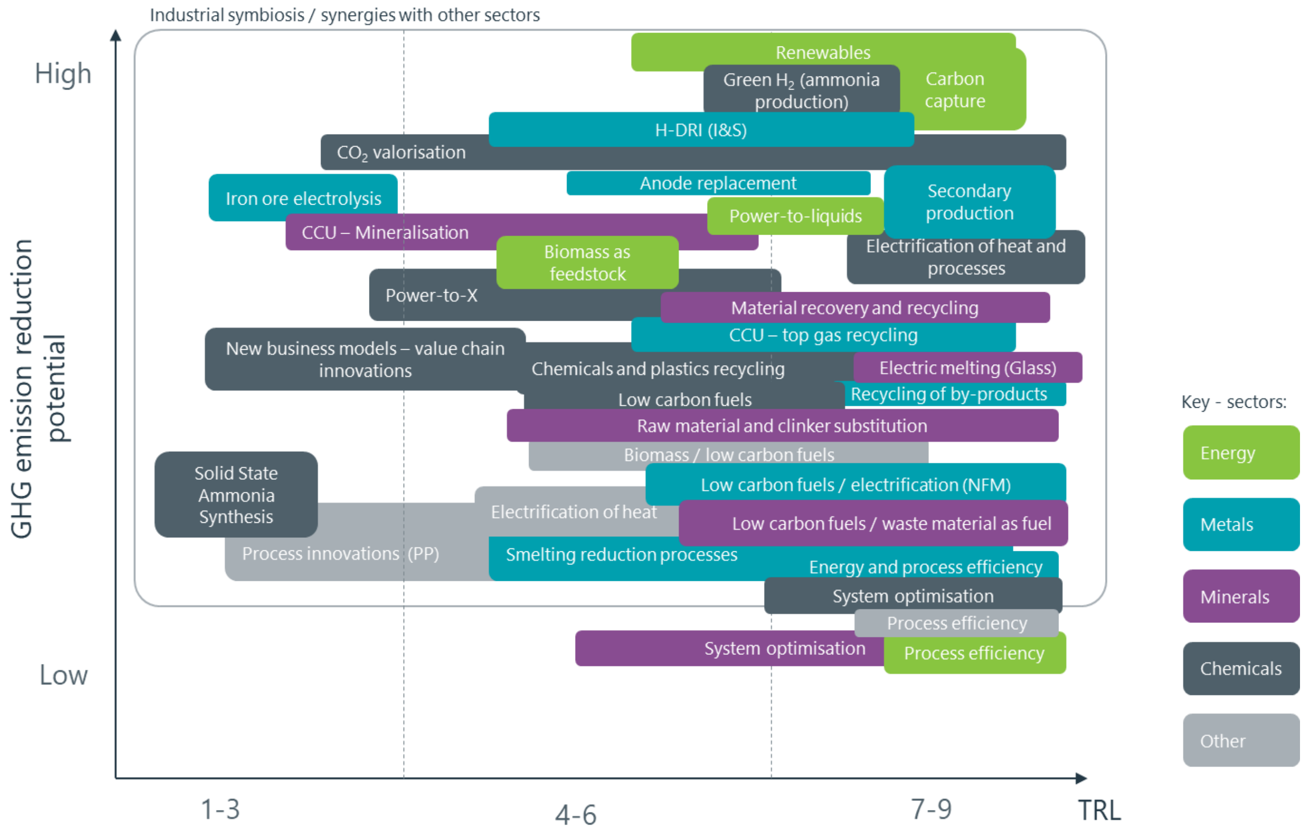
Data gaps were mainly linked to the low maturity of most of the decarbonisation options and the consequent lack of evidence on the wider environmental impacts. Depending on the data availability a semi-quantitative assessment was performed within the study to show the scale of the impacts using the following scoring system:

- '**+**': Positive environmental impact;
- '**-**': Negative environmental impact;
- '**-/+**': Positive or negative environmental impact (depending on certain conditions);
- '**0**': no effect;
- '**?**': unknown effect

The study provides a detailed overview of the decarbonisation options, grouped by sector, under the scope of the IED. The main options, their level of readiness (Technology Readiness Level - TRL)[3] and potential for GHG emissions reduction (qualitatively presented as low/medium/high) are summarised in the figure below. Some of the categories presented in the figure refer to a single technology with potentially high implications for the sector (e.g. low carbon ammonia production or the direct reduction of iron ore using hydrogen), whilst others in this figure combine several technologies, such as the valorisation of CO_2 in the chemical industry or the system optimisation options in the various IED sectors.

[3] The TRL identifies the maturity by phase of development which a technology is at. The TRL scale defines 9 levels.

Figure ES.1 Main identified decarbonisation options, their TRL and GHG emission reduction potential



There is a high variety in the **type of technologies and their potential impact on GHG emission reductions**. When referring to decarbonisation, reference in literature as well as by stakeholders was made to either the high level pathways, such as green hydrogen or carbon capture and use, whilst in other instances reference was provided to well-established practices, such as energy efficiency measures, insulation of equipment, or combustion optimisation. Not only is there a big difference in terms of the potential impact on GHG emissions between those types of options, but the timeline for uptake of these measures is also completely different. Many of the more high level pathways are often still in the early stages of development, with TRLs below 5 or 6. This often implies that (i) information on these, likely promising, options, is more scarce, (ii) their application at an industrial scale, and if relevant, to other activities than those currently being tested, has not been proven, and (iii) the time for uptake of these options is still uncertain and will require further evidence. The study attempted to capture the entire spectrum of measures, however, with a focus on those technologies leading to the highest impact in the longer term.

There are clear differences in options available between industrial sectors. In sectors such as iron and steel or the production of organic chemicals, innovative process technology changes are available, potentially leading to a step change in terms of GHG emissions from those activities by 2050. This is somewhat reflected by the various decarbonisation roadmaps produced for those sectors with the highest potential for future, more **innovative technologies**, such as cement, metals processing and the chemical industry. This is different from activities where the majority of GHG emissions are not related to process emissions, but rather originate from the **combustion of fossil fuels** for the generation of energy for the processes. In these examples, such as many of the food production or the pulp and paper production activities, the potential for further reduction of GHG emissions is very much reliant on the continued decarbonisation of the energy sector, both on site and off site. The number of options available for these sources of emissions are smaller compared to the process related sources, though could have a high potential for further reduction of GHG emissions. Many industries have already taken steps to reduce these emissions, for example by the use of renewable energy sources, switching to electricity driven processes and recovery of energy (heat).

Apart from some process (and activity) specific decarbonisation options, there are several important themes or **pathways applicable to many sectors** which are expected to contribute to a significant decrease in GHG emissions by 2050. These options have been categorised in the study as 'cross-cutting technologies' and cover options such as fuel switching (biomass, hydrogen), electrification and carbon capture technologies. It is important to note that the implementation of some of these options is somewhat out of the control of the operators of IED installations. In particular, industrial symbiosis, which requires multiple sites to collaborate in order to exchange resources (including waste, by-products, energy, etc.), involves improvements and decisions at many levels, including planning, regulatory framework, transport/logistics. Similarly, evolutions in segments of products value chains, other than those under the scope of the IED, could potentially drive or necessitate changes in the production process with an impact on the associated GHG emissions of production. Such changes, important regarding the decarbonisation of the industry, are not always controlled by individual sites.

Regarding the **wider direct environmental impacts** of the identified decarbonisation options, overall the deployment of decarbonisation options would have a **positive direct impact on air emissions**, particularly of NOx and SOx. Only certain technologies might lead to an increase of certain pollutants, for example, the use of biomass as feedstock in energy industries is associated with an increase of NOx and NH_3 but a decrease of unburned hydrocarbons and CO emissions. Nevertheless, **uncertainties exist in relation to certain decarbonisation options** where emissions are subject to the specific characteristics of the technologies and the process. This is particularly relevant for certain renewable energies, namely biomass and hydrogen. Specifically, air emissions resulting from the combustion of biomass differ depending on the purity and composition of the biomass. Furthermore, emissions to air related to hydrogen production depend largely on the source used for the generation of electricity and the associated emissions. The same applies to technologies that involve electrification of processes.

The risks associated with the **contamination of water and soil deriving from conventional technologies** in general are also reduced with the introduction of decarbonisation technologies. This is achieved mainly through the reduction of atmospheric pollutant emissions and therefore **reduction of pollutant deposition** that is caused through the pollution of the precipitation that falls into water bodies and soils. In certain cases the technologies might generate additional impacts on water (e.g. eutrophication from hydropower facilities) or increased water use (e.g. for washing in SOLPART).

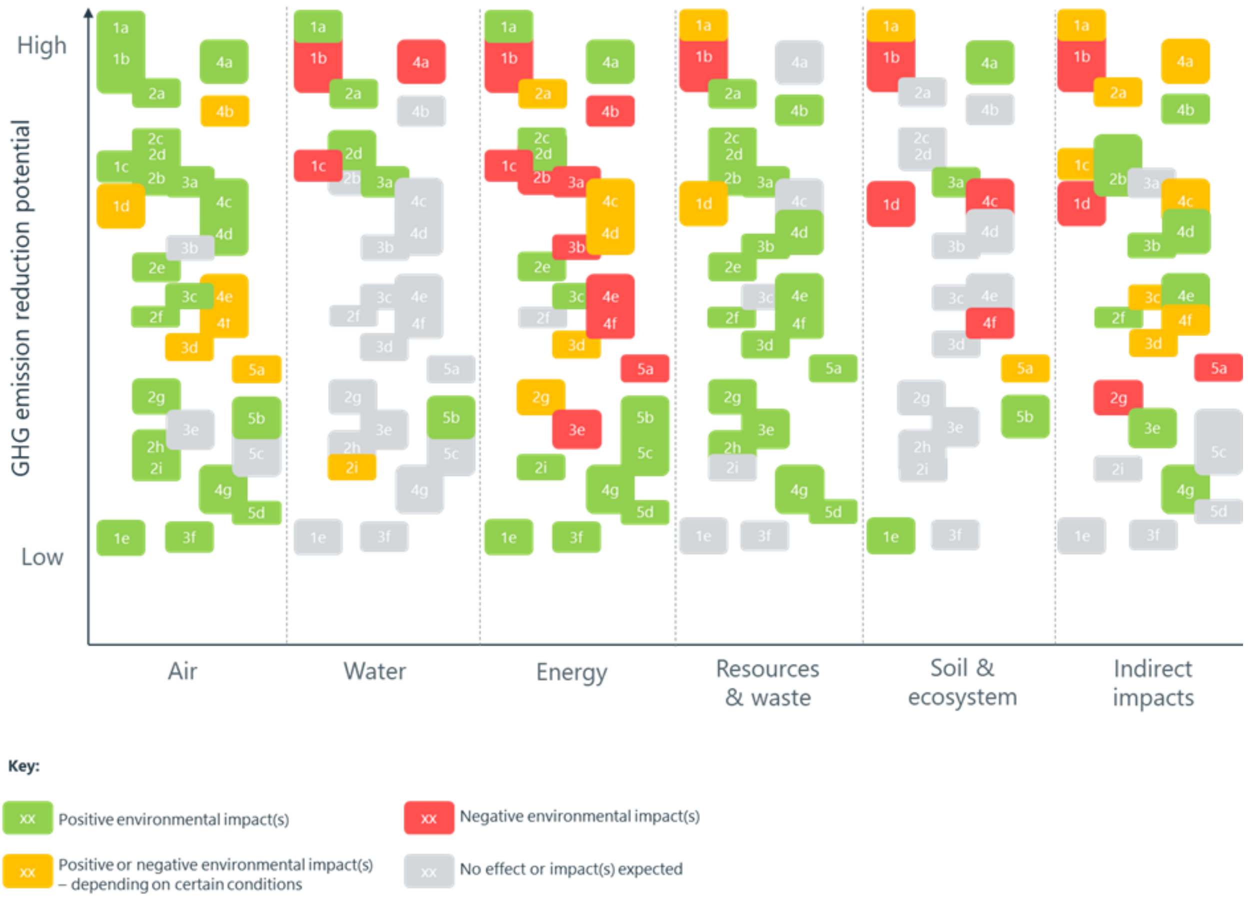
The decarbonisation options are also linked to a reduction of **energy use and to improvements in energy efficiency.** In most cases the decarbonisation achieved is a direct result of improvements in energy performance. However, certain exceptions exist, for example in the use of power to-liquid as alternative feedstock, hydrogen production through electrolysis, or the use of carbon capture technologies.

Resource savings can be achieved mainly when waste is used as an alternative fuel (presuming there are no other treatment options) or feedstock. Nevertheless, these savings mostly refer to the reductions of raw materials directly in the process (e.g. as a fuel) without considering additional infrastructure for the deployment of these technologies. For example, the use of hydrogen can lead to a significant reduction of fossil fuel use but in parallel, the development of the required infrastructure may need additional resources (e.g. for additional pipes).

The **indirect impacts** relate mainly to the production or transportation of alternative fuels and feedstock but also to the whole value chain involved in the manufacturing process of the technologies. In relation to the alternative fuels and feedstock the impacts might be higher compared to the conventional materials (e.g. for the transportation of hydrogen through pipes or trucks). The same also applies for the manufacturing of certain technologies such as windmills that might require more material and land per MW. Nevertheless, such impacts are expected to be reduced as the technologies are advancing and the effectiveness of the required logistics are improving. In addition, impacts associated with the transportation of biomass are greater than those from conventional fuels, as biomass is less energy dense and has to be collected from dispersed locations. More land is needed if raw biomass is used instead of waste unless if the comparison is done against the use of coal or shale gas that also require a large size of land for the extraction and production processes. Similarly, in relation to CCS, negative environmental impacts are associated with the development of energy infrastructure or with the extraction and transport of additional fossil fuels.

An overview of the assessment of the wider environmental impacts for the main decarbonisation options, as presented in Figure ES.1, is provided in the figure below, for all sectors and environmental aspects under the scope of the study.

Figure ES.2 Assessment of the wider environmental impacts for the main decarbonisation options and their potential for GHG emissions reductions across all sectors and environmental aspects under the scope of the study



1a	Energy – Renewables	2g	Metals – Low carbon fuels	4a	Chemicals - Green H_2 (ammonia production)
1b	Energy – Carbon Capture	2h	Metals – Smelting reduction	4b	Chemicals – CO_2 valorisation
1c	Energy – Power-to-liquids	2i	Metals – Energy and process efficiency	4c	Chemicals - Electrification of heat and processes
1d	Energy – Biomass as feedstock			4d	Chemicals – Power-to-X
1e	Energy – Process efficiency	3a	Minerals – CCU	4e	Chemicals – Chemicals and plastics recycling
		3b	Minerals – Material recovery and recycling	4f	Chemicals – Low carbon fuels
2a	Metals - H-DRI (I&S)	3c	Minerals – Electric melting	4g	Chemicals – System optimisation
2b	Metals – Secondary production	3d	Minerals – Raw material and clinker substitution		
2c	Metals – Anode replacement	3e	Minerals - Low carbon fuels / waste material as fuel	5a	Waste & Other - Biomass / low carbon fuels
2d	Metals – Iron ore electrolysis	3f	Minerals – System optimisation	5b	Waste & Other – Electrification of heat
2e	Metals – CCU – top gas recycling			5c	Waste & Other – Process innovations
2f	Metals – Recycling of by-products			5d	Waste & Other – Process efficiency

Potential contribution of IED installations to the circular economy

The methodology was based around two types of information gathering: a literature review and 25 interviews with stakeholders (industry, Member States officials (including competent authorities), NGOs and academic/research specialists). The literature review focused on recent material, including recent BREF developments and material supplied by interviewees. The study takes account of an earlier 2019 report on "IED Contribution to the Circular Economy" undertaken for the Commission by Ricardo and Vito. The study does not seek to replicate this earlier, and much larger, project, but takes account of its findings.

It was agreed not to include the waste sector in the scope of the study as, while it is a critical sector for operation of the circular economy, its relationship to material inputs and outputs is quite different to other industrial sectors using materials and producing products. Also sectors such as the rearing of pigs and poultry and slaughterhouses were excluded as their operations are highly constrained on health/hygiene grounds and much of the material that they do use and produce is renewable. In conclusion, 13 major and contrasting industry sectors were included in the analysis[4]. The study included relevant material uses and outputs by installations. Water reuse, however, was not included in the study as this is conceptually different to most other materials, being both renewable and the relevance of which being highly dependent on whether installations are in water rich or water scarce areas.

It was concluded that many IED installations have made considerable progress in resource efficiency and the circular economy, reducing waste production and increasing use of secondary raw materials. There is little untapped potential for further reduction in waste generated by many installations (there are some exceptions highlighted in the study), as waste disposal is expensive and operators will seek to avoid this. However, some efforts to improve waste quality could promote more circularity by facilitating material recovery.

IED operators do not control the supply of secondary materials in the wider economy to feed into their installations and are typically keen to use more. For this to happen, two conditions need to be met – the material must be of a minimum quality and the price must be competitive compared to virgin materials. There may be potential for IED operators to take more life-cycle considerations into account when developing materials supply strategies. This could include consideration of material recovery rather than energy recovery of non-renewable materials. Other sustainability considerations could also be integrated into operators parameters used for selecting supply materials.

The IED itself has not been a significant driver in these developments due to range of important legal and market constraints and opportunities that lie outside of the scope of the instrument. However, IED has helped to facilitate them through the flexible provisions in the directive. IED currently refers to resource efficiency in several articles. If it were to be amended, these could refer to circular material use to help support operators and regulators to deliver the circular economy.

There is no "magic bullet" in the application or development of IED (such as an amendment in the directive, a type of BAT, etc.) to improve circular material use by IED installations. Many other factors strongly determine the performance of installations with respect to circular material use (and these should be addressed by within other policy areas where possible). Implementing the IED with regard to the circular economy requires operators and regulators to consider increasingly complex information, such as understanding material markets and to think beyond the specific limits of the directive. Some competent authorities are doing this, but it would be a challenge for smaller authorities with limited capacity.

[4] Energy sector, Refineries, Iron and Steel, Non-ferrous metals, Chemicals, Food and Drink, Cement, Lime and Magnesium Oxide, Surface Treatment with Solvents, Pulp and Paper, Rendering, Ceramics, Glass and Textiles.

Whilst information provided in BREFs and guidance documents is useful and largely recognised, circular economy improvements require operator decisions that are adapted to the specific circumstances of the plant. Thus, a one size fits all approach in BREFs is unlikely to be generally effective (except maybe in very clear and documented issues) or appropriate (as market fluctuations occur). For most issues, allowing flexibility on how operators can improve circularity is likely to be more effective, e.g. as part of the operators' Environmental Management System that could include a plan to increase the circularity of materials for the installation (inputs, outputs, opportunities, constraints, etc.). . This would be usefully supported by a dialogue between the operator and the permitting authorities.

There are many constraints (and some opportunities) in other areas of EU law and policy (waste, chemicals, food, products, etc.). Some of these areas are under review. Further, there are national policy developments that are both positively and negatively affecting the use of secondary raw material (SRM) and use of waste from installations. Ensuring integrated policy making to support the circular economy will be important if IED installations are to maximise their role in using secondary materials and reducing waste.

Contents

List of acronyms and abbreviations

Acronym / abbreviations	Description
ADP	Abiotic Depletion Potential
AP	Acidification Potential
AQ	Air quality
BAT	Best Available Technique
BAT AEL	BAT associated emission level
BAT AEPL	BAT associated environmental performance level
BATC	BAT conclusions
BREF	BAT reference document
CCPs	Coal combustion products
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CDW	Construction and demolition waste
CE	Circular Economy
CEAP	Circular Economy Action Plan
CHP	Combined heat and power
COS	Carbonyl sulphide
EAF	Electric arc furnace
EC	European Commission
ELV	End of life vehicles
EP	Eutrophication Potential
E-PRTR	European Pollutant Release and Transfer Register
FAETP	Freshwater Aquatic Ecotoxicity Potential
FGD	Flue Gas Desulphurisation
GHG	Greenhouse gas
HTP	Human Toxicity Potential
IED	Directive 2010/75/EU of the European Parliament and the Council on industrial emissions
MAETP	Marine Aquatic Ecotoxicity Potential
MEA	Monoethanolamine

Acronym / abbreviations	Description
MS	EU Member State
N/A	Not available
NFM	Non-Ferrous Metals
NMVOC	Non-methane volatile organic compounds
ODC	Oxygen-depolarised cathodes
ODP	Ozone Depletion Potential
PFC	Polyfluorocarbons
PM	Particulate Matter
POM	Polyoxometalate
POX	Partial Oxidation
PtL	Power-to-Liquid
SMR	Steam Methane Reforming
TETP	Terrestrial Ecotoxicity Potential
TRL	Technology readiness level
VOC	Volatile organic compounds

1. Introduction

1.1. Purpose of this report

This is the final report for the study on "Wider environmental impacts of industry decarbonisation" (specific contract No 070201/2019/814817/ENV.C.4 implementing Framework Contract No. ENV.C.4/FRA/2015/0042 (service request 21)).

Wood E&IS GmbH (hereafter 'Wood'), with support from the Institute for European Environmental Policy (IEEP) and Deloitte, have been contracted with the aim to provide insights into the potential wider environmental impacts of the transition of the industry under the scope of the Directive 2010/75/EU on industrial emissions (IED)[5] to a low carbon, circular economy, based upon a review of relevant literature.

This final report presents the approach and results of the project.

1.2. Structure of the report

The sections below provide the approach and findings of each of the project tasks, as follows:

- Section 2 provides the context and objectives of the project;
- Section 3 presents the process for the identification of decarbonisation options as well as findings on the assessment of wider environmental impacts of the decarbonisation options (Tasks 1, 2 and 3); and
- Section 4 provides the results of an assessment of the impacts of the circular economy on IED installations (Task 4).

[5] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32010L0075

2. Project objectives and context

2.1. Project objectives

The project has two main objectives[6], which have been addressed in this report, i.e.:

- The first objective was to provide a clear picture of the potential wider environmental impacts of the transition of the industry under the scope of the Directive 2010/75/EU on industrial emissions (IED) to a low carbon, circular economy, based upon a review of relevant literature (section 3).
- The second aim was to get a better understanding of the potential of IED plants to contribute to a circular economy (section 4).

An introduction to both project objectives, providing context to the findings of the project, is presented in the sections below, covering industry decarbonisation (section 2.2, related to objective 1) and the contribution of the IED to the circular economy (section 2.3, related to objective 2).

2.2. Industry decarbonisation

2.2.1. Introduction

In the 2015 Paris Agreement, all parties, including the EU Member States, agreed to limit global temperature rise to 2°C and to pursue efforts to keep it to 1.5°C. In line with the Paris Agreement, the EU has the ambition to become the first climate-neutral bloc in the world by 2050, an economy with net-zero greenhouse gas (GHG) emissions, as reflected in the European Green Deal[7]. The vision for a climate-neutral EU was set out by the European Commission in 2018, which looks at all the key sectors and explores pathways for the transition.

As part of the European Green Deal, the Commission proposed (in March 2020) the first European Climate Law which sets the 2050 target (binding target of net zero GHG emissions by 2050). The Climate Law also addresses the pathway to get to the 2050 target, including a proposal for a new 2030 target for GHG emission reductions[8] (raising the EU's ambition on reducing GHG emissions to at least 55% below 1990 levels by 2030 - compared to the existing target of at least 40%) and the setting of a 2030-2050 EU-wide trajectory for GHG emission reductions, to measure progress and give predictability to public authorities, businesses and citizens.

The focus of this project is the industry sectors under the scope of Directive 2010/75/EU on industrial emissions (IED). The IED was adopted in 2010 and aims at achieving a high level of protection of human health and the environment by reducing harmful industrial emissions. The IED applies a general permitting framework for activities falling within its scope (Annex I activities) which includes: energy industries, production and processing of metals, mineral industries, the chemicals industry, waste management and other activities. The industry sectors are composed of many diverse subsectors, each with their own

[6] Terms of reference: https://circabc.europa.eu/w/browse/39928fd6-dcea-4fbc-b798-70e816bdecb0
[7] COM(2019) 640 final
[8] 2030 Climate Target Plan: https://ec.europa.eu/clima/policies/eu-climate-action/2030_ctp_en

particularities: end products and processes with different energy and material needs resulting in different types, mixture, volumes, and concentration of industrial emissions containing GHGs.

The sections below provide an overview of the GHG emissions resulting from the industrial sectors and activities (section 2.2.2) and an introduction to the decarbonisation pathways and efforts required in these sectors (section 2.2.3). The aim of these sections is to set the context for the identification of decarbonisation options by presenting the share and origin of GHG emissions in each sector.

2.2.2. GHG emissions from the energy and industry sectors

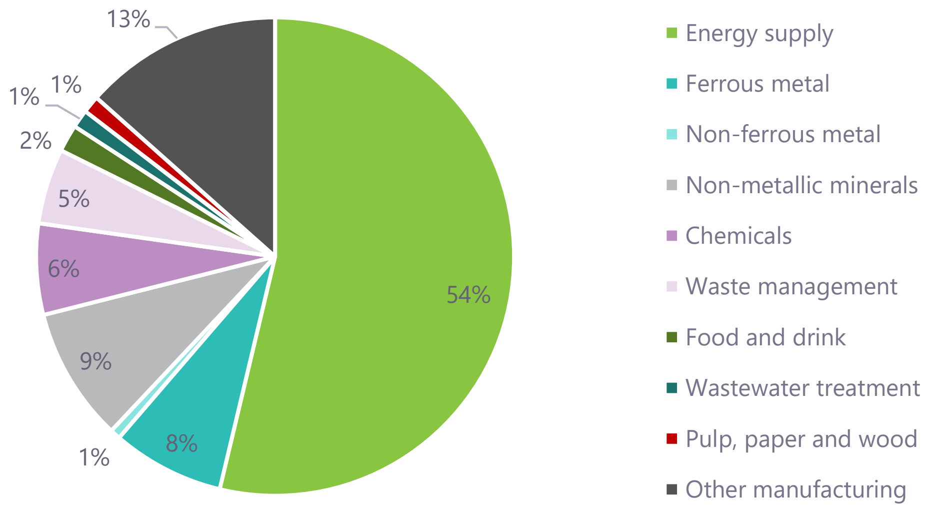
The European Environment Agency (2020)[9] reported that the total GHG emissions from the European industry and energy sectors (EU-28) were at a level of 2,195 Mt CO_2-equivalents in 2017 (excluding the extractive industry). The split per sector and activity is presented in Table 2.1 (absolute values) and Figure 2.1 (relative share).

Table 2.1 Level of GHG emissions (CO_2-eq) per industry sector in 2017 (EEA, 2020)

Sector (EEA)	GHG emissions in 2017 (Mt CO_2-eq)
Energy supply (incl. refineries, electricity and heat production)	1,179.30
Ferrous metal industry	166.69
Non-ferrous metal industry	15.32
Mineral (non-metallic) industry	198.75
Chemical industry	135.15
Waste management (incl. treatment, incineration and landfill)	111.87
Waste water treatment	27.00
Total (industry sectors, excl. extractive industry)	2,195.05
Extractive industry	86.24
Non-industry (incl. transport, residential, commercial, agriculture. LULUFC, other)	2,039.82
Total (all sectors)	4,321.10

[9] EEA, 2020. EU-28 – Industrial pollution profile 2020 (based on data reported under LRTAP and GHG MMR): https://www.eea.europa.eu/themes/industry/industrial-pollution/industrial-pollution-country-profiles-2020/eu28

Figure 2.1 Share of GHG emissions (CO_2-eq) per industry sector in 2017 (EEA, 2020)



The majority of the GHG emissions from the **energy sector** originate from thermal power stations and other combustion installations, followed by emissions from oil and gas refineries. Within the **mineral industry** (non-metallic minerals), the bulk of the GHG emissions originate from the production of cement and lime. The production of iron and steel, metal ore roasting, and sintering installations are responsible for the majority of the GHG emissions in the sector of **production and processing of metals** (ferrous and non-ferrous metals). In the **chemical sector,** process related GHG emissions (i.e. emissions from reactions/processes other than combustion) mainly originate from the production of organic chemicals, inorganic chemicals and the production of fertilisers (phosphorous-, nitrogen- or potassium-based).

Emissions of **carbon dioxide** (CO_2) make up the majority of the GHG emissions in the energy and industry sectors, originating from the combustion of fossil fuels (generation of heat or electricity) or as process related emissions. The energy sector and industrial activities can also lead to emissions of **non-CO_2 GHG emissions**, such as methane (CH_4), polyfluorocarbons (PFCs), nitrous oxide (N_2O) or hydro-fluorocarbons (HFCs), resulting from chemical reactions in the production and processing of materials.

GHG emissions from the industrial activities can be split into **direct and indirect emissions**. Direct GHG emissions are those originating at the installation, whilst indirect GHG emissions are those occurring off site, for example associated with the use of electricity in the installation (combustion of fossil fuels at power plants), or with the extraction of materials.

A more detailed overview of the GHG emissions resulting from each industry sector is provided in the paragraphs below.

Energy industries

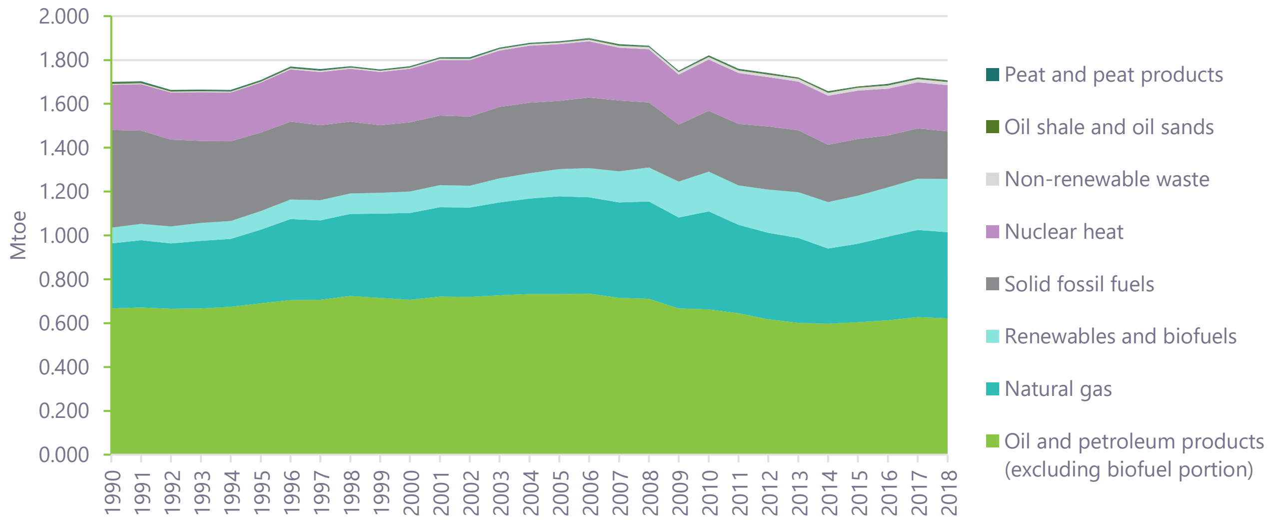
The categories of activities in the energy industries under the scope of the IED (Annex I), include:

- Combustion of fuels in installations with a total rated thermal input of 50 MW or more;
- Refining of mineral oil and gas;
- Production of coke; and
- Gasification or liquefaction of (a) coal and (b) other fuels in installations with a total rated thermal input of 20 MW or more.

According to the data from the European Pollutant Release and Transfer Register (E-PRTR), the energy industries accounted for 1,176 Mt of CO_2 emissions in 2017[10], with the majority of CO_2 emissions (87%) from thermal power stations and other combustion installations, followed by mineral oil and gas refineries (11.5%). Furthermore, a total amount of 98.3 kt of methane emissions was reported in 2017 for the energy sector, as well as levels of N_2O emissions (22.4 kt). The GHGs are released during the combustion and during handling of fossil fuels (fugitive emissions of natural gas).

The **energy mix in the EU** has changed over recent decades and is expected to experience a further transition towards 2030 and 2050, with a move increasingly towards renewable energy sources. In most European countries, a coal phase-out is set to take place between 2025 and 2038, with natural gas being considered as a transitional fuel. The Gross Inland Energy Consumption in the EU was 1,675 Mtoe in 2017[11], a value that has been relatively stable since 1990. According to this data, there was a rise of over 200% in renewable energy and 34% in natural gas (mainly to the detriment of coal) during the period between 1990 and 2017.

Figure 2.2 EU Gross inland energy consumption by fuel, EU-28, 1990-2017 (after: ETIP Sent, 2020)



The **production of coke** in the EU occurs by processing low-ash, low sulphur bituminous coal at high temperatures (1200-1300°C). The necessary heat is provided by external combustion of fuels and recovered gases. Similarly, **refining of oil and gas** is an energy-intensive process. Fuels most often used in refineries include fuel gas, catalyst coke, natural gas and fuel oil. The combustion of fuels in boilers and furnaces, hydrogen production, catalyst regeneration, and other process equipment and reactions makes up the oil refining sector carbon footprint[12].

[10] E-PRTR data for EU-28 (2017): https://www.eea.europa.eu/data-and-maps/data/industrial-reporting-under-the-industrial (June 2020). Note that an update of the Industrial Reporting database was published on 16 December 2020. Specific pollutant thresholds for each media - air, water and land – are set in Annex II of the E-PRTR Regulation; data is reported when a facility releases pollutants which exceed these thresholds.

[11] ETIP Sent (2020). Flexible Power Generation in a Decarbonised Europe: https://www.etip-snet.eu/new-white-paper-flexible-power-generation-decarbonised-europe/

[12] WSP and DNV GL (2015). Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 – Oil refining: https://www.gov.uk/government/publications/industrial-decarbonisation-and-energy-efficiency-roadmaps-to-2050

Production and processing of metals

The metals sector consists of metal production facilities that smelt, refine, and/or cast ferrous and non-ferrous metals from ore, pig iron, or scrap using electrometallurgical and other methods.

The categories of activities as part of production and processing of metals under the scope of the IED (Annex I), include:

- Metal ore (including sulphide ore) roasting or sintering;
- Production of pig iron or steel (primary or secondary fusion) including continuous casting, with a capacity exceeding 2,5 tonnes per hour;
- Processing of ferrous metals:
  - (a) operation of hot-rolling mills with a capacity exceeding 20 tonnes of crude steel per hour;
  - (b) operation of smitheries with hammers the energy of which exceeds 50 kilojoule per hammer, where the calorific power used exceeds 20 MW;
  - (c) application of protective fused metal coats with an input exceeding 2 tonnes of crude steel per hour.
- Operation of ferrous metal foundries with a production capacity exceeding 20 tonnes per day;
- Processing of non-ferrous metals:
  - (a) production of non-ferrous crude metals from ore, concentrates or secondary raw materials by metallurgical, chemical or electrolytic processes;
  - (b) melting, including the alloyage, of non-ferrous metals, including recovered products and operation of non-ferrous metal foundries, with a melting capacity exceeding 4 tonnes per day for lead and cadmium or 20 tonnes per day for all other metals.
- Surface treatment of metals or plastic materials using an electrolytic or chemical process where the volume of the treatment vats exceeds 30 m^3.

According to data from E-PRTR, the production and processing of metals accounted for 130 Mt of CO_2 emissions in 2017[13], with the majority of CO_2 emissions (63%) from the production of pig iron or steel, followed by metal ore roasting or sintering (11.4%); processing of ferrous metals (11.3%); production of non-ferrous metals (7.2%); and surface treatment of metals or plastic materials (5.9%).

The largest sources of GHG emissions from the production and processing of metals, and from iron and steel production in particular, are the process-related CO_2 emissions from the use of fossil fuels (mainly coke and coal) as reducing agents for the reduction of iron ore; the direct emissions from on-site combustion of fossil fuels; and the indirect emissions from electricity consumed during the production process. The use of energy carriers[14] in the sector is dominated by coal and coke followed by the use of natural gas, coke oven gas and purchased electricity as energy sources. Waste gases, such as CO, CH_4 and H_2, can be recovered and reused, in the production process and for electricity generation.

[13] E-PRTR data for EU-28 (2017): https://www.eea.europa.eu/data-and-maps/data/industrial-reporting-under-the-industrial

[14] Transmitter of energy, including electricity and heat as well as solid, liquid and gaseous fuels.

In general, the production and processing of non-ferrous metals is highly electro-intensive (indirect emissions), with direct CO_2 emissions resulting from fossil fuel and coke input as well as from the carbon (roasting and smelting). Manufacturing of primary aluminium utilises a carbon anode in the smelting (Hall-Héroult) process. The carbon is consumed during the electrolytic process and, therefore, a constant supply is required for the smelting process. Similarly, during copper anode production, direct CO_2 emissions occur due to fossil fuel input. The European ferro-alloy and silicon production process is electro-intensive, with carbon used in the process for its chemical properties (not for its energy content).

In the production process of primary aluminium, during the electrolysis stage, there is also a potential for emissions of polyfluorocarbons (PFCs) in connection with anode effects (in addition to carbon emissions). The amount of PFCs generated is directly linked to the frequency and the duration of anode effects and to the overvoltage reached. PFC emissions have reduced from 22.8 to 0.4 Mt between 1990 and 2015[15], due to better process management (avoiding flaring in aluminium cell pots) and flue gas treatment.

Mineral industry

The mineral industry covers the production of cement, lime, magnesium oxide, asbestos (and asbestos-based products), glass (including glass fibre), ceramic products and the melting of mineral substances.

The categories of activities in the mineral industry under the scope of the IED (Annex I), include:

- Production of cement, lime and magnesium oxide:
  - (a) production of cement clinker in rotary kilns with a production capacity exceeding 500 tonnes per day or in other kilns with a production capacity exceeding 50 tonnes per day;
  - (b) production of lime in kilns with a production capacity exceeding 50 tonnes per day;
  - (c) production of magnesium oxide in kilns with a production capacity exceeding 50 tonnes per day.
- Production of asbestos or the manufacture of asbestos-based products;
- Manufacture of glass including glass fibre with a melting capacity exceeding 20 tonnes per day;
- Melting mineral substances including the production of mineral fibres with a melting capacity exceeding 20 tonnes per day;
- Manufacture of ceramic products by firing, in particular roofing tiles, bricks, refractory bricks, tiles, stoneware or porcelain with a production capacity exceeding 75 tonnes per day and/or with a kiln capacity exceeding 4 m^3 and with a setting density per kiln exceeding 300 kg/m^3.

The majority of the industry's GHG emissions are CO_2 emissions, which accounted for **147.6 Mt of CO_2 emissions** (8.7% of the total CO_2 emissions from industry and energy sectors) in 2017[16], split per activity as follows (CO_2 emissions in 2017 – relative % to the total sector emissions):

- Production of cement clinker or lime in rotary kilns or other furnaces: 138.3 Mt (93.7%);
- Manufacture of glass, including glass fibre: 8.3 Mt (5.6%);

[15] PFC emissions as reported by EU member states to the UNFCCC and the EU's GHG monitoring mechanism
[16] Excluding mining and quarrying; E-PRTR data for EU-28 (2017): https://www.eea.europa.eu/data-and-maps/data/industrial-reporting-under-the-industrial

- Melting mineral substances, including the production of mineral fibres 0.5 Mt (0.3%); and
- Manufacture of ceramic products, including tiles, bricks, stoneware or porcelain: 0.5 Mt (0.3%).

The **cement-making process** can be divided into two main steps. Firstly, clinker is made in a kiln, which heats raw materials such as limestone with small quantities of other materials to approximately 1,450°C using fossil and non-fossil fuels. During this process, the CO_2 is disassociated from the limestone allowing the calcium oxide to react with alumina, silica and iron minerals (calcination). Secondly, clinker is ground with gypsum and other materials to produce cement powder. The calcination process gives rise to approximately 60-65% of total CO_2 emissions[17]. The remainder of emissions arise from combustion of fossil fuel and non-biomass waste fuel, transport and indirect emissions from electricity consumption.

For the **manufacturing of lime**, a rotary kiln is used in which limestone (calcium and/or magnesium carbonates) is burnt at a temperature of between 900 and 1200 ºC, which is sufficiently high to liberate carbon dioxide, and to obtain the derived oxide. The calcium oxide product from the kiln is generally crushed, milled and/or screened before being conveyed to silo storage. From the silo, the burned lime is either delivered to the end user for use in the form of quicklime or transferred to a hydrating plant where it is reacted with water to produce hydrated or slaked lime[18].

Glass manufacturing starts by melting glass. Glass melting requires raw materials (different types of sand and minerals or recycled glass), which are mixed together and charged in a furnace where they are melted at ca. 1,500°C. The molten glass is then taken out of the furnace to be shaped and cooled down, and possibly further processed to have specific properties. During this manufacturing process, CO_2 emissions arise from the combustion of fossil fuels (natural gas or oil) in the furnace, and by the chemical decomposition of carbonate components in the raw materials.

Ceramic manufacturing processes all involve firing the ceramic material to a temperature to instigate chemical and physical changes that develop the final properties of the product, including bonding to form a rigid matrix. Firing requires raw materials (e.g. clay, sand, other natural or synthesised materials), to be prepared and formed according to various processes (which vary by subsector), before being heated in a kiln to temperatures between 900°C and 2750°C. The fired product is then cooled and taken out of the kiln and possibly further processed with additional coating and firing steps or machining to produce the end product. During these manufacturing processes, direct CO_2 emissions arise from the combustion of fossil fuels in the kilns, the chemical decomposition of carbonate minerals and the combustion of organic material in the raw materials.

Chemical industry

The chemical industry covers a wide range of diverse processes, ranging from complex continuous processes making large-volume basic chemicals to smaller scale batch processes producing speciality chemicals and pharmaceuticals. Many chemical sites operate multiple different (or separate) processes which are linked together to carry out a number of sequential steps to convert raw materials (feedstock) into products.

The categories of activities in the chemical industry under the scope of the IED (Annex I), include:

- Production of organic chemicals;

[17] Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050: Cement. Accessed at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/416674/Cement_Report.pdf
[18] CLM BREF, 2013: https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/CLM_Published_def_0.pdf

- Production of inorganic chemicals;
- Production of phosphorous-, nitrogen- or potassium-based fertilisers (simple or compound fertilisers);
- Production of plant protection products or of biocides;
- Production of pharmaceutical products including intermediates; and
- Production of explosives.

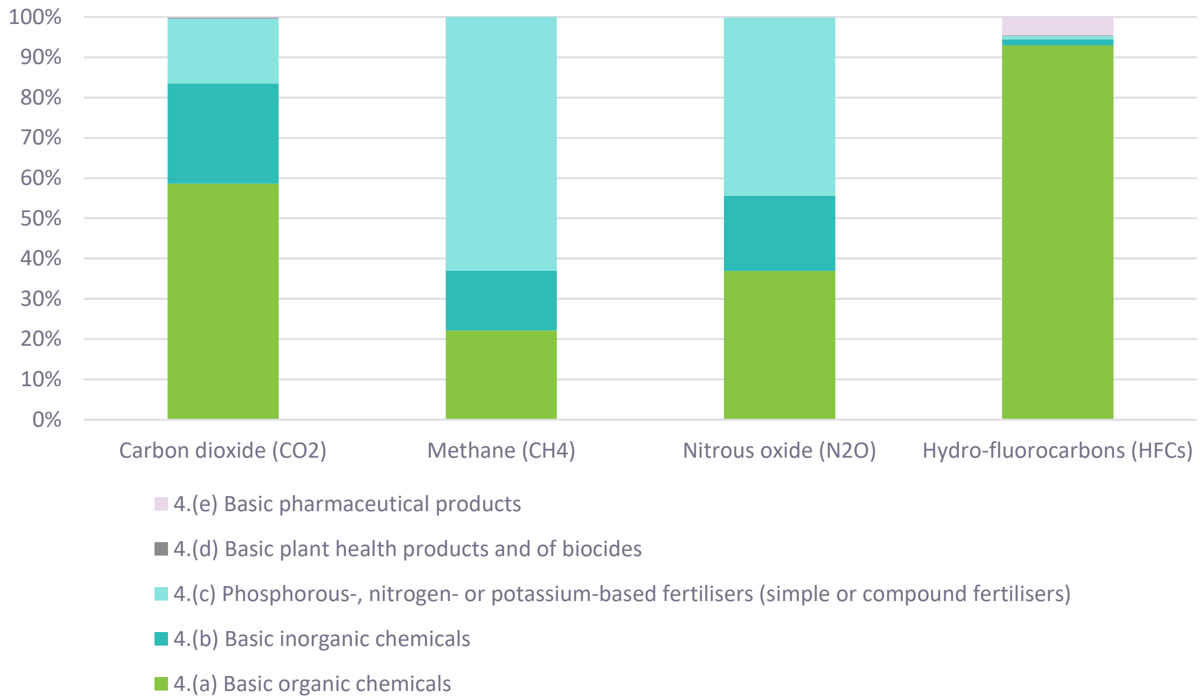
Material transfer, reaction, separation and recycling processes in the chemical industry all require energy which is provided as heat or electricity. Heat is needed to provide the high temperatures necessary for many reactions and separations (e.g. distillation), while electricity is used to drive pump motors, compressors, chillers, etc. Some chemical reactions are exothermic (i.e. they generate excess heat) and this heat is often captured through heat recovery for use elsewhere in the process. A range of technologies are used to deliver heat to chemical processes. The most widespread is the use of steam at a variety of different pressures. Steam is generated in boilers which are fired by natural gas or other fuels, or by heat recovery techniques. Furnaces are also used to provide heat directly in some processes where very high temperatures are required, for example in the cracking stage of olefin production.

GHG emissions from the chemical industry originate either directly from chemical process plants, or indirectly from the use of electricity generated off site. Direct emissions can be further divided into combustion emissions (e.g. related to burning fuel in boilers) and process emissions (where a greenhouse gas is produced as a by-product of the chemical reaction). The ammonia and hydrogen processes, which make CO_2 as a by-product, are responsible for the majority of the process emissions from the sector.

According to data from the E-PRTR[19], the chemical industry, in 2017, accounted for 109.9 Mt of carbon dioxide (CO_2) emissions, 8,309 t of methane (CH_4) emissions, 17,840 t of nitrous oxide (N_2O) emissions and 556 t of hydrofluorocarbons (HFCs) emissions. The relative share of emissions from each subsector is shown in Figure 2.3.

[19] https://www.eea.europa.eu/data-and-maps/data/industrial-reporting-under-the-industrial

Figure 2.3 Relative share of CO_2, CH_4, N_2O and HFCs emissions per activity of the chemical industry in 2017 (E-PRTR, EU-28)



Waste management and other activities

In this section, IED Annex I activities 5 (waste management) and 6 (other activities) are combined. Waste management includes the activities of waste treatment (biological and physico-chemical treatment), waste (co-)incineration and landfills. As part of the other activities, the project focussed on the energy intensive sectors of pulp and paper making; production of food and drink; and the intensive rearing of poultry or pigs (NB: these and other IED Annex I activities are also indirectly covered by some of the so-called cross cutting decarbonisation technologies in this report).

Waste management includes activities such as collection, transfer, pre-treatment, treatment (biological, mechanical, physico-chemical) and landfilling. Furthermore, thermal treatment is used to degrade waste in incinerators. Waste incinerators are equipped with energy recovery systems, enabling electricity and / or heat generation. According to the E-PRTR data, waste and waste water management emitted in 2017 (EU-28) 82.0 Mt CO_2 (78% from incineration of non-hazardous waste), 862.6 kt CH_4 (92% from landfills) and 4.6 kt N_2O (50% from incineration). Direct GHG emissions occur from process or equipment such as the combustion installations, landfills (fugitive emissions), transport etc. Methane can be released from landfill sites, waste water treatment and from incineration of waste, when biodegradable waste decomposes anaerobically. Landfills are one of the main GHG emissions sources in the waste management sector. Disposal of waste in landfills generates landfill gas, due to waste decay. This landfill gas is mainly composed of CO_2 and CH_4 (as well as trace elements such as N_2, O_2, H_2S, CO, NH_3, H_2, VOC). Carbon dioxide comes from the aerobic decomposition of organic components in waste, with methane coming from anaerobic decomposition (EPE, 2013). Certain waste treatment activities generate energy (electricity and heat) as a by-product and/or contribute to the re-use of materials or fuels.

According to the E-PRTR data, **pulp and paper production** accounted in 2017 (EU-28) for 80.6 Mt CO_2, and 3.3 kt N_2O. Primary energy use and CO_2 emission from the pulp and paper production process are mainly associated with the production of pulp (mechanical and chemical pulping or dissolving recycled paper), drying (cast-iron cylinders, heated to a temperature in excess of 100 °C), coating and finishing. According to CEPI (2013), drying the paper web is an important energy-consuming process in paper mills leading to around 60% of the CO_2 emissions from the papermaking process. Over recent decades, the recycling rate of paper in Europe has increased substantially from an average of 40% in 1991 to 72.5% in 2016 (ICF, 2019). Recycled fibres are used for pulp production, which has a significantly lower specific energy need compared to pulp production from virgin fibres. Compared to other energy-intensive industries, the pulp and paper sector only generates energy-related but no process-related emissions and the industry's demand for steam is quite flexible in terms of the energy carrier used for its production. Further research is ongoing on sustainable paper production technologies and the industry noted in its 2050 roadmap that breakthrough technologies would be needed by 2030 to achieve the targets (CEPI, 2017)[20].

The **food processing industry** is very heterogeneous (in terms of size of companies, raw materials, products and processes), manufacturing a highly diverse range of food and drink products. The industry consists of subsectors such as the production and processing of animal feed, fruit and vegetables, dairy products, sugar, meat processing, etc. The main processing techniques and operations applied throughout the sector include materials reception and preparation, size reduction, mixing and forming, separation techniques, product processing technologies, heat processing, concentration by heat, chilling and freezing, post-processing operations, and utility processes (BEIS, 2015; EC, 2019). According to the E-PRTR data, the production of food and beverage products accounted in 2017 (EU-28) for a total of 9.2 Mt CO_2 emissions. The manufacturing processes require electrical and thermal energy for most of the steps. Electricity is needed for lighting, process control of the installation, heating, refrigeration and as the driving power for machinery (supplied and/or generated on site). Thermal energy is needed for heating processes in production lines and buildings and is generated by the combustion of fossil fuels (steam, hot water, air or thermal oil). The main sources of GHG emissions relate to the use of energy (direct CO_2 emissions from burning fossil fuels and indirect emissions from grid electricity). Other GHG food processing emissions can originate from sources such as leaking refrigerants, methane from effluent treatment and process CO_2 from fermentation.

Intensive livestock farming or the **intensive rearing of poultry and pigs**, include activities such as animal housing, handling of feed, processing and storage of manure and other associated activities (waste water treatment, residue treatment etc). The main GHGs emitted from these activities are CO_2, CH_4 and N_2O. Emissions of CO_2 result from direct energy consumption in the running of the installations, i.e. mainly heating and ventilation, but also for lighting, feeding, manure handling and energy for distribution. Energy sources depend on the type of installation and location, but typically can include electricity, gas or fuel oil. The main measures applied in poultry and pig housing systems for reducing energy consumption consist of the control of heaters for the rearing of young livestock, the insulation of buildings, control of ventilation and artificial lighting systems. Emissions of CH_4 and N_2O can arise from animal housing, storage and processing of manure. According to the E-PRTR data, installations for the intensive rearing of poultry and pigs emitted in 2017 (EU-28) a total of 37.8 kt CH_4 and 1.3 kt N_2O.The amount of CH_4 generated by a specific manure management system is affected by the extent of anaerobic conditions present, the temperature of the system, and the retention time of organic material in the system. Most of the nitrous oxide in livestock systems occurs through the microbiological transformation of nitrogen (EC, 2017).

2.2.3. Reduction of GHG emissions and decarbonisation pathways

The European Environment Agency (EEA) annual GHG inventory report (2019)[21], indicates that GHG emissions in the EU decreased in the majority of sectors between 1990 and 2017[22]. Emission reductions for

[20] CEPI, 2017. Investing in Europe for Industry Transformation2050 Roadmap to a low-carbon bioeconomy https://www.cepi.org/wp-content/uploads/2020/11/Roadmap-2050-Final-2017.pdf

[21] EEA Annual European Union greenhouse gas inventory 1990–2017 and inventory report 2019. https://www.eea.europa.eu/publications/european-union-greenhouse-gas-inventory-2019

[22] With the notable exception of transport, including international transport, and refrigeration and air conditioning.

manufacturing industries (particularly iron and steel production), electricity and heat production are amongst the largest at aggregate level. However, the current reduction rate will not be sufficient to deliver the savings needed to achieve the EU's 2030 reduction target[23] (reducing GHG emissions to at least 55% below 1990 levels by 2030)[24]. Achieving the 2030 targets will require a focused effort across the EU and achieving the long-term goals of even greater levels of decarbonisation will require faster rates of reduction than those currently projected. Major changes will need to be made in the way industry consumes energy and produces its products.

At European level, a number of policies have been adopted in recent years to achieve mid- and long-term- reductions in GHG emissions. In 2018, the European Commission published a strategic long-term vision for a climate-neutral economy by 2050[25]. The in-depth analysis accompanying this vision[26] describes how climate neutrality could be achieved by 2050, rendering GHG emissions net zero, including land use, land use change and forestry (LULUCF) contributions as well as negative emissions technology, e.g. in the form of bioenergy combined with carbon capture and storage (CCS)[27]. In total, the in-depth- analysis describes eight separate scenarios that would contribute to achieving long-term reductions in emissions. The assumptions taken into account in these scenarios are presented in Figure 2.4.

[23] Commission proposal (September 2020) to raise the 2030 GHG emission reduction target to at least 55% compared to 1990 – as part of the 2030 Climate Target Plan.
[24] The European Parliament is calling for a reduction of 60% in 2030 and for an interim target for 2040 to be proposed by the Commission following an impact assessment (to ensure the EU is on track to reach its 2050 target). Source: https://www.europarl.europa.eu/news/en/headlines/priorities/climate-change/20201002IPR88431/eu-climate-law-meps-want-to-increase-2030-emissions-reduction-target-to-60
[25] Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions and the European Investment Bank — A clean planet for all: a European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy (COM(2018) 773 final).
[26] In-depth analysis in support of the Commission Communication COM(2018) 773: A clean planet for all — a European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, European Commission (https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf).
[27] EEA, 2019. Trends and projections in Europe 2019, Tracking progress towards Europe's climate and energy targets. EEA report No 15/2019. https://www.eea.europa.eu/publications/trends-and-projections-in-europe-1

Figure 2.4 The assumptions taken into account in the eight long-term vision scenarios (after EC, 2018)[26]

Long Term Strategy Options								
	Electrification (ELEC)	**Hydrogen (H2)**	**Power-to-X (P2X)**	**Energy Efficiency (EE)**	**Circular Economy (CIRC)**	**Combination (COMBO)**	**1.5°C Technical (1.5TECH)**	**1.5°C Sustainable Lifestyles (1.5LIFE)**
Main drivers	Electrification in all sectors	Hydrogen in industry, transport and buildings	E-fuels in industry, transport and buildings	Pursuing deep energy efficiency in all sectors	Increased resource and material efficiency	Cost-efficient combination of options from 2°C scenarios	Based on COMBO with more BECCS, CCS	Based on COMBO and CIRC with lifestyle changes
GHG target in 2050	~80% GHG (excluding sinks) ["well below 2°C" ambition]					~90% GHG (incl. sinks)	~100% GHG (incl. sinks) ["1.5°C" ambition]	
Major Common Assumptions	• Higher energy efficiency post 2030 • Deployment of sustainable, advanced biofuels • Moderate circular economy measures • Digitalisation				• Market coordination for infrastructure deployment • BECCS present only post-2050 in 2°C scenarios • Significant learning by doing for low carbon technologies • Significant improvements in the efficiency of the transport system			
Power sector	Power is nearly decarbonised by 2050. Strong penetration of RES facilitated by system optimisation (demand-side response, storage, interconnections, role of prosumers). Nuclear still plays a role in the power sector and CCS deployment faces limitations.							
Industry	Electrification of processes	Use of H2 in targeted applications	Use of e-gas in targeted applications	Reducing energy demand via Energy Efficiency	Higher recycling rates, material substitution, circular measures	Combination of most cost-efficient options from "well below 2°C" scenarios with targeted applications (excluding CIRC)	COMBO but stronger	CIRC+COMBO but stronger
Buildings	Increased deployment of heat pumps	Deployment of H2 for heating	Deployment of e-gas for heating	Increased renovation rates and depth	Sustainable buildings			CIRC+COMBO but stronger
Transport sector	Faster electrification for all transport modes	H2 deployment for HDVs and some for LDVs	E-fuels deployment for all modes	Increased modal shift	Mobility as a service			• CIRC+COMBO but stronger • Alternatives to air travel
Other Drivers		H2 in gas distribution grid	E-gas in gas distribution grid				Limited enhancement natural sink	• Dietary changes • Enhancement natural sink

As stated in the European Green Deal[28], energy-intensive industries, such as steel production, production of chemicals and cement manufacture, are indispensable to Europe's economy, as they supply several key value chains. The decarbonisation and modernisation of this sector is essential. The Commission's in-depth analysis[26] in support of the long-term vision for a prosperous, modern, competitive and climate neutral economy indicates that there is a plethora of deep decarbonisation options for industry, but no single silver bullet for all subsectors.

A portfolio of options to decarbonise industry is described in the literature, presenting a range of choices to industry to reduce GHG emission (combinations of increased material and energy efficiency, greater material recirculation, new production processes and carbon capture technologies). However, studies also indicate that comprehensive assessments are ideally conducted in order to capture the likely impacts from decarbonisation. Changes can be expected in processes or technologies and these changes will eventually require increased R&D, economic incentives, transformation of value chains and development of infrastructure. Any such radical changes in industry require careful examination of the wider environmental impacts, identifying any potential new environmental challenges or opportunities for a successful transition.

To ensure the best pathways to decarbonisation are adopted, it is important to assess wider environmental impact of available options. Some studies are available, such as LCA studies for a specific industrial process or technology, or more general studies on the benefits of energy efficiency measures. There is, however, a gap in knowledge of the expected impact when different decarbonisation pathways across different sectors are

[28] The European Green Deal – COM(2019) 640 final

combined. Limited information is also available on the wider environmental impacts of the available options. Addressing this gap is a major focus of this study.

2.3. The contribution of the IED to the circular economy

IED installations are important potential contributors to the circular economy. Some operate within a linear economy – consuming materials, producing products and waste. If the materials in the products and waste are not brought back into the economy, this is a linear model. However, IED installations also operate a circular model, where materials are reused within the installation, or where they used secondary materials from other sources and produce by-products instead of waste. Some of these material flows are in the control of the installation (e.g. technical decisions), while some flows are dependent on other factors (such as market and legal requirements).

Linked to the issue of circularity of resources is the concept of resource efficiency – using fewer materials and less energy in production, etc. However, while resource efficiency is essential for a greener economy, being resource efficient alone does not necessarily deliver a circular economy – it could simply deliver a more efficient linear economy.

The relative emphasis on efficiency and circularity is important when considering the obligations in implementing the IED and what operators and regulators should do and what they could do.

In relation to the fundamental objectives of the IED, it is important to stress that resource (and energy) efficiency has been a key objective since the IPPC Directive was adopted in 1996. Resource efficiency, however, did not have the focus of attention in the early years of implementation which it might have had (attention, not surprisingly, focused on pollution reduction, and corresponding BAT and BAT-AELs, etc.). The specific objective of circularity of materials is not explicit within the IED. It may now be viewed as part of the primary objective of the directive – protection of the environment as a whole. However, the regulatory requirements do not focus on the circularity of material leaving an installation – neither the products (addressed under other legislation) nor waste (where the emphasis is ensuring appropriate waste management, rather than on waste quality leading to future end-of-waste or potentially production of alternative by-products). This is not to say that there are no regulatory decisions that deliver these outcomes (there are), nor that IED somehow prevents such decision-making (it does not), but that it does not oblige operators to do this.

The project Terms of Reference (ToR) highlights the recent report commissioned by The Commission (DG ENV) on the "IED Contribution to the Circular Economy" delivered by Ricardo and Vito (2019). This is a starting point for work within this project (although there are several other studies exploring different aspects of resource use in IED, value chains and BAT, etc, which will be taken fully into account in this support contract). It is important, therefore, to note the key contributions and limitations in this study (see text box below).

IED Contribution to the Circular Economy (Ricardo/VITO study for DG ENV, 2019) – key contributions and limitations

First of all, the report focused heavily on energy and resource efficiency. As noted above, these are key elements within a functioning circular economy, but are not themselves "circular".

Related, but different, is the emphasis on waste reduction. Waste reduction may reflect resource efficiency (e.g. being less wasteful) (so being more efficient, but still linear), or it may reflect a change in how unwanted material is managed (e.g. generating by-products, or reuse within the installation, etc.). This would be a circular outcome. However, it is difficult to determine from the report what circular changes are occurring.

Further, where such changes are occurring, it is unclear why they are happening. What is driving waste reduction? Understanding this is essential to determining the potential for future change and, therefore, the answer to the key question of this part of the present support contract – what is the potential of IED to contribute to the circular economy?

A further important area examined is that of hazardous chemicals use. The report explores the extent of such chemical use, how this varies across installation categories and how it is addressed in BREFs. However, the emphasis is on reducing the use of such chemicals. While this is important, not least in contributing to the current EU ambition for zero-pollution, a key issue for the circular economy is the presence of such chemicals in by-products or in waste (so affecting waste processing, end-of-waste determination, etc.). This is a key issue within the current examination of the relationship between EU chemicals and waste legislation. The quantity of waste (above) is important, but so is its quality, if IED installations are to contribute to the circular economy. Reducing the presence of such chemicals in waste may be delivered by reducing their use but may also be delivered by process changes.

The report also explores industrial symbiosis. The Ricardo and Vito report uses the definition of Marian Chertow in that industrial symbiosis "engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water and by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity". This is a particular example of circular behaviour by installations and is important to examine. The final point of the definition is key, in that it is focuses on geographic proximity and broader relationships between IED (and non-IED) installations may occur for material exchange that are not geographically close. However, the more complex examples of industrial symbiosis may include IED and non-IED activities and this can raise questions about the limits of what is required under IED and/or the flexibilities of its regulatory framework. This is not addressed in the report but is important if one is exploring the potential of IED installations to contribute to the circular economy.

A different, though related area to industrial symbiosis is where movement of material may take place through a chain of two or more businesses when these are not necessarily located in the same industrial zone. Regulators may have different rules when material is shipped to another operator in another region. This presents challenges as to what is in a permit for the original site operation, what requirements may be placed on the materials that are moved, whether links can be made with the permit conditions of a receiving operator and, also, how much can be included in any formal contractual arrangements between operators. This is not addressed in the report but is important as movement of material some distance from an installation would be more common than movement in co-located activities.

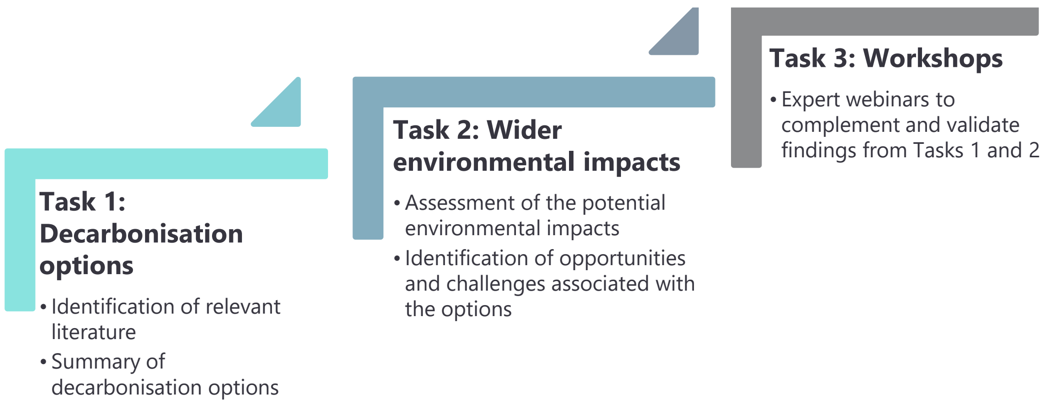
In exploring the different issues, the report focuses mainly on the performance of IED installation (e.g. waste from different categories of installation) and on how relevant issues (usually energy and resource efficiency) are addressed in the BREFs. The exception was in considering industrial symbiosis, which is a very case-specific activity. While looking at installations as a whole is important (e.g. in understanding total quantities of material flows), to understand the potential of IED installations to contribute to the circular economy it is also important to consider front runners (or similar), where circular practices are taking place, as this shows both potential and limitations (physical, technical, regulatory, etc.). The Ricardo report is, therefore, a good starting point, but further analysis is needed. This further analysis is the key objective of this report in relation to the circular economy.

3. Wider environmental impacts of industry decarbonisation

3.1. Introduction

This section of the report presents the methodology and the results addressing the first objective of the project, i.e. to provide a clear picture of the potential wider environmental impacts of industry decarbonisation. The work under this first objective was delivered through three project tasks, as presented in Figure 3.1.

Figure 3.1 Project tasks informing the assessment of wider environmental impacts of industry decarbonisation



The combination of the outcomes from these three project tasks has led to the final results presented in sections 3.3 to 3.9. The approach followed under each project task is presented in section 3.2.

3.2. Approach to evidence gathering and review

3.2.1. Industry decarbonisation options (Task 1)

The aim of the first task was to identify and review existing literature that includes or generates data or information on the transition pathways to effectively zero GHG emissions for industry sectors within the scope of the IED. The outcome of this task was the basis for the assessment of the wider environmental impacts under Task 2.

The identification and review of information was done in a systematic and transparent way. In summary, the approach set out below allowed pre-defined research questions to be addressed and an overview provided of available information under identified constraints, accompanied by a critical evaluation of the quality and strength of evidence. The steps followed are presented in Figure 3.2 and described in the paragraphs below.

Figure 3.2 Steps for the identification and assessment of relevant literature on decarbonisation options (Task 1)

Step 1. Definition of scoping and development of a search protocol

This first step consisted of defining the scope and the research questions for the identification of the information. The literature review focussed on the sectors under the scope of the IED (Annex I activities). Although from the onset of the work no selection or prioritisation of industry sectors was made, it was expected that the majority of the information would relate to the most energy intensive (and carbon emitting) IED sectors and activities.

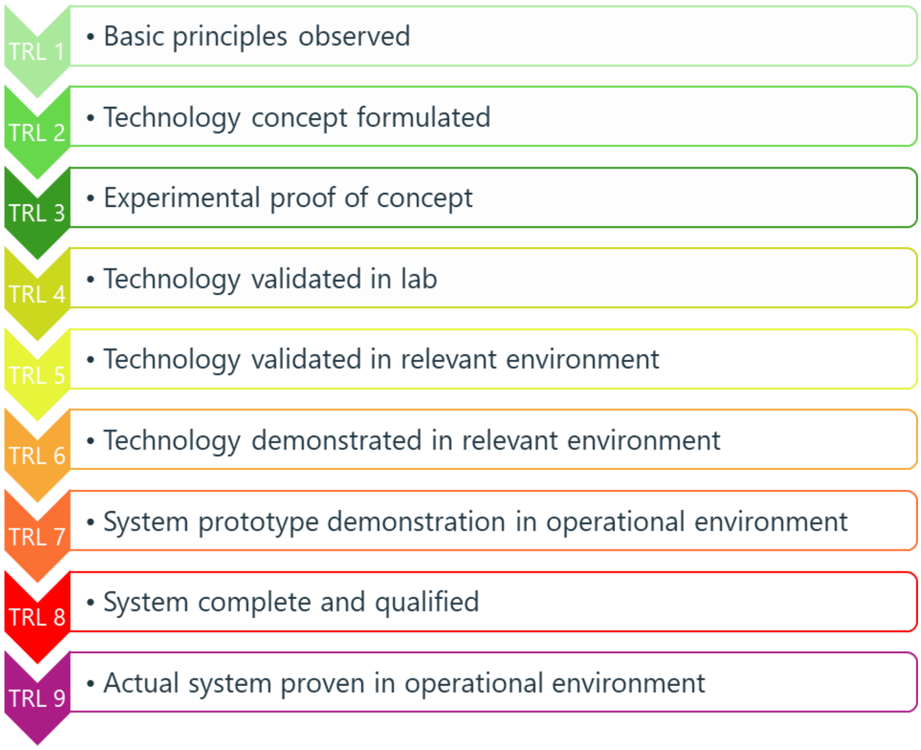
Table 3.1 presents the research questions addressed in this task and also provides further details on the scope of the work. These questions assisted in guiding the identification of relevant literature.

Table 3.1 Overview of the research questions

Research questions	Details
Main research questions	
What are the decarbonisation pathways and technologies for each IED sector?	Identification of possible pathways and technologies for decarbonisation
What are the wider environmental impacts of the technologies?	Consideration of studies looking in the expected changes in resources use, both materially and energetically. Further considerations investigated of the likely emissions to air, water, and soil. Studies can include academic papers or Life Cycle Assessment studies of specific technologies or processes. Wider impacts of the technologies can for example relate to either direct or indirect AQ and GHG emissions, water pollution, soil pollution, land use, the use of raw materials, energy, waste generation, biodiversity. The aim of this question is to identify the available information as input to the assessment under Task 2.
Are technologies ready for deployment?	To understand readiness of different technologies the Technology Readiness Level (TRL) is indicated where possible. This identifies the maturity by phase of development which a technology is at. The TRL scale has been used in the EU Horizon 2020 programme and defines 9 levels (see Figure 3.3 for an overview of the 9 levels).
What is the level of decarbonisation achieved?	To provide an indication of the degree of GHG reduction by the decarbonisation option.
Additional context	
Are decarbonisation pathways technologically feasible?	To assess the technological feasibility of decarbonisation pathways, including details on the complexity of the technology, changes to infrastructure and changes to operation and maintenance procedures.
What are the barriers to the deployment of technologies?	To identify the key obstacles from a regulatory, economic, and social perspective.

Research questions	Details
	Barriers can relate to the policies or lack of policies that restrict the uptake of technology by industry; potential administrative hurdles and existing impractical government commitments; lack of product standards (limiting the ability to take up new technology). Economic barriers can relate to financial factors which hinder the deployment of technologies. Social barriers include evidence of public resistance to technologies that are being suggested for decarbonisation.
What are the interactions between the above-mentioned factors?	To identify evidence on interactions since many of the factors noted above interact with one another. For instance, the lack of technical feasibility increases economic barriers which limit the likelihood of deployment and reduce the potential environmental impact.

Figure 3.3 Technology Readiness Levels (TRL) – overview of 9 levels



Step 2. Identification of evidence

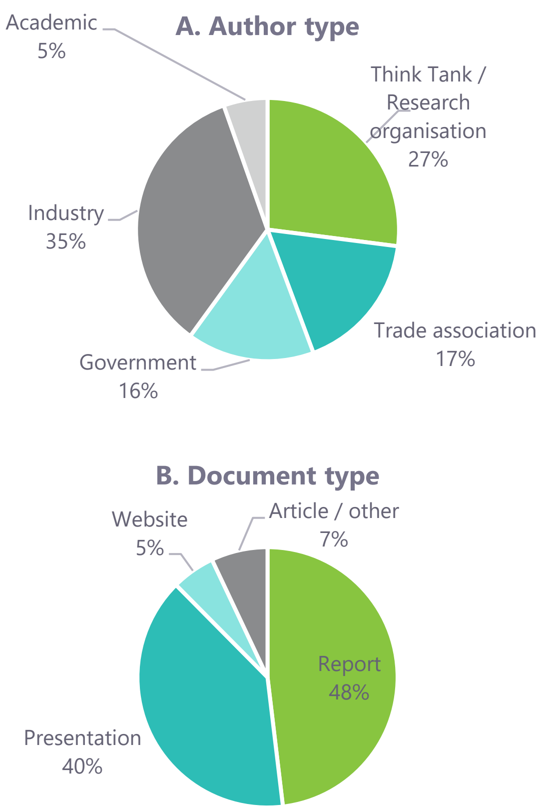
The information was identified through two main routes, i.e. i) literature review, and ii) stakeholder consultation.

The literature review involved online search for evidence, guided by the scope and research questions, using literature research tools.

For the stakeholder consultation, a request for information on decarbonisation options in IED sectors was sent to the IED Article 13 Forum members as well as to wider stakeholders, such as research organisations, NGOs and consultancies (see Appendix A for the list of organisations contacted).

A total of 185 documents have been identified and reviewed (covering over 1100 techniques, many of which being duplicates). An overview of the identified literature under Task 1 and of the inputs received from stakeholders is presented in Appendix A. Figure 3.4 presents the split of literature by type of author or organisation and by document type.

Figure 3.4 Split of references by (A) author type and (B) document type



Step 3. Extraction and appraisal of evidence

In a following step, the documents have been reviewed to appraise and extract the relevant evidence, i.e. to answer the research questions. A template (Table 3.2) was used to ensure consistency in information extracted for each decarbonisation technology.

Table 3.2 Information collection template (Task 1)

IED sector(s)	
Technology	
Description	
Environmental impacts	
Readiness to deployment	
Degree of decarbonisation	
Additional context:	
Main barriers to deployment	
Potential interactions with other processes technologies	
Implications for the sector	

For the decarbonisation options, information on the degree of possible decarbonisation was extracted from literature, whenever available (as per the template above). Such information is presented in literature in different ways, e.g. as an expected reduction of CO_2 emissions in comparison to a reference scenario, an absolute reduction in GHG emissions based on a pilot installation or a qualitative description of the likely implications for decarbonising the industrial process or activity. In order to be able to provide a consistent indication of the **GHG emission reduction potential** for the identified options, the compiled information was used in this project to categorise the options as follows:

- high GHG emission reduction potential (>70% reduction),
- medium GHG emission reduction potential (30-70% reduction), or
- low GHG emission reduction potential (<30% reduction).

This is a categorisation based on emission reduction in comparison to current reference technology. It does not compare emissions across the industry or broader emission projections. Feedback from stakeholders, during the webinars and interviews, was used to fill gaps or revise the initial assessment where applicable. This grouping, presented in the summary tables in this report, also allowed for a prioritisation of technologies which have been assessed in more detail under task 2 (see section 3.2.2 for more details).

Apart from the information collected and reviewed, the source itself was also assessed by applying a **critical appraisal** of the identified literature, covering:

- Adequacy (independence of the author, evidence of acceptance / criticism);
- Relevance (scope: sectors, geographical coverage, addresses the research questions);
- Accuracy (qualitative / quantitative, transparency of assumptions, potential bias);
- Robustness (clear, replicable method, clear underlying information, clear limitations, theory / reality); and
- Key strengths and weaknesses.

Notes from the critical appraisal of all literature are provided in Appendix A.

Step 4. Data gap filling

It was expected that literature review would not necessarily provide a detailed answer to all research questions under Task 1. For example, information related to the environmental impacts of a technology was expected to be rather limited. Apart from the potential wider environmental impacts, other types of gaps relate to the readiness of implementation of techniques or to the IED sectors, e.g. sector or activities for which little or no information has been identified on decarbonisation options. After extracting and appraising the literature, such information gaps from the literature were highlighted.

In order to fill the main data gaps, the following steps have been undertaken under this project:

- Consultation of experts via targeted interviews (Task 2);
- Expert judgement from the project team and expertise within the organisations; and
- A series of expert webinars (Task 3).

Step 5. Reporting

The final step of Task 1 involved the reporting on the previous steps and including the results in this final report.

3.2.2. Assessment of wider environmental impacts (Task 2)

This section presents the approach for Task 2 of the project, i.e. assessment of the wider environmental impacts of the identified decarbonisation options. The aim of Task 2 was to:

- Characterise the direct and indirect impacts based on the summary provided under Task 1;
- Where possible provide a quantified assessment or describe these impacts in a qualitative manner; and
- For each impact, identify and describe the respective challenges and opportunities.

To reach these objectives, a key component is the identification of a set of indicators for the assessment of both the direct and indirect environmental impacts. The indicators used correspond to the following research questions:

- What are **the direct non-GHG emission-related impacts** on the following areas (at plant level or directly linked to the technology), particularly in relation to the following?
  - Air emissions other than GHG e.g. particles (TSP, PUF, PM_{10}, $PM_{2.5}$, nanoparticles, etc.), NOx, SOx, VOCs (including PAHs and BTEXs), POPs (e.g. dioxins, furans), toxic metals (e.g. mercury, arsenic, cadmium))
  - Water use and pollution (e.g. pH, dissolved oxygen and conductivity by direct electrochemical measurements, nitrate and ammonia by specific ion electrodes, metals by anodic stripping voltammetry, ammonia, phosphate, total phosphorus (TP) and iron by spectrophotometry)
  - Energy use and efficiency (e.g., the energy consumption and its source of generation implied by the decarbonisation technologies)
  - Resource use and waste generation (including the share of hazardous waste as part of the total waste generation, the generation or the potential for reuse of the waste, etc).
  - Soil pollution, land use and biodiversity and ecosystems
- Are there any **indirect environmental impacts** associated with the decarbonisation technologies (linked to the energy source , or other stages of the whole value chain (e.g. fuel and feedstock substitution))?
- Are there any **quantitative estimates** concerning the identified direct and indirect environmental impacts?
- Are there any **differences in the impacts** in different stages of the production chain (for the direct impacts) or the value chain (for the indirect impacts)?
- Is there potential for **establishing a synergy** between decarbonisation technologies between the different IED sectors (e.g. through the use of alternative resources or waste)?
- Are there any **opportunities or challenges** linked to these environmental impacts (e.g. due to additional pollution caused from additional consumption of energy and resources)?

The induced risks of accident were not included in the scope of assessment of the environmental impacts. It is generally assumed that the decarbonisation options have been or will be deployed following a risk analysis.

In addition, the relevant socio-economic impacts are also not addressed in this study.

The direct and indirect environmental impacts for each of the impact categories (e.g. air pollution, water pollution, energy efficiency) and the relevant indicators are assessed in the following sections for different sectors of the IED. The inclusion or exclusion of certain impact categories and indicators depends on the data availability. In general, there are several data gaps mainly linked to the low maturity of most of the decarbonisation options and the consequent lack of evidence on the wider environmental impacts.

Depending on the data availability a semi-quantitative assessment was performed to show the scale of the impacts compared to the conventional technologies currently in use, using the following scoring system:

- '+': Positive environmental impact;
- '-': Negative environmental impact;
- '-/+': Positive or negative environmental impact (depending on certain conditions);
- '**0**': no effect;
- '**?**': unknown effect

The information on the different areas of the assessment was collected through a literature review, interviews with experts from the industry and an expert webinar. The list of literature sources consulted for the environmental impacts and the organisations that were interviewed are listed respectively in section 5 and Appendix B.

3.2.3. Delivery of expert workshops (Task 3)

Within the data compiled and assessed under tasks 1 and 2, several information gaps were identified, related to the decarbonisation options applied in IED sectors/activities and to the wider environmental impacts of these options (both direct and indirect). Efforts have been made to fill these gaps via consultation of experts in interviews and through the delivery of expert workshops (Task 3). The aim of Task 3 was to organise and deliver expert workshops with the intention to:

- Present and discus the draft findings of the tasks 1 and 2;
- Identify any weaknesses of the methodology applied and how to address them; and
- Identify any sources of relevant information not yet exploited.

The original plan for Task 3, as set out in the terms of reference and the project inception report, was to organise a face-to-face meeting with stakeholders in Brussels. Given the outbreak of COVID-19 during the delivery of the project and following discussions with the Commission, this approach was changed into the delivery of three online webinars, each focussed on a specific sector or group of industrial activities, i.e.:

- Production and processing of metals (Tuesday 13 October 2020);
- Mineral industry (Wednesday 14 October 2020); and
- Chemical industry (Thursday 15 October 2020).

The discussions with the experts informed the assessment and conclusions drawn, and focussed on i) the identification of decarbonisation options, and ii) their wider environmental impacts. The agenda of the webinars is presented in Table 3.3.

Table 3.3 Agenda for the expert webinars

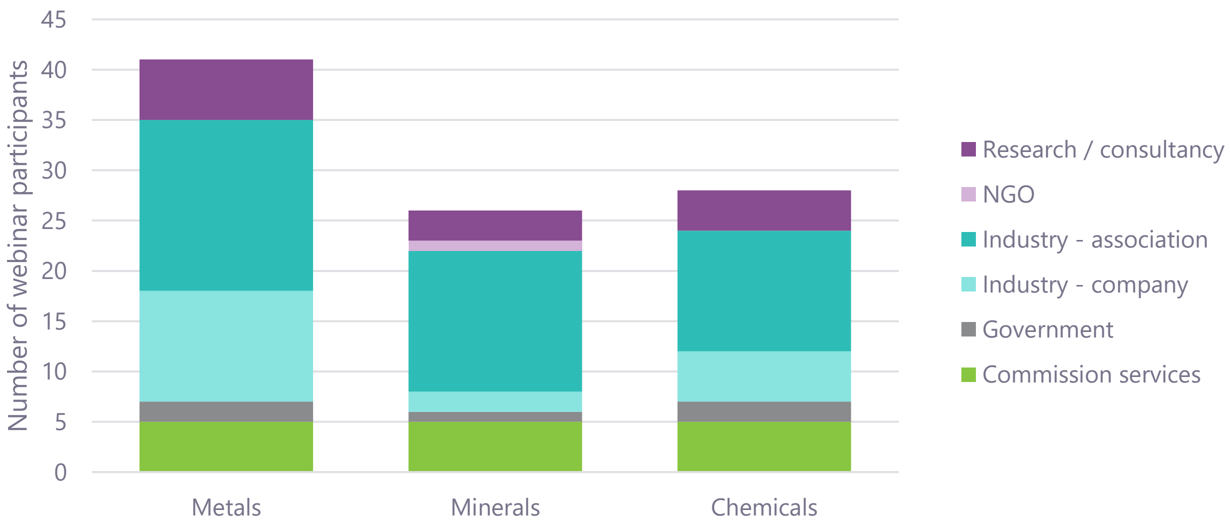
Time	Session
10:00	Welcome and instructions *Project team*
10:15	Introduction and project context

Time	Session
	Project team / European Commission (DG ENV)
10:30	**Decarbonisation options and their GHG reduction potential** *Presentation by the project team* *Discussion and Q&A*
11:00	**Wider environmental impacts of decarbonisation options** *Presentation by the project team* *Discussion and Q&A*
12:00	Summary and concluding remarks *Project team*
12:15	End of event

In advance of the webinars a background paper was shared with registered participants which included an introduction to these discussion topics and an indication of the questions that were covered during the discussions.

The webinars brought together experts from the European Commission, industry, NGOs, governments and academic experts. Around 25-45 experts participated in each webinar. The figure below presents the split of participants by type of organisation.

Figure 3.5 Number of webinar participants by type of organisation



A summary report of the expert webinars, background papers and the slides presented during the webinars are provided in Appendix C.

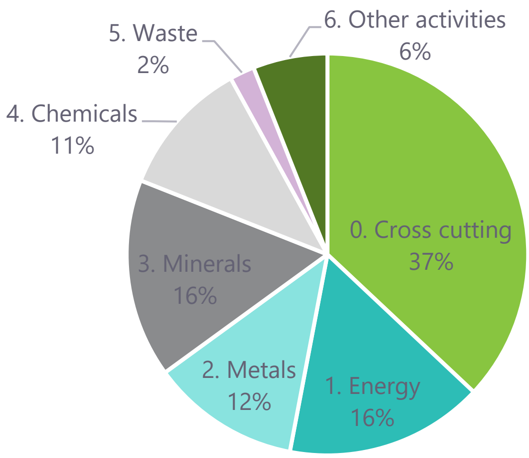
3.3. Overview of decarbonisation options

The decarbonisation pathways, extracted from the literature and with input from stakeholders, are summarised below, separated into sections according to the categories of activities as defined in Annex I of the IED[29]. Under each sector, individual tables present the pathways split by common pathway groups. An additional sector grouping presents the cross cutting pathways which have been identified as being applicable across multiple IED sectors and activities. Cross cutting technologies (such as hydrogen as an alternative fuel) have been lifted from the individual sector summaries and are presented in a section on 'cross cutting decarbonisation pathways'. As such, the information is presented in the following sections:

- Section 3.4: Cross cutting decarbonisation pathways (e.g. CCS, energy efficiency, hydrogen);
- Section 3.5: Energy industries;
- Section 3.6: Production and processing of metals;
- Section 3.7: Mineral industry;
- Section 3.8: Chemical industry; and
- Section 3.9: Waste management and other activities.

The identified literature with information on the decarbonisation pathways (number of references) is split by these sections (IED activities) as presented in Figure 3.6.

Figure 3.6. Split of references by categories of IED activities (and cross cutting activities)



In order to summarise the information, the decarbonisation options have been grouped and presented into several pathway groups as follows:

- Alternative feedstock or material inputs;
- Alternative energy sources;
- Alternative process;
- Recycling;
- System optimisation; and

[29] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32010L0075

- Carbon capture (CCS/CCU).

A description of these pathway groups and an indication of how each group can potentially contribute to the decarbonisation of the industrial activities is presented in Table 3.4. This grouping is in line with how information on decarbonisation options often is presented in the available literature, though variations to these categories exist. The main objective, however, is to be able to compare the pathways across IED activities and to present the information in a systematic manner.

Table 3.4 Pathway groups for industry decarbonisation

Pathway group	Description	Potential contribution to industry decarbonisation
Alternative feedstock or material inputs	Involves utilising a new feedstock or utilising alternative process material.	Using alternative (auxiliary) materials as input in production processes can reduce direct and/or indirect GHG emissions. The emission reductions can be related to the production of the alternative materials or to the use phase in the production process. The alternative feedstock can have an overall lower carbon intensity. Examples include the use of bio-based feedstock as input to the chemical industry.
Alternative energy sources	Involves switching from fossil fuels to low carbon fuel alternatives (e.g. biomass, hydrogen, geothermal energy, biogas, synthetic fuels), including electrification of heat and processes (which can utilise renewable energy).	Switching from fossil to low-carbon fuels and renewable energy will lead to lower GHG emissions due to the lower carbon content of the alternative fuels or energy sources. In addition to the use of fuels for heat and electricity production, this group also relates to the use of energy carriers (and production thereof) in industrial processes. An example is using hydrogen as a reducing agent as an alternative to coke in the iron and steel sector. In order to prevent or abate pollution from fuel combustion in energy and industry sectors, Best Available Techniques (BAT) are defined and implemented. Fuel switching with the intention to reduce GHG emissions, can potentially also lead to such pollution and therefore require BAT to be implemented, depending on the alternative energy source (details are provided in section for the various industry sectors).
Alternative process	Entails using a different production process but typically with the same feedstock.	An alternative production process can potentially eliminate or generate lower GHG emissions compared to the original/conventional process. The alternative process could also use different feedstock or energy sources (see above), however producing the same outputs. Examples include novel or innovative techniques in the food and drink industry, pulp and paper sector or iron and steel sector (e.g. neo-carbon food, high consistency, iron ore electrolysis).
Recycling	Involves recycling materials in the production process.	Recycling and recovery of materials (and by-products, waste) can have an impact on both direct and indirect GHG emissions. Direct emissions can decrease when waste is not disposed of in landfills or treated in any other way (e.g. incineration). Indirect emissions can be reduced by decreasing the energy consumption related to the production of raw materials and to the manufacturing phase of the product itself. Replacing virgin material with recovered materials avoids the emissions from manufacturing a product from virgin material. GHG emissions can also be reduced by avoiding the use of materials, which produce emissions directly in the production phase (i.e. material efficiency). It should be noted that recycling can also generate GHG emissions (or even increase emissions in some cases), for example related to the treatment and transportation of the recovered/recycled materials.
System optimisation	Technologies that improve the efficiency of the activity or process.	System optimisation covers options that lead to an increase in energy and/or process efficiency. Energy and process efficiency can deliver several environmental benefits, but in particular can lead to a reduction in GHG emissions, i.e. both direct emissions from fossil fuel combustion or consumption, and indirect emissions reductions from electricity generation. Examples of the efficient use of energy or process efficiency improvements include the recovery and use of heat, reducing energy demand (e.g. lower product weight, insulation, etc) and process and combustion optimisation options (e.g. oxy-fuel combustion).

Pathway group	Description	Potential contribution to industry decarbonisation
Carbon capture (CCS/CCU)	Technologies relating to the capture and storage (CCS) or to the utilisation of carbon from the activity (CCU).	CCS is a way of decarbonising fossil fuel power generation and involves capturing CO_2 emitted from high-producing sources, transporting it and storing it (in secure geological formations). The captured CO_2 can also be reused in processes such as enhanced oil recovery (EOR) or in the chemical industry (CCU). Carbon capture options can mitigate carbon emissions from energy production and/or directly from the industrial processes (e.g. direct separation and calcium looping). Furthermore, utilising the captured CO_2 as input for the production of chemicals, fuels or other products (i.e. valorisation) decreases the reliance on the virgin materials.

3.4. Cross cutting pathways

3.4.1. Decarbonisation technologies

The aggregation of pathways and technologies enabled the identification of key cross-cutting decarbonisation options which could possibly be used across several industry sectors. These options relate to reducing or eliminating energy related emissions through similar technologies such as renewables, carbon capture, and general efficiency improvements.

A matrix detailing which cross cutting options can be applied to which sectors and activities is presented in Table 3.5. The matrix indicates for each sector which pathway could be considered as a realistic decarbonisation option. For some of the options, such as biomass and hydrogen use as fuel or feedstock, literature often did not specify the specific activities in which the technologies could be used; however, often it was noted that they are generally applicable to meet (some of) the energy requirements. The stage of development of certain decarbonisation technologies varies across industry sectors, with some in development stage whilst for other sectors pilot installations might have been successful, with others even being applied at industrial scale. Furthermore, the potential of these technologies for reducing carbon emissions is different across the industry sectors.

Table 3.5 Cross cutting pathways with potential for IED sector-activities as identified in the literature

Pathway group	Pathway	1. Energy	2. Metals	3. Minerals	4. Chemicals	5. Waste	6. Other
Alternative feedstock	Biomass	√ (REF)			√		√
Alternative feedstock	Hydrogen	√	√ (Iron and steel)		√		
Alternative energy source	Biomass (solid biomass, charcoal, biogas, bioethanol, etc)	√	√ (Iron and steel, NFM)	√ (Cement)	√	√	√
Alternative energy source	Hydrogen	√	√ (Iron and steel)	√ (Lime; Ceramics)	√		√
Alternative energy source	Electrification	√	√	√	√	√	√
System optimisation	Energy efficiency improvements	√	√	√	√	√	√

Pathway group	Pathway	1. Energy	2. Metals	3. Minerals	4. Chemicals	5. Waste	6. Other
Recycling / System optimisation	Industrial symbiosis	√	√	√	√	√	√
Carbon Capture	CCS/CCU (Pre-, Post-, Oxy-fuel combustion, membrane)	√	√	√ (Cement)	√	√	

The information on the cross-cutting techniques is summarised below in Table 3.6.

Table 3.6 Summary of cross cutting pathways and technologies which have been identified across IED sectors and activities

Pathway group	Pathway	Descriptions	TRL	Main barriers	GHG reduction*
Alternative feedstock	Biomass	Biomass can be used as a feedstock for many industrial processes, in particular in the cement sector and chemical industry.	8-9	Limited availability of sustainable biomass.	MEDIUM The CO_2 emissions reduction varies across sectors, depending on the possibilities to use biomass. More details of GHG reduction potential for each IED sector included in the sections below.
Alternative feedstock	Hydrogen	The use of hydrogen as a feedstock, in particular as a reducing agent in the metallurgic industry and for the production of ammonia.	5-8	Breakthroughs will be required for hydrogen generation at significantly lower energy demand and for providing significant excess hydrogen from renewable energy sources.	HIGH Abatement potential is high for hydrogen use presuming hydrogen is sourced from renewable energy.
Alternative energy source	Biomass	The use of biomass as an alternative energy source (including solid biomass, charcoal, biogas, bioethanol).	8-9	Limited availability of sustainable biomass. Likely to be significantly more expensive than fossil fuels.	MEDIUM The use of biomass as an energy source could be considered as carbon neutral since the carbon that is released during combustion has previously been sequestered from the atmosphere (presuming a sustainable production method). However, the full supply chain must be considered, and all emissions associated with the production, processing, transport and use of biomass need to be included (IEA Bioenergy).
Alternative energy source	Hydrogen	Switching from fossil fuel combustion to hydrogen combustion. Hydrogen combustion can be considered as a replacement to fossil fuel used for heating purposes. For natural gas turbines, a mixture of natural gas and hydrogen can be used as an intermediate whilst hydrogen supply chain and infrastructure is established.	5-8	Breakthroughs will be required for hydrogen generation at significantly lower energy demand and for providing significant excess hydrogen from renewable energy sources. If hydrogen is a by-product from other industrial activity, then the combustion site must be located nearby.	HIGH Abatement potential is high for hydrogen use, with sectors indicating hydrogen combustion can provide 80-100% CO_2 emission reduction (hydrogen must be sourced from renewable energy for this to be correct). More details of GHG reduction potential for each IED sector are included in the sections below.

Pathway group	Pathway	Descriptions	TRL	Main barriers	GHG reduction*
Alternative energy source	Electrification	Adoption of electricity driven processes and heat production (see details in the individual sector sections).	6-9	Supply of (renewable) energy; electricity prices.	HIGH
System Optimisation	Process and energy efficiency	Energy efficiency options, reducing energy demand, are widely applicable across all sectors and activities. These options include, amongst others heat recovery, improved insulation, low energy lighting, energy management systems, energy demand management, developing and deploying energy storage systems, motors / variable speed drives, compress air, gas recycling.	6-9	These measures are widely applicable.	LOW The techniques are estimated to provide between 10% - 20% emissions reduction.
Recycling / System optimisation	Industrial symbiosis	The use by one company or sector of underutilised resources broadly defined (including waste, by-products, residues, energy, water, logistics, capacity, expertise, equipment and materials) from another, with the result of keeping resources in productive use for longer.[30]	1-9	Availability of streams of waste or by-products. Regulatory compliance issues and public acceptance (waste streams and by-products)	HIGH
Carbon Capture	Pre-combustion	Conversion by gasification or partial oxidation of fuel into a synthesis gas which is then reacted with steam in a shift reactor to convert CO into CO_2 or another organic substance. The process produces highly concentrated CO_2 that is readily removable by physical or chemical absorbents. H_2 can then be burnt in a gas turbine. The CO_2 captured can be used as feedstock for other industries (CCU) or stored.	3-7 (9 for NG)	Significant capital investments. Energy penalty creates larger operational cost. Size of full-scale capture plants is challenging. Capture technology must be flexible enough to adapt to energy market. Little demand for captured CO_2. Availability of suitable and long-term reliable storage (e.g. in depleted oil/gas fields or as	HIGH The final emission reduction of this technology will depend on the CO_2 use and storage time (temporal or permanently stored). More efficient than post-combustion technology because the CO_2 is removed from a more concentrated stream and at a higher pressure. More details of GHG reduction potential for each IED sector are included in the sections below.

[30] https://ec.europa.eu/environment/ecoap/about-eco-innovation/experts-interviews/making-industrial-symbiosis-business-usual-europes-circular_en

Pathway group	Pathway	Descriptions	TRL	Main barriers	GHG reduction*
				part of enhanced oil recovery (EOR) schemes). For sectors consisting of SMEs (e.g. ceramics), the scale and economics of the technology are not favourable.	
Carbon Capture	Post-combustion	Process extracts the CO_2 from the combustion flue-gas. The solvents for CO_2 post-combustion capture can be physical, chemical, or intermediate. Chemical solvents, such as amines, are most likely to be used. Other post-combustion capture solutions are absorption (new solvents, chilled ammonia), adsorption, anti-sublimation, and membranes. The CO_2 captured can be used as feedstock for other industries (CCU) or stored.	3-9	Significant capital investments. Energy penalty creates larger operational cost. Size of full-scale capture plants is challenging. Capture technology must be flexible enough to adapt to energy market. Little demand for captured CO_2. Availability of suitable and long-term reliable storage (e.g. in depleted oil/gas fields or as part of enhanced oil recovery (EOR) schemes).	HIGH The final emission reduction of this technology will depend on the CO2 use and storage time (temporal or permanently stored). Up to 95% of the CO2 emissions may be captured with this technology. More details of GHG reduction potential for each IED sector are included in the sections below.
Carbon Capture	Oxyfuel	Oxy-combustion processes consist of burning a fuel in pure oxygen. The gases produced by the oxy-combustion process are mainly water and CO_2, from which CO_2 can easily be removed at the end of the process. The pure oxygen gas is produced from an air separation unit. The CO_2 captured can be used as feedstock for other industries (CCU) or stored.	4-7	Significant capital investments. Energy penalty creates larger operational cost. Size of full-scale capture plants is challenging, not proven at demo scale in cement industry. Capture technology must be flexible enough to adapt to energy market. Little demand for captured CO_2. Availability of suitable and long-term reliable storage (e.g. in depleted oil/gas fields or as part of enhanced oil recovery (EOR) schemes).	HIGH The final emission reduction of this technology will depend on the CO_2 use and storage time (temporal or permanently stored). Up to 95% of the CO_2 emissions may be captured. More details of GHG reduction potential for each IED sector are included in the sections below
Carbon Capture	Membrane Capture	Polymeric and density inorganic membranes are being developed with the potential to separate flue gases from fuel combustion.	3-7	Membrane material and design must be carefully considered when designing systems in which it will be placed as it can influence performance. Separation efficiency and temperature resistance have to be improved	HIGH Between 90-95% of direct emissions reduced across all activities. More details of GHG reduction potential for each IED sector included in the sections below

Pathway group	Pathway	Descriptions	TRL	Main barriers	GHG reduction*
				Availability of transport (pipeline) grid and operated storage sites.	

** Indication of the GHG emission reduction potential: high (>70% reduction) / medium (30-70% reduction) / low (<30% reduction) – see section 3.2.1.*

3.4.2. Wider environmental impacts

The wider direct and indirect environmental impacts of the cross-cutting technologies are provided in Table 3.7 below. The approach for the assessment is described in section 3.2.2. Often, the environmental impacts of cross-cutting technologies highly depend on the exact characteristics of the solutions (e.g. the source of energy for the electrification of processes). The table indicates the cases where the impacts are highly dependable.

Table 3.7 Wider direct and indirect environmental impacts of cross cutting pathways and IED sector-activities

Pathway group	Pathway	Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	Indirect environmental impacts
Alternative energy source or feedstock	Biomass	See sector-specific sections -/+ In the case of biomass as an energy source, combustion of biomass will lead to emissions of air pollutants (CO, PM, VOCs, NOx). As for conventional routes (fuels), abatement techniques (BAT) will need to be implemented. In some instances, the biomass burnt can emit more pollution than fossil fuels.	See sector-specific sections 0 Impacts on water pollution are mainly linked to the production of biomass (ecosystems).	See sector-specific sections - In the case of biomass as an energy source: biomass contains water so its combustion is less efficient than fossil fuels.	+ In the case of bio-based waste, the impact on resource use is in general positive.	- Negative impacts on ecosystems can be expected, particularly when biomass derives from non-waste sources. Direct and indirect land use change effects from the expansion of biomass feedstock for energy production have resulted in habitat and biodiversity loss, especially when large-scale land conversion using mono-cultural feedstock production is adopted. Ecosystems: Most biomass production pathways emit GHGs and atmospheric/ water pollutants that can have negative effects on ecosystems and biodiversity, e.g. eutrophication, acidification and toxicity.	- Impacts associated with the transportation of biomass are greater to those from conventional fuels or feedstock, as it is (i) less energy dense and (ii) has to be collected from dispersed locations.

Alternative energy source or feedstock	Hydrogen	+ In general, the environmental impacts depend on the site-dependent electricity mix. Lower air emissions are achieved, however various acidification potentials depending on the technology. Biomass gasification has the highest potential compared to other. The higher flame speed increases the flame temperature locally, which can generate high levels of NOx. In addition, emissions of VOCs may derive from the solvents that are used in the cleaning process.	+ Overall a positive impact as the water discharge network and the wastewater streams (cleaning water, cooling water...), cleaning water may contain solid particles and dust.	-/+ Energy consumption: not necessarily highly efficient because the production of hydrogen requires a large amount of energy that needs to come from renewable sources. In that case this would imply a lower use of energy resources (e.g. oil and coal). In terms of energy consumption, biomass gasification has an advantage over other methods, whereas solar-based electrolysis is not effective.	- Additional infrastructure is required for the deployment of hydrogen, including the installation of pipes that are in general thicker than conventional ones. Nevertheless, the infrastructure is in general made of metal which can be reused or recycled therefore in the long term. Waste generation: use of catalysts (nickel) that contain biotoxic metals and must be recycled or carefully disposed of.	-/+ Potential impacts on land use, if renewable energy technologies are developed on the site for the generation of electricity: large portions of land will be required to install energy generation equipment (for example solar panels).	- Additional land is required for developing renewable energy infrastructure. This depends on the conventional source that is replaced as more land might be required for certain fossil fuels. Impacts also derive from the transportation of the hydrogen if this occurs outside the production site (e.g. through road transportation or pipes). If additional land is required on the site (e.g. for the installation of solar panels), then less land will be required for the extraction of fossil fuels elsewhere.
Alternative energy source	Electrification	-/+ Dependent on the source of energy used for the generation of electricity. Overall, the air emissions are eliminated when renewables are used except if biomass or geothermal energy is used for the generation of electricity (see section on energy industries)	-/+ Dependent on the source of energy used for the generation of electricity. Significantly lower risk of water pollution when renewables. A potential increase of eutrophication is associated with hydropower installations.	+ Highly dependent on the source deployed for the generation of electricity. Renewables have a positive impact on energy efficiency as the substitution of conventional sources of energy occur mainly at peak time.	- Highly dependent on the source deployed for the generation of electricity. The deployment of renewables may require additional resources for the required for the development of infrastructure.	-/+ Highly dependent on the source deployed for the generation of electricity. Overall, compared to conventional sources of energy, the negative impacts on land use and biodiversity might be caused by certain renewables (see also	- Highly dependent on the source deployed for the generation of electricity. Negative impacts are also associated with the development of infrastructure both for conventional and renewable sources of energy.

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						section on energy industries).	
System optimisation	Process and energy efficiency	+ Overall lower air emissions are achieved due to lower energy consumption.	0 No significant changes on water use and risks on water pollution.	+ Energy savings in general depend on the effectiveness of the specific solutions.	+ Process and energy efficiency solutions, typically require additional resources (e.g. pipes for heat transfer, insulation material). Nevertheless, resource savings are achieved through the reduced requirements for fuel and machinery for the production of energy.	-/+ Highly dependent on the exact characteristics of the solution.	-/+ The development of process and energy efficiency solutions requires additional resources for the production and transportation across the whole value chain. This generates further impacts (e.g. air emissions in the production). Nevertheless, the positive environmental impacts from the reduced energy consumption, balance the impacts associated with the production and transportation of the alternative solutions.
Recycling / System optimisation	Industrial symbiosis	+ Highly dependent on the exact characteristics of the solution. In general, this type of solution reduces air emissions particularly when these are associated with the reduction of the use of conventional sources of energy.	-/+ Highly dependent on the exact characteristics of the solution. Typically the solutions reduce water consumption but certain risks for water pollution exist (e.g. in heat exchange installations).	+ Certain solutions for industrial symbiosis are linked to significant energy savings (e.g. through the use of excess heating on other production facilities or through the reduction of transportation). As result the use of conventional sources of energy is reduced.	+ By default, industry symbiosis leads to reduction of resource use and reduced amounts of waste.	? Highly dependent on the exact characteristics of the solution.	+ Additional resources are required for the manufacturing of products and the infrastructure that is required in most cases to establish the industrial symbiosis solutions. Nevertheless, the positive environmental impacts are typically higher than any negative effects.

Carbon capture	Pre-combustion	+ Emissions of CO_2 and air pollutants occurring from CCS-equipped facilities are generally considered to be beneficial both in terms of air quality and climate change. In general, for fossil-fuel power generation, the increased fossil fuel combustion (due to increase in primary energy use), can lead to an increase in air pollutant emissions. However, Pre-combustion technology has the lowest increase in primary energy use. The Integrated Coal Gasification Combined Cycle (IGCC) coal system significantly reduces the SO_2 and NOx content in the flue gas from syngas combustion. In addition, the following reductions are achieved:	- Water pollution : Fresh water eutrophication results show significant increases of 120% for coal and 94% for natural gas CCS systems. Water pollution: no discharges of process water in the sea, during the transport and storage phase. Surface water can be affected by the capture process if the plant needs to abstract additional quantities of water. Groundwater can be affected by the presence of the pipeline, with potential impacts on the aquatic ecology.. The post-combustion CCS systems show significant increase in freshwater eutrophication and various toxicity potentials. Results show an increase of 136% for	- Energy efficiency : less energy consumption compared to post-combustion technologies. CCS technologies require approximately 15% to 25% more energy depending on the particular type of technology used, so plants with CCS need more fuel than conventional plants. This in turn can lead to increased 'direct emissions' occurring from facilities where CCS is installed, and increased 'indirect emissions' caused by the extraction and transport of the additional fuel. The efficiency loss due to 'water-gas-shift' reaction and solvent circulation is assumed to be 6.5% Transport and storage require additional	- Waste generated during operation of CO_2 capture systems include slag and ash from increased coal usage, residues from FGD systems, recovered sulphur and spent sorbents.	- Ecosystems and biodiversity: potential strong increase in the Human Toxicity Potential[31], that can represent around 200% compared to systems without CCS. Pre-combustion capture results in higher toxicity impacts compared to systems without CCS.	- Environmental impacts associated with the development of renewable energy infrastructure or to the extraction and transport of additional fossil fuels.

[31] The human toxicity potential (HTP), is a calculated index that reflects the potential harm of a unit of chemical released into the environment and is based on both the inherent toxicity of a compound and its potential dose

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		- lower SO_2 emissions due to the removal of sulphur compounds in the acid gas removal section (though the increased energy demand will lead to an increase in SO_2 and needs to be taken into account) - NOx emissions lower than in coal-fired power plant - NH_3 emissions are negligible - PM emissions are already low in IGCC plants and are not expected to be impacted - VOC emissions are expected to be lower due to CO_2 capture	the coal CCS system and 200% for the natural gas CCS system in FEP scores.	energy consumptions that have to be supplied by renewable sources. The energy requirements for the capture process are for regeneration of solvent, solvent pumps, flue gas blower, cooling water pumps and CO_2 compression, resulting in an energy penalty of 10.2% and 8% respectively for coal and natural gas plant.			
Carbon capture	Post-combustion	+ Emissions of CO_2 and air pollutants occurring from CCS-equipped facilities (are generally considered to be beneficial both in terms of air quality and climate change. In general, for fossil-fuel power generation, the increased fossil fuel combustion (due to due to increase in primary energy use), can lead to an increase in the air pollutant emissions, if no	? The post-combustion CCS systems show significant increase in freshwater eutrophication and various toxicity potentials. Results show an increase of 136% for the coal CCS system and 200% for the natural gas CCS system in FEP scores.	- Increase in primary energy use, needed for CO_2 separation and compression. high energy consumption for MEA regeneration (through low-pressure steam), it is the least energy-efficient CCS technology.	- CO_2 capture is often performed in absorption processes with amines. Portions of the amines will degrade, leading to large volumes of degraded amine that must be handled as hazardous waste. Moderate requirements for resources due to the intermediate storage solutions that are needed.	- The land use impacts of the storage are very limited as it is done undersea, as well as the transport through pipes. The capture is done directly on industrial sites. Land pollution: trace metal emissions to soil Ecosystems and biodiversity: can bring a more	- Environmental impacts associated with the development of renewable energy infrastructure or with the extraction and transport of additional fossil fuels.

	additional mitigation measures are taken. The coal CCS system also shows co-reduction of 13% in acidification potential (TAP) due to co-capture of SO_2 and NOx. In addition the following reductions are achieved: - SO_2 emissions decrease, as sulphur is removed to avoid CO_2 solvent degradation (post-combustion is best technology to reduce SO_2 emissions) - NOx and NH_3 emissions increase proportionally to the increase in primary energy demand, and NH_3 linked to the degradation of amine-based solvents, but with high uncertainty - VOC emissions are not influenced by the CO_2 capture process and will increase proportionally to primary energy use - PM emissions need to be removed, but with the increase of energy consumption, emissions are expected to increase.			No waste is generated during the transport and storage phases	pronounced increase in all kinds of toxicity potential (ADP, AP and EP), due to the incremental use of coal and hence NOx and NH_3 emissions to air. Since MEA CO2 capture can remove atmospheric emissions of trace metals further after the FGD, the FAETP, HTP, TETP and MAETP are decreased relative to conventional power plants without CCS.

Carbon capture	Oxyfuel	+ Emissions of CO_2 and air pollutants occurring from CCS-equipped facilities (are generally considered to be beneficial both in terms of air quality and climate change. Air emissions: - SO_2 emissions decrease compared to conventional coal-fired power plants, have to be removed because high SOx concentration could poison the solvent - NOx emissions are expected to be very low as thermal NOx formation is suppressed and fuel NOx is reduced - Strong reduction in PM emissions (more than 90% compared to conventional coal-fired plants) - No clear information on NH_3 and VOCs. Less air emissions of NOx, SOx HCl, HF and vapour mercury compared to post-combustion systems, reducing AP and EP.	- Water emissions: harmful air emissions are converted to liquid emissions contained in the discharged water from the CO_2 conditioning unit. This implies the need to use a discharged water treatment method for the oxy-fuel combustion CO_2 conditioning unit. HF emissions leading to increases in FAETP, HTP and MAETP Oxyfuel CCS also shows a considerable increase in freshwater eutrophication and toxicity potentials. FEP scores show increases of about 60% for the coal system and 110% for the natural gas system.	- Energy consumption: air separation process is energy intensive. The energy consumption is lower compared to the post-combustion CCS technologies. Capture and compression of CO_2 have the largest energy requirements.	- Resource use: abundant use of oxygen Large resource use associated with the feedstock requirements in terms of chemicals and fuels, and potentially additional CO_2 contamination of drinking water and oil & gas reservoirs that may eliminate these resources from future uses. Waste generation : additional waste generation during the operation phase from degradation products of solvent usage.	-/+ Soil pollution might be caused but this is uncertain. Specifically, the soil quality could be affected by abnormal releases of CO_2 that could modify soil pH, reduce its quality and result in toxic conditions for flora.	- Additional environmental impacts linked to the air separation and production of oxygen. Environmental impacts associated with the development of renewable energy infrastructure or to the extraction and transport of additional fossil fuels.
Carbon capture	Membrane Capture	? No information found	? No information found	- Small increase in energy consumption.	+ Resource use: no Reduced need for	? No information found	- Environmental impacts associated with the

	chemicals, for the treatment of associated emissions as polymeric and density inorganic membranes are used for the separation of flue gases from fuel combustion.	development of renewable energy infrastructure or with the extraction and transport of additional fossil fuels.

3.5. Energy Industries

3.5.1. Decarbonisation technologies

The energy industries sector under the scope of the IED covers combustion of fuels (installations >50 MW), refining of mineral oil and gas, production of coke, gasification or liquefaction of coal or other fuels (installations >20 MW). The majority of pathways identified relate to combustion of fuels and oil refining.

Carbon capture has been identified extensively in the literature with regards to energy industry activities; for information on this see the section above (3.4 Cross Cutting). The use of bioenergy in combination with CCS (Bio-CCS or BECCS) is a particular option relevant for the energy sector as it has the potential for a carbon negative footprint and could result in the net removal of CO_2 from the atmosphere. Calcium looping has been identified as a use for carbon dioxide; this technology is described in the Mineral industry (section 3.7).

Other cross cutting technologies relevant for the energy sector include the use of biomass and hydrogen as alternative energy sources; electrification of processes (electric heaters in refineries); system optimisation; and energy efficiency processes. In addition to the cross-cutting decarbonisation technologies, relevant to the energy industries, in Table 3.8 specific decarbonisation pathways are presented related to (i) **feedstock switching**, i.e. pathways relating to alternative feedstocks in the refining sector (biomass, CO_2, hydrogen), (ii) **alternative process** relating to the production of coke, and (iii) **electrification of processes** and use of renewables. A detailed list of the technologies identified for the energy industries is presented in Appendix A.

For activities classified as refining of oil and gas, alternative feedstocks have been suggested. However, limited information was identified in the literature on the impacts on supplying, transporting and storage of the new feedstock. For power-to-liquid and hydrogen use, there is a key gap on quantities of hydrogen needed to meet existing demand of the refined products. Greater understanding of this would provide an indication of how infrastructure for renewable power and hydrogen storage needs to be developed.

Electrification through renewable energy is as a key pathway to decarbonisation. The high uptake and adoption of renewables will affect the demand for key materials needed to manufacture the renewable technologies. Greater presence of fluctuating and intermittent renewable energy on the electricity grid will impact the operation of conventional combustion installations. Changes in operation of combustion installations during the transition period will impact the environmental performance of the site.

Table 3.8 Specific decarbonisation technologies identified for the **energy industries**

Pathway group	Pathway	Energy Industries activity	Descriptions	TRL	Main barriers	GHG reduction*
Alternative feedstock	Biomass	Refining of oil and gas	Oil refining feedstock, (biocrude) can be based on a variety of oily biomass such as low ILUC vegetable oil, used cooking oil, free fatty acids, animal fats. In the future algae oil or other non-food competing oil plants will be a potential feedstock. These feedstocks can be converted to crude oil by either: • Hydrothermal liquefaction • Hydrotreatment-hydrocracking pyrolysis • Gasification using the Fischer-Tropsch process	3-7	Limited availability of sustainable biomass. Currently significantly more expensive than fossil feedstock	HIGH The use of biocrude emits 65-85% less carbon than petroleum. However, this is dependent on the suitability of the biomass source. The use of biocrudes will reduce the need for cracker units which will lead to a carbon saving further down the value chain.
Electrification (low carbon / renewables)	Renewables	All	Use of renewable electricity and heat -adoption of electricity driven processes such as: • Electrical heating, cooling, and pumping, • General operational equipment, • Rotating machines	3-7	Electricity prices have been identified as a key barrier. Supply of renewable energy for electricity generation.	HIGH Abatement potential is stated to be up to 100%.
System optimisation	Process efficiency	All	Several process efficiency options can reduce the energy demand of every sector. Options for the refining of oil and gas are: • Improved recovery of Hydrogen and LPG from fuel gas. • Reduction of flaring and fugitive emissions	6-9	These measures are widely applicable.	LOW The techniques are estimated to provide between 10% - 25% emission reduction.
Alternative feedstock / Carbon capture	Power-to-Liquid	Refining of oil and gas	Power-to-liquid technology uses CO_2 and hydrogen to produce synthetic fuels (e-fuels). Direct Air Capture (DAC) provides CO_2 which is reacted with hydrogen produced from electrolysis driven by renewable energy. Synthesis of the fuel is achieved by Fischer-Tropsch reaction with subsequent refining. Several companies and consortia are developing the pathway.	6-8	The uptake of this pathway still requires further development of its economics, optimal location, capital requirements, supply of CO_2 gas streams.	HIGH

Pathway group	Pathway	Energy Industries activity	Descriptions	TRL	Main barriers	GHG reduction*
Alternative process	Coke dry quenching	Production of coke	Coke is cooled by inert gas instead of by spraying water, allowing recovery of thermal energy in the quenching gas; steam or electricity can be produced.	8-9		LOW The technology has been adopted in BAT 51 in the IS BREF[32]; however the technology is not widely used. The BAT is reported to reduce energy consumption by 15-20%.
Carbon capture	CCS	All	See details in the cross cutting pathways sections	7-9		HIGH

** Indication of the GHG emission reduction potential: high (>70% reduction) / medium (30-70% reduction) / low (<30% reduction) – see section 3.2.1.*

32 https://eippcb.jrc.ec.europa.eu/reference/iron-and-steel-production

3.5.2. Wider environmental impacts

The wider direct and indirect environmental impacts of the energy industries are provided in Table 3.9 below. The symbols and the overall approach are described in section 3.2.2. The table also indicates any uncertainties and data gaps. As in the case of the cross-cutting technologies, the impact in certain energy industries might be variable, depending on the exact characteristic of the technologies (e.g. the type of renewable sources deployed).

Table 3.9 Wider direct and indirect environmental impacts of **energy industries**

Subgroup	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	**Water**	**Energy use and efficiency**	**Resource efficiency/ waste generation**	**Soil, land use and biodiversity**	
Alternative feedstock	Biomass	+/- Increase of emissions of NOx (up to 20%) and NH_3 during the production of vegetable oils with potential increases of O_3 and acidification problems. Reduction in the emissions of unburned hydrocarbons, carbon monoxide (up to 40%), sulphates, polycyclic aromatic hydrocarbons, nitrated polycyclic aromatic hydrocarbons, NMVOCs (up to 7%), and particulate matter (up to 60%).	? No information found	? No information found	+ In case biomass derives from waste, the impact on resource use is in general positive.	- Negative impacts on ecosystems can be expected, particularly when biomass derives from non-waste sources. Direct and indirect land use change effects from the expansion of biomass feedstock for energy production have resulted in habitat and biodiversity loss, especially when large-scale land conversion using mono-cultural feedstock production is adopted. Ecosystems: Most biomass energy production pathways emit GHGs and atmospheric/ water pollutants that can have negative effects on ecosystems and biodiversity, e.g. eutrophication, acidification and toxicity.	- Impacts associated with the transportation of biomass are greater to those from conventional fuels, as it is less energy dense and has to be collected from dispersed locations.
Electrification	Renewables	+ Geothermal power: emits GHGs (CO_2), air pollutants (NH3, H_2S) and other gases (H2, O2, N_2) and elements (Rn, He, As, Hg, B).	+ Overall, there is a positive impact compared to conventional sources as the risk of water pollution is	+ Renewable sources of energy usually substitute the energy generated from conventional sources. In relation to electricity this has a positive impact on	+/- While overall, a decrease of needed resources is achieved (especially energy resources), the deployment of renewables might lead to additional resource use on the site (e.g.	+/- Wind power: The use of land per MW generated is higher compared to other sources of energy. In addition, there are negative environmental impacts linked to potential collisions of birds and bats.	+/- Despite a reduction in the use of resources is achieved compared to conventional technologies (particularly energy resources) an increased use of resources might be required in parallel for the deployment of

Subgroup	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
			lower. Nevertheless, negative impacts occur for certain renewable sources. For example, in hydropower there is a potential increase of eutrophication , water quality reduction in the reservoir due to the growth of phytoplankton and algae.	energy efficiency as the substitution occurs mainly at peak time. electrical energy storage systems required to address variations of variable renewable electricity sources.	pipes in geothermal energy).	Hydropower: source of habitat loss (most significant environmental impact) and change due to the modification of upstream and downstream regimes, as well as decline in water quality. Ocean power: direct loss of a small habitat area, operation of ocean energy devices that can hinder the normal movement and feeding activity of bird and aquatic species, or even change the characteristics of the marine environment adjacent to the installations Solar power: development of solar energy infrastructure can take up significant amounts of land modifying and fragmenting habitats. For all renewable sources of energy there is a reduced risk of soil contamination deriving mainly from lower atmospheric emissions.	renewables. For example, rare earth elements are required for the magnets in wind turbines.
System optimisation	Process efficiency	+ Generally, lower air emissions due to process and energy efficiency improvements, for	0 No significant impacts on water use and water pollution.	+ Energy consumption: reduction of the amount of energy used in the process.	0 No significant impacts on resource use and waste generation.	+ In general, lower risks of soil contamination and biodiversity due to the lower use of fuel gas.	0 No significant impacts expected.

Subgroup	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	**Water**	**Energy use and efficiency**	**Resource efficiency/ waste generation**	**Soil, land use and biodiversity**	
		example when less energy is consumed or a reduction of flaring and fugitive emissions is achieved. Uncertainties exist when hydrogen is used as the emissions depend on the source of energy deployed for its production.					
Alternative feedstock	Power-to-Liquid	+ Lower air emissions compared to conventional fuel production.	- The higher net water demand results from the hydrogen production via water electrolysis and the water generated by the synthesis reaction and further downstream processing steps.	- The energy efficiencies of PtL production pathways investigated can be as low as 38% and as high as 63% Large amounts of energy required to adapt to intermittent supply.	? No information found	? No information found	+/- Indirect environmental impacts are linked to the impacts of renewable energy production, in particular land use. However, renewable power generation in principle does not depend on arable land, with desert regions, for example, offering highly suitable conditions for photovoltaic or solar-thermal power generation, hence reducing the risk of competition between energy and food production.
Alternative fuel	Ammonia	- Higher emissions of NOx from ammonia fuelled	- Water and soil pollution: ammonia can	- Energy efficiency : The ability to regenerate power	- Resource use : The ability to become a liquid at moderate	- Soil: ammonia can lead to eutrophication, and in the soil it can be degraded to nitric and	? No information found

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Subgroup	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
		combustion devices may be mitigated in a similar fashion. However, it should be noted that for devices fuelled by ammonia a ready reservoir of ammonia for NOx reduction will exist and therefore it may be possible to design ammonia fuelled systems that do not require secondary exhaust clean-up or high cost catalyst systems to achieve emission free exhaust. One sure-fire strategy for avoiding NOx emissions from using ammonia fuel is simply to replace the internal combustion engine with the fuel cell, which emits atmospheric nitrogen and water. Ammonia vapours cause irritation at low concentration and are life-threatening at high concentration. This is because of ammonia's extraordinary affinity for water, including water in human flesh and organs. Ammonia,	lead to eutrophication , and in the soil it can be degraded to nitric and nitrous oxides and molecular nitrogen. The environmental load of ammonia production process depends strictly on the method of obtaining hydrogen. SMR has lower negative impact on the environment than POX. In order for ammonia to be considered as a potential transportation fuel, the use of hydrogen generation pathways that are less burdensome to the	from energy stored in ammonia's chemical bonds will allow far greater penetration of intermittent renewable resources like wind and solar, enabling deep decarbonisation of power grids and broader energy economies. However, replacing these fossil energy storage assets with ammonia is cost competitive and provides the opportunity to decarbonise economies without compromising (more likely, increasing) energy security. The energy content of ammonia is 40% less compared to fuel gas. The most important environmental effect due to ammonia production is a high energy consumption, mainly from the combustion of fossil	pressure allows ammonia to store more hydrogen per unit volume than compressed hydrogen or even cryogenic liquid hydrogen. In addition to providing a practical means to store and transport hydrogen, ammonia can be burned directly in internal combustion engines and direct-ammonia fuel cells. Larger amount of resources used than for the production of conventional fuels. Ecosystems and biodiversity: ammonia represents a chronic hazard to ecosystems, with health risks linked to potential leaks.	nitrous oxides and molecular nitrogen.	

Subgroup	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
		however, is lighter than air and rapidly dissipates in open spaces, or can be controlled with water. Ammonia can be converted to NOx.	environment should be promoted. Water use: the production of ammonia requires much more water than the production of conventional fuels (gasoline and diesel oil).	fuels (larger consumption than for the production of conventional fuels). In general ammonia needs to be mixed with other conventional fuels.			
Alternative processes	Coke dry quenching	+/- Air emissions: dust, CO and hydrogen sulphide emissions are reduced as there are no dust-laden steam clouds released to the atmosphere during wet quenching. Emissions of PM due to the use of dry quenched coke, and due to transport.	+ Water pollution: water is not wasted from the process and not contaminated with toxic pollutants. Resource use: The process uses less water, which is an issue in dry or cold regions.	+ Energy consumption: electricity is produced through the reuse of the waste heat generated by the cooling of the coke.	0 No impact expected	0 No impact expected	0 No impact expected

Subgroup	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
Carbon capture	CCS	See details in the cross cutting pathways sections					

3.6. Production and processing of metals

3.6.1. Decarbonisation technologies

The sector covers the metal ore roasting or sintering, production of pig iron and steel, processing of ferrous metals and non-ferrous metals, operation of metal foundries and surface treatment of metals or plastic materials.

In Table 3.10 specific decarbonisation technologies related to these industrial activities are presented. In addition to these technologies, cross cutting technologies are also applicable, i.e. the use of alternative energy sources (biomass, hydrogen, electricity driven processes), system optimisation, improvements in energy efficiency and carbon capture (CCS/CCU) options. Decarbonising the energy sector is an important factor for the sector, in particular due to a high electricity use (in particular in the non-ferrous metals).

The main pathways for the production and processing of metals are presented in Figure 3.7.

Figure 3.7 Main decarbonisation pathways for the production and processing of metals.

Iron and Steel

- Low carbon and bio-based fuels (waste/materials) / electrification
- Recycling - shifting to secondary production and enhanced recycling of by-products
- Alternative processes or reducing agents:
  - H-DRI
  - Alternative/upgraded reduction
- Energy and process efficiency
- Synergies with other sectors - industrial symbiosis
- Carbon capture (CCS/CCU)

Ferrous and non-ferrous metals

- Low carbon and bio-based fuels / electrification
- Recycling - enhanced metal recovery
- Process and feedstock innovations, incl. anode replacement, hydrogen as reducing agent
- System opyimisation and energy efficiency, incl. heat recovery, process integration
- Carbon capture (CCS/CCU)

Surface treatment

- Electrification of process
- System optimisation
- Alternative feedstock (biomass)

A detailed list of the technologies identified for the metals sector is presented in Appendix A.

Table 3.10 Specific decarbonisation technologies identified for the **production and processing of metals**

Pathway group	Pathway	Metals activity	Descriptions	TRL	Main barriers	GHG reduction*
Alternative fuel	Low carbon and bio-based fuels	Production of iron and steel; Processing of ferrous and non-ferrous metals	The use of biomass and other low carbon fuels, including (green) gas, biogas, solid biomass etc. Biochar - Pulverised coal injection with bio-charcoal.	5-9	Availability of low carbon fuels	MEDIUM
Alternative fuel	Biocoal (Torero Project[33])	Production of iron and steel	Torero project aims to demonstrate a cost-, resource-, and energy-efficient technology concept for producing bioethanol from a wood waste feedstock, fully integrated in a large-scale, industrially functional steel mill: • Wood waste is converted to biocoal by torrefaction, • Biocoal replaces fossil powdered coal in a steel mill blast furnace	7-8	Production of at least 80 million litres of bioethanol per year per every steel mill that implements this technology	MEDIUM
Alternative fuel / Electrification	Electrification of process	Production of iron and steel; Processing of ferrous and non-ferrous metals	Electrification of heating and metal production - Use of electricity as substitute of fossil fuels for production of heat in industrial applications – offering the opportunity for large scale use of renewable energy (see details under cross cutting pathways)	6-9	Supply of (renewable) energy; electricity prices.	HIGH
Alternative fuel / Electrification	Induction and infra-red curing	Surface treatment of metals	Induction curing to replace gas-fired curing - where the metallic substrate is heated via electrical induction to cure the paint and drive off residual solvent.	9[35]	Operational limitations compared to the traditional gas ovens hence limited use within the industry.	LOW No direct CO_2 emissions (reduction from 8 kg/t for gas ovens).

[35] Technology identified as BAT in recent STS BAT conclusions.

Pathway group	Pathway	Metals activity	Descriptions	TRL	Main barriers	GHG reduction*
			Infra-red curing to replace gas-fired curing - heating units which emit infra-red radiation are used to heat the organic coating. An example is the adphosNIR Technology[34]: a combination of near-infrared (NIR) light energy, management of the NIR energy, integrated hot air knives and moisture extraction.			
Alternative process / reducing agent	Hydrogen direct reduction of Iron (H-DRI)	Production of iron and steel	The use of hydrogen instead of coal as the 'reducing agent' to produce iron, which in turn can be further processed into steel via an electric arc furnace (EAF) followed by several downstream steps. Many different companies are developing their own version: tkH2Steel, Hybrit, GrINHy, H2Steel (H2Future, SuSteel), Hybrid Steel Making, SALCOS; DILCOS	4-8	Cost of hydrogen production, electricity	HIGH The potential to reduce GHG emissions varies depending on the source of hydrogen and the switch from fossil fuels to renewables to deliver the demand for process energy. The Hybrit process achieves a 98% CO_2 emission reduction per tonne of steel, when compared to conventional manufacturing process.
Alternative process / reducing agent	Hydrogen as reducing agent	Processing of non-ferrous metals Copper production	Hydrogen can be considered as a replacement to coke or natural gas as a reducing agent in the copper fire refining process.	4-8	Cost of hydrogen production, electricity	HIGH
Alternative process	Smelting reduction - COREX[36]	Production of iron and steel	Direct smelting reduction process that allows production of hot metal directly from iron ore and non-coking coal. Iron ore is charged into a reduction shaft where it is reduced to DRI (direct reduced iron) by a reduction gas moving in	7-9	Commercially available, with several operational plants. Limitations include for example that an optimised distribution of coal and DRI is	LOW Reduced GHG emission approximately 20%

34 https://www.adphos.com/technology/adphosnir-technology/
36 https://www.primetals.com/portfolio/ironmaking/corexr

Pathway group	Pathway	Metals activity	Descriptions	TRL	Main barriers	GHG reduction*
			counter flow. In the melter gasifier, the final reduction and melting take place in addition to all other metallurgical reactions.		needed, in the melter-gasifier, to avoid peripheral flow of hot gases; the melter-gasifier is subjected to high occurrence of pressure peaks.	
Alternative process	Smelting reduction - FINEX[37]	Production of iron and steel	An optimised fine-ore reduction process for the reduction of iron ore fines. The smelting reduction process is based on the direct use of non-coking coal and fine ore. The fine ore is preheated and reduced to fine DRI in a multi-stage fluidised bed reactor, progressively reducing the fine ore to fine DRI. This fine DRI is then compacted and charged as hot compacted iron into the melter gasifier. This charged iron is subsequently reduced to metallic iron and melted	6-9	Commercially available Limitations relate to the design and scale up of the fluidised bed reactors.	LOW 4% GHG emission reduction.
Alternative process	Smelting reduction - HIsarna[38]	Production of iron and steel	Hisarna employs an upgraded smelt reduction process that processes iron ore in a single step, eliminating coke ovens and agglomeration. It is more efficient and produces a concentrated CO_2 stream.	5-7	Requires new plant, cannot be retrofitted.	MEDIUM 20% carbon emission reduction compared to conventional process, 80% if it is combined with CCS.
Alternative process	Anode replacement	Processing of non-ferrous metals (Aluminium)	Carbon anodes produced from petroleum coke are used in aluminium smelting. Decarbonisation pathways highlighted substitute the carbon rich anodes with novel materials. Literature has identified potential substitute materials	5-7	Development of technique is only carried out if the market situation is promising or equipment very old.	HIGH Wetted cathodes could reduce energy use by approximately 20-55% compared to conventional carbon cathodes. Potential to reduce emission

[37] https://www.primetals.com/portfolio/ironmaking/finexr
[38] https://www.tatasteeleurope.com/en/innovation/hisarna

Pathway group	Pathway	Metals activity	Descriptions	TRL	Main barriers	GHG reduction*
			including: wetted materials, such as titanium diboride (inert materials) and bioanodes.			by 72% if the electrolysis process is powered through renewable energy.
Alternative process	Carbo-thermic Reduction	Processing of non-ferrous metals (Aluminium)	Carbothermal reduction is an alternative to the Hall–Héroult process. Carbothermal reduction reacts alumina with carbon to form aluminium and carbon monoxide.	3	Once available, a carbothermic plant is likely to be the preferred option for new plants, however, this is not expected before 2050.	LOW Reduces energy per unit aluminium by around 20-30%.
Alternative process	Advanced Mineral Recovery Technology (AMRT)	Production of iron and steel	A novel EAF technology, it can smelt red mud (the waste product from alumina production-Bayer process) without any pre-treatment, producing pig iron and viscous slag suitable for industrial mineral wool.	7	No strong economic case.	LOW
Alternative process	Iron ore Electrolysis	Production of iron and steel	Electrolysis of iron ore into metal and oxygen using electrical energy only. The process will eliminate coke ovens and blast furnaces. There are four projects in the early stage of developing the process ULCOLYSIS, ULCOWIN, SIDERWIN, Boston Metal.	2-3	The process is heavily dependent on electricity, thus dependent on power sector decarbonisation.	HIGH The process achieves 100% reduction in direct CO_2 process emissions. Total reduction depends on carbon intensity of power sector.
Alternative process	Copper sulphide electrolysis	Processing of non-ferrous metals	Selectively separates pure copper and other metallic elements from sulphur-based minerals, using molten electrolysis.	3	The process is heavily dependent on electricity, thus dependent on power sector decarbonisation.	MEDIUM
Recycling	Shift to secondary production	Production of iron and steel	Electric Arc Furnace (EAF) to melt scrap steel. This recycling process already accounts for 39% of the annual EU production (2017). The scrap share of steel production could reach up to 70%.	9	High scrap steel quality required, and it is necessary to reduce 'tramp elements' or impurities (copper)	HIGH GHG emissions: 0.1 t CO_2 per tonne steel + 0.3 t CO_2 per tonne steel for electricity usage (could be further reduced when using renewable energy) Emissions from primary production (EU): approx. 1.9 t CO_2 per tonne steel

Pathway group	Pathway	Metals activity	Descriptions	TRL	Main barriers	GHG reduction*
Recycling	Enhanced recycling of materials	Production of iron and steel, Processing of non-ferrous metals	Enhanced recycling of scrap (such as ferrous scrap) and steel's by-products (such as slags) in iron and steel and metal production.	9	Need for improved sorting and treatment techniques	HIGH
System optimisation	Heat recovery	Production of iron and steel, Processing of non-ferrous metals	Utilisation of off-heat from high temperature processes. Waste heat recovery and use from pyrometallurgical processes. (See details on energy efficiency and system optimisation in the cross cutting pathways)	7-9	Barriers relate to retrofitting constraints: space and time required for installing equipment	MEDIUM
System optimisation	Multipolar cells (Hell-Héroult process)	Processing of non-ferrous metals (Aluminium)	While conventional Hall-Héroult cells have a single-pole arrangement, multipolar cells could be produced by using bipolar electrodes or having multiple anode-cathode pairs in the same cell.	6		MEDIUM Potential to reduce energy consumption by 40%, due to lower operating temperatures and higher current densities.
Alternative feedstock	Solvent-free coatings	Surface treatment of metals or plastic materials	Substitute of solvent from coating, e.g. water-based solvents.	2-3* 9**	*In the case of non-porous metallic substrates, the use of solvent-free coatings presents a challenge. Product performance is limited, consequently not widely adopted by the industry. **Other industries successfully use solvent-free coatings on a range of porous substrates.	MEDIUM
Alternative feedstock	Biomass	Surface treatment of metals or plastic materials using an electrolytic or chemical process.	Biomass derived epoxy primer or bio-primer substitute fossil-based additives and polymers with chemicals that are derived from natural sources. It is possible to derive bio-primers from algae.	N/A	For the industry to remain globally competitive, the coatings formulated with bio-based ingredients need to offer the same final product performance as those derived from fossil-fuels.	MEDIUM

Pathway group	Pathway	Metals activity	Descriptions	TRL	Main barriers	GHG reduction*
Carbon capture	CCU - top gas recycling	Production of iron and steel	Steelanol[39]: making industrial waste gases into liquid fuels, through biotech solutions for transformation of carbon monoxide to ethanol. Carbon2Chem[40]: Based on utilisation of industrial waste gases, aiming to use top gases for chemicals production (e.g. methanol). IGAR technology (Injection de Gaz Réformé): Process-integrates CO_2-capture through top-gas recycling in a blast furnace. Use of plasma torch and reactor to heat and reform gases, enabling less coke/coal consumption.	7-8 4 (IGAR)	Substantial modifications required in the process	MEDIUM Reduced direct emissions and 65% secondary reduction. CO_2 emissions from Steelanol-biofuels are 50-70% lower than petroleum-based fuels, and around 35% compared to when steel plant off-gases are converted into electricity. IGAR is reported to generate potential CO_2 savings of 0,1 - 0,3 t CO_2/t of crude steel (from approx. 2 t CO_2/t steel)
Carbon capture	CCU - STEPWISE (SEWGS technology)[41]	Production of iron and steel	Pre-combustion technology from Blast furnace gas from a nearby steel plant (SSAB). SEWGS is multi-column reactive hot Pressure Swing Adsorption (PSA) system where three processes are combined in one reactor: (1) water-gas shift reaction, (2) CO_2 adsorption, (3) simultaneous acid gas removal.	4-5	Not specified in literature.	HIGH Aim to reduce CO_2 emissions from 2 t CO_2 / t steel towards 0.5 t CO_2 / t steel

** Indication of the GHG emission reduction potential: high (>70% reduction) / medium (30-70% reduction) / low (<30% reduction) – see section 3.2.1.*

[39] http://www.steelanol.eu/en
[40] http://www.circulary.eu/project/carbon2chem/
[41] https://www.stepwise.eu/project/

3.6.2. Wider environmental impacts

The wider direct and indirect environmental impacts of the decarbonisation pathways that could be used in the production of metals are provided in Table 3.11 below. The symbols and the overall approach are described in section 3.2.2. Overall, there are significant data gaps, particularly in relation to the low carbon and bio-based fuels, induction and infra-red curing, FINEX and solvent-free coatings. Based on the feedback received from experts, this lack of information is mainly due to the low maturity of the technologies.

Table 3.11 Wider direct and indirect environmental impacts in the **production and processing of metals**

Pathway group	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
Alternative fuel	Low carbon and bio-based fuels	+ Recovery of materials such as old tyres does not give extra emissions in terms of PCDD/F, heavy metals, PAH, SO_2, and VOC.	0 No impact expected.	0 No additional demand for energy.	+ Allows for the recovery of materials such as old tyres and a decrease in the demand of coal.	0 No impact expected.	- Negative impacts on ecosystems can be expected, particularly when biomass derives from non-waste sources. Direct and indirect land use change effects from the expansion of biomass feedstock for energy production have resulted in habitat and biodiversity loss, especially when large-scale land conversion using mono-cultural feedstock production is adopted.
Alternative fuel	Torero Project	+/- Air emissions: Reduces the air emissions linked to coke-making as the energy source is changed. The direct impact of combustion in the steel-making process is not significant. Nevertheless, when	? No information found	? No information found	+ Resource use: shift from fossil resources to wood waste streams. Waste generation: The process uses demolition wood that would otherwise be landfilled or incinerated.	? No information found	? No information found

Pathway group	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
		incinerated, waste wood produces harmful gases, whether no such pollutants are produced in blast furnaces.					
Alternative fuel / Electrification	Electrification of process	See details under cross cutting pathways					
Alternative fuel / Electrification	Induction and infra-red curing	0 Due to the radiant heat from the dryers, solvents are evaporated as for conventional heating processes.	0 No impacts expected.	+ Energy consumption: potential reduction of 44% compared to conventional technologies.	0 No impacts expected.	0 No impacts expected.	0 No impacts expected.
Alternative process / reducing agent	Hydrogen direct reduction of Iron (H-DRI)	+ Air emissions will be limited to H2O during the reduction process. There will be no indirect air emissions (no emissions of NOx and SOx either) produced by the coking plants in the preliminary phase.	+ Water pollution: No more use of cooling water associated with the heat coming from the blast furnaces.	+/- Energy consumption: The technology implies the consumption of very large amounts of electricity (3.5 TWh per million tonne steel), in particular for the preparation of water before the electrolysis, and the electrolysis process itself. The sustainability of the solution depends on the provision of carbon-free electricity. The technology can offer a	+ Resource use: Use of carbon, coal and coke completely reduced. Large amounts of water necessary as input for the electrolysis. Less iron ore is required per output, leading to lower energy consumption in all process steps before the EAF. Waste generation: No more waste associated with the use of coal and coke. The only waste	0 Ecosystems: No significant impact, as the current process has a low impact on ecosystems for now.	+/- Indirect environmental impacts are linked to the impacts of renewable energy production, in particular land use for the production of renewable energy through wind turbines for example. Nevertheless, less land is required for the extraction of fossil fuels (e.g. oil, gas and coal).

Pathway group	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	**Water**	**Energy use and efficiency**	**Resource efficiency/ waste generation**	**Soil, land use and biodiversity**	
				good solution for the electricity grid to balance the power network, as the system can consume unused electricity and lower the demand when electricity is more scarce.	generated by the process are vapour emitted during the direct reduction.		
Alternative process / reducing agent	Hydrogen as reducing agent	? At least in relation to the reduction of copper that is achieved through the use hydrogen the impacts are uncertain. No information is available at the industrial scale.	0 No impacts expected.	- Energy consumption: A significant amount of energy is required for the production of hydrogen.	? No information found	0 No impacts expected.	- Linked to the production of hydrogen
Alternative process	Smelting reduction (COREX, FINEX)	+ Air emissions: Reduction by 30% NOx, no VOC; significantly lower SOx	0 No impacts expected.	? No information found	+ Resource use: No need for coking; Fuel savings of 18%; Reduced oxygen consumption of 13% Waste generation: Lower slag production (18% reported)	0 No impacts expected.	? No information found
Alternative process	Hisarna	+ Air emissions: reduction of the emission of NOx, SOx and fine dust, heavy metals and	+ Limited use of water because cooling water is	+ Energy efficiency: A complete production stage can be phased out: coking plants, sinter	+ Resource use: Reduction of the use of resources through the reutilisation of by-	0 No impacts expected.	? No information found

Pathway group	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
		dioxins, due to the elimination of iron ore sintering and cokemaking.	used in the furnace in closed loop.	plants and pellet plants, saving a large amount of energy (10% less energy used)	products, closing the loop of the steel manufacturing process. Hisarna also enables the use of a wider range of ore and coal qualities, which will allow steel companies to produce the same high quality steels using less expensive and more widely available raw materials. Waste generation: Reduces substantially the mining waste because the different qualities do not have to be separated.		
Alternative process	Anode replacement	+ Lower emissions of POM generated during anode manufacture, HF and COS during electrolysis.	? No information found	+ Wettable (inert e.g. titanium diboride (TiB2) composite) cathodes improve energy efficiency (-20% energy use) by means of providing a geometrical stable cathode surface.	+ The pathway extends the life of cells and reducing the amount of toxic waste.	0 No impacts expected.	? No information found
Alternative process	Carbo-thermic Reduction	+ The formation of gaseous Al should	? No information found	+ Carbothermic reduction could lead to reduction	+ The process is free of solid waste	? No information found	? No information found

Pathway group	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
		occur without the accompanying formation of Al_2O, Al_4C_3, and of Al-oxycarbides.		of energy consumption of 21%. Assuming utilisation of coal based electricity generation the total energy savings would increase to 32%, as more carbon would be utilised directly in the chemical reduction process rather than being burned to produce electricity to power the electrochemical reduction process.			
Alternative process	Advanced Mineral Recovery Technology (AMRT)	0 No impacts expected.	0 No impacts expected.	+ The new proposed process for complete bauxite exploitation (for alumina, pig iron and mineral wool production) could increase the exergy efficiency from 3% in the conventional Bayer Process to 9-13 %.	+ The process converts a hazardous waste into two viable co-products, also preventing accidental discharge into the environment. This technology would also offer a solution for cleaning-up legacy red-mud.	? No information found	? No information found
Alternative process	Iron oxide electrolysis	+ There is no combustion step in the SIDERWIN process, thus NOx, SOx are negligibly small (coming only from the agglomeration phase,	+ Water pollution: No aqueous waste generated.	+ The reaction of iron oxide reduction is carried out by application of electricity in exceptionally favourable conditions of	+ Waste generation: SIDERWIN process will generate the waste from gangue compounds SiO2 and Al2O3, which find application in the	0 No significant difference compared to the conventional route. Land occupation: Land use is essentially related	? No information found

Pathway group	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
		that also generates dust). The SIDERWIN process generates oxygen gas as a by-product.		energy efficiency (more efficient than use of hydrogen).	cement industry. Additionally, it is a possible outlet for wastes generated by non-ferrous industries, essentially aluminium but also Ni and Zn. Resource use: There is iron ore consumption. There are no critical elements involved in the components of the process such as Pt Group Elements or Rare Earth Elements, etc.	to mining operation. It is part of the objectives of the SIDERWIN technology to reduce the footprint area of steel plants by purposely developing electrolytic cells with high vertical extension.	
Alternative process	Copper sulphide electrolysis	+ Elimination of toxic by-products such as SO2	? No information found	+ This one-step process simplifies metal production. It yields >99.9% pure copper, which is equivalent to the best current copper production methods but without having to undergo multiple (energy-intense and polluting) process stages. Furthermore, it is more energy efficient (50% energy savings compared to pyrometallurgical route) and eliminates toxic by-products such as sulphur dioxide.	- There is no possibility to recycle several elements and there is a lower purity of products to recycle a lot of elements as it is not possible to use molten electrolysis. There are other disadvantages as well, especially no possibility to recover the other metals such as precious metals associated with copper, which is well done in the pyro route and electro-refining.	? No information found	? No information found

Pathway group	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
Recycling	Shift to secondary production	See section on waste management and other activities					
Recycling	Enhanced recycling of materials	See section on waste management and other activities					
System optimisation	Heat recovery	+ Lower air emissions due to a reduced use of fuel gas or other types of conventional fuels.	- Potential risks of water contamination.	+ Significant savings in energy consumption.	0 No impacts expected.	0 No impacts expected.	0 No impacts expected.
System optimisation	Multipolar cells (Hell-Héroult process)	0 No impacts expected.	? No information found	+ Multipolar cells (with inert anodes) would make energy savings of around 40% possible through lower operating temperatures (around 700˚C), higher current densities, better control of heat losses and improved circulation of the electrolyte.	? It is not known if multipolar cells can be applied to the current Hall-Heroult process with fluoride-based electrolytes. In the chloride process, they have been used at industrial scale.	? No information found	? No information found
Alternative feedstock	Solvent-free coatings	+ Reducing of VOC emissions	0 No impacts expected.	-/+ Drying process requires a higher energy demand, however, by avoiding the thermal treatment of waste	0 No impacts expected.	? No information found	? No information found

Pathway group	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
				gases, overall energy savings can be achieved. .			
Carbon capture	Steelanol	+ Strong reduction in air emissions, due to the utilisation of waste gases.	? No information found	+ Improvements in energy efficiency are achieved.	+ Resource use: Bio-ethanol produced replaces fossil resources (naphtha and oil) that is otherwise used. Waste generation: 15% of the waste gases are further used at the moment, and the volume could increase.	? No information found	? No information found
Carbon capture	STEPWISE (SEWGS technology)	+/- Slight increase in the AP indicator; lower AD, ODP and HTP than for the CCS with MEA.	+ Lower eutrophication potential	+ Up to 60% energy efficiency due to lower energy consumption for capture.	? No information found	? No information found	? No information found
Carbon capture	IGAR technology (Injection de Gaz Réformé)	? No information found	? No information found	? No information found	+ Resource use: Strong reduction in the fossil fuel used. Carbon is used circularly, there is no more need for coal and coke to produce syngas for the iron production	? No information found	? No information found

Pathway group	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
Carbon capture	Carbon4PUR	? No information found	? No information found	+ Energy consumption: 70% reduction of process energy in the polyol producing industry, including 15-36% reduction of petrochemical epoxy compounds.	+ Resource use: reduces the amount of resources needed for the production of polyols, and reduces the amount of CO and CO_2 that are produced and need to be disposed of.	? No information found	? No information found

3.7. Mineral industry

3.7.1. Decarbonisation options

The sector consists of the following industrial activities: production of cement, lime and magnesium oxide; production of asbestos or the manufacture of asbestos-based products; manufacture of glass including glass fibre; melting mineral substances including the production of mineral fibres; and, manufacture of ceramic products by firing. The main processes leading to GHG emissions from these activities are described in section 2.2.2.

Many of the cross-cutting pathways set out in section 3.4 are relevant for the mineral industry, including in particular the use of biomass and hydrogen as alternative fuels, electrification of processes (kilns / glass melting), energy efficiency improvements and carbon capture technologies. As with other sectors, a collaboration with other sectors or symbiosis also offers a lot of potential for decarbonising the mineral industry.

Low carbon fuels are already used in the sector, in particular for firing the cement kilns with bio-based waste or other waste materials (e.g. waste from the wood construction sector, food waste, textile, paper, etc.). Furthermore, biomass or hydrogen, replacing fossil fuels, could also offer potential for the other mineral industry activities. Hydrogen GHG potential reduction changes throughout different activities of this sector. For cement production the reduction is small and stated to be 10% as the CO_2 emissions which originate from input limestone cannot be avoided.

The mineral industry utilises large quantities of heat energy and consequently many decarbonisation pathways attempt to **electrify the process** such that renewable energy can be utilised. In glass manufacturing electrification of the melting process is available for smaller furnaces, though has its challenges for the larger furnaces. Demonstration projects are looking into the use of electric kilns for the cement and ceramic industries. The technologies will require substantial modification to sites and potentially require electrical energy storage technology. Greater investigation of these impacts is needed.

Another important pathway for the cement and lime sector, given the importance of process related CO_2 emissions, is the use of **alternative feedstock materials**. This can include substitution of limestone as the raw material (directly avoiding the associated CO_2 emissions of the calcination process), but also clinker substitution options and the use of novel cement types. It is noted that the use of alternative material inputs into the final composition requires greater understanding of the implications for the product quality and environment, with changes in material demand and transporting being key factors in impacting the environment.

For all mineral industry activities, material recovery, recycling and downstream innovations offer potential for decarbonisation. Although **recovery and recycling of materials** (concrete, glass, ceramics) exists, a higher uptake could be possible through improved collection and treatment technologies as well as acceptance of the final product. Reducing the final product weight, for concrete and ceramic materials (e.g. bricks), will also have an impact on the CO_2 emissions from the production processes.

As part of the carbon capture technologies, which offers high GHG reduction potential in particular for the cement and lime sector, is the **(enhanced) re-carbonation** of concrete. This is the process whereby concrete re-absorbs some of the CO_2 that was released during clinker production. Re-carbonation is a natural process, but can be enhanced by bringing recycled concrete into contact with kiln exhaust gases increasing the CO_2

captured up to 50% of process CO_2 emissions[42]. Other **carbon capture technologies**, such as direct separation and calcium looping, target the CO_2 emissions generated during the clinker production process, i.e. the calcination process. It has been indicated that high capital costs associated with capture technologies is a hurdle making the cost of clinker likely uncompetitive.

In particular for the mineral industry, it is important to note that CCS projects are typically developed in clusters of different emitters. This also highlights the importance of **synergies between industrial sectors** and plants, not only in relation to carbon emissions, but also regarding the use of materials and by-products, i.e. industrial symbiosis. A good example is potential symbiosis between cement and steel plants, whereby slags and ashes from steel production are used as feedstock for cement production.

The main pathways for the mineral industry are presented in Figure 3.8, for the Cement & Lime, Ceramics and Glass sectors.

Figure 3.8 Main decarbonisation pathways for the mineral industry

Cement and Lime

- Alternative feedstock: raw material substitution / new binders, clincker substitution, low carbon cement
- Alternative fuel: bio-based waste, waste materials, hydrogen
- Recycling concrete
- System optimisation and improving energy efficiency
- Carbon capture: mineraisation / re-carbonation, calcium looping, direct separation
- Synergies with other sectors

Ceramics

- Alternative fuel and electrification: low carbon fuels, electrification of kilns, hybrid kilns
- Material recovery and recycling / re-use from other industries
- Process innovations
- System optimisation and improving energy efficiency

Glass

- Alternative fuel and electrification: low carbon fuels, electric melting
- Improved glass recycling
- System optimisation and improving energy efficiency

A detailed list of the technologies identified for the mineral industry is presented in Appendix A and a summary of the sector specific decarbonisation technologies is provided in Table 3.12.

[42] Cembureau, 2020. Cementing the European Green Deal: https://cembureau.eu/media/kuxd32gi/cembureau-2050-roadmap_final-version_web.pdf

Table 3.12 Specific decarbonisation technologies identified for the **mineral industry**

Pathway group	Pathway	Mineral industry activity	Descriptions	TRL	Main barriers	GHG reduction*
Alternative feedstock	Raw material substitution / new binders	Production of cement	Substitution of limestone by a range of alternative calcium containing materials, including waste and industrial by-products, such as: crushed concrete, ashes from lignite or coal, blast furnace slag, aerated concrete meal and fractions from demolition waste.	6-9 depending on the substitute	• Availability of the raw material in the vicinity of the cement plant • Need for further preparation steps, increasing the production costs • Different properties and therefore, used for specific applications.	MEDIUM Dependant on the substitute. Generally, 20-30% reduction but some binders predicted to give up to 90% GHG reduction compared to Portland cement.
Alternative feedstock	Clinker substitution / Novel Cement	Production of cement	Decreasing the clinker-to-cement ratio. Reducing content of carbon heavy clinker by using alternative material. Suggested alternatives are: • Alkali/geopolymer binders, • Magnesium silicate, • Fly ash / blast furnace slag, • Pozzolans, • Limestone, • Sulphoaluminate belite.	4- 9 depending on the substitute	• Availability of substitutes as demanded will be very high. • Fly ash by-product of coal combustion and blast furnace slag is by-product of primary steel production, activity of both will decrease in the future. • Ensuring product standard is maintained. • Technical performance and durability.	LOW Dependant on the substitute. Ultimately will depend on the quantities of feedstock used which depends on the application.
Alternative feedstock	Adding biomass to clay	Manufacture of ceramic products	Addition of finely divided biomass to clay before forming reduces fossil fuel requirement for firing.	5-6	Not specified in literature.	LOW 5% CO_2 emission reduction.
Alternative feedstock	Low carbonate clay	Manufacture of ceramic products	Production of yellow bricks with low carbonate clay options with colorant instead of conventional clay.	6-7	Not specified in literature.	LOW 10% CO_2 emission reduction.
Alternative fuel	Biomass (waste) / low carbon fuels	All	The use of less carbon intensive alternative fuels, such as bio-based waste (waste wood, sewage sludge, animal meal, waste sawdust, pre-processed or raw industrial waste, etc.)	8-9	Availability of biomass (waste)	MEDIUM

Pathway group	Pathway	Mineral industry activity	Descriptions	TRL	Main barriers	GHG reduction*
Alternative fuel	BiOxySorb[43]	Production of lime	BIOXYSORB - Biomass co-combustion under both air and oxyfuel conditions.	6-7	Not specified in literature.	MEDIUM
Alternative fuel	Hydrogen	All	Hydrogen firing technologies (see details in the cross cutting pathways section)	5-8	Infrastructure and supply	MEDIUM
Alternative fuel / Electrification	Electrification of kilns; Electric melting	All	Switch from fuel combustion to electricity operating (cement, lime, glass, ceramics). Electrification of kilns using low-carbon electricity could be an option to reduce fuel emissions. Electrification of smaller glass furnaces (up to 150 tonnes). Although electric melting is available for small furnaces (< 150 tpd), it still needs to be demonstrated for large furnaces such as those used in flat or container glass production.	3-6	Price of electricity; Loss of heat recovery	HIGH Eliminating CO_2 emissions from the combustion of fossil fuels (not of process emissions). Ceramics: Emission could be reduced by up to 65-78% by 2050 compared with 1990. This assumes that half of all kilns are converted to electric kilns in the period 2030-2050.
Alternative fuel / Electrification	SOLPART project[44]	Production of cement clinker	SOLPART High temperatures Solar-Heated Reactors for Industrials Production of Reactive Particles. Two types: • Solar Fluidized Bed Reactor (PROMES technology) and • Solar Rotary reactor (DLR technology). Calcination levels of >90%	4-5	Development of the energy storage required to operate when sunlight is not available.	HIGH Reduction of GHG emissions by at least 80% compared to the current standard technologies.

[43] http://bioxysorb.eu-projects.de/
[44] https://www.solpart-project.eu/

Pathway group	Pathway	Mineral industry activity	Descriptions	TRL	Main barriers	GHG reduction*
Alternative fuel / Electrification	Hybrid kiln	Manufacture of ceramic products	Restructure of kiln to disband the thermal link between kiln cooling and drying systems. Instead, use of desulphurised kiln and dryer exhaust gases supplemented with a gas-driven heat pump to maximise quantity of high-quality thermal energy. This coupling allows choice between electric heating and primary fuel.	1-4	Not specified in literature.	HIGH 65% savings on energy.
Alternative process	CER-Wave project	Manufacture of ceramic products	A hybrid prototype gas oven and microwave technology for porcelain sintering.	6	Not specified in literature.	LOW A reduction in energy consumption up to 10% and reducing the sintering cycle up to 15%, compared to the conventional process (heating by combustion of natural gas).
Alternative process	Vertical roller mills and roller presses	Production of cement	A significant reduction of the specific energy demand for cement grinding can be achieved by grinding either in vertical roller mills (VRMs) or high pressure grinding rolls (HPGRs) in addition to existing ball mills or by a complete substitution of these mills.	8-9	• Vibration can impact stable operation (depending on feed properties and product fineness). • Sufficient dehydration of sulphate agents cannot always be ensured due to low residence times. • Durability is limited by wear elements.	MEDIUM Reduction of energy demand by 5 to 14 kWh/t cement. This translates to a reduction of carbon dioxide emission by 2.6-6.8 kg CO_2 / t cement (depending on electricity grid).
Alternative process	High efficiency separators	Production of cement	High efficiency separators feature optimised air ducts and additional external air circuits. The high separation efficiency leads to a higher proportion of fines and increasing throughput by up to 15%.	8-9	• Workability of grinding aid.	MEDIUM Reduction of energy demand by 2.3 to 4.5 kWh/t cement. This translates to a reduction of carbon dioxide emission by 1.1-2.3 kg CO_2 / t cement (depending on electricity grid).

Pathway group	Pathway	Mineral industry activity	Descriptions	TRL	Main barriers	GHG reduction*
Alternative process	Fluidised bed kiln	Production of cement clinker	Clinker production in a fluidised bed kiln under the addition of ground coal and raw material injection. Clinker is cooled by fluidised bed quenching and a packed bed cooler.	4	No applicability issues reported and could be applied the whole sector.	LOW CO_2 reduction 3%. Electricity reduction: 5%
Alternative process	Low mass refractory for kiln car/furniture	Manufacture of ceramic products	The heat load represented by continuously heating the cold kiln car refractory/furniture as it travels through the kiln would be reduced by the use of low mass refractory.	5-8	Not specified in literature.	LOW New kiln cars can provide a CO_2 saving of 7.5% and other furniture is able to save up to 20%.
Alternative process	Field Assisted Sintering Technology (FAST)	Manufacture of ceramic products	New sintering techniques based on FAST possess the ability to lessen the temperature for sintering by several hundred degrees. The following technologies can be classified as FAST: • Spark plasma sintering (SPS) • Flash sintering • Laser sintering • Fast-firing sintering • Liquid-phase sintering • Cold sintering	5	Not specified in literature.	LOW
Recycling	Material recovery and recycling	All	Improving the recovery and recycling of materials into the production of cement, lime, glass and ceramics. • Cement and Lime: recycled concrete, repurpose lime by-products. • Glass: improving glass recycling rates. • Ceramics: material recovery such as sludge recycling, re-use from other industries.	7-9	Quality of products varies greatly according to the origin and treatment; Need for improved collection and treatment.	HIGH
Recycling	Thermal cement recycling	Production of cement	Cleaned and broken up concrete is heated to 650-700˚C. The process facilitates further processing of recycling concrete. When reused it can replace 10-20% Portland cement. Crushed concrete fines can be used as raw material or limestone replacement.	4	Not specified in literature.	LOW CO_2 emission reduction between 17.5-32.5%.

wood.

Pathway group	Pathway	Mineral industry activity	Descriptions	TRL	Main barriers	GHG reduction*
Recycling	Mechanical cement recycling (Smartcrusher)	Production of cement	Mechanical cement recycling via C2CA or 'smart crushing' is a mechanical treatment of used concrete which enables the extraction of sand, aggregates, and cement stone. The cement stone can be used as filler in concrete with binding capacities, filler in cement with binding capacities, added to the production process of Portland cement (lowering the process emissions).	5-7	Not specified in literature.	MEDIUM
System optimisation	Closed-loop heat pump	Manufacture of ceramic products	Technology to maximise heat recovery from kiln exhausts, kin dryers and from cooling zones. DryFiciency project involves a consortium of partners developing the technology.	5-7	Not specified in literature.	MEDIUM 57-73% CO_2 abatement potential.
System optimisation	Design for energy efficient kiln	Manufacture of ceramic products	Radically improved kiln architecture through the design of innovative hardware furnace components (biofuel-fed CHP unit, heat pipes and emissions abatement system), and major developments in hardware-software kiln parts (kiln control tool, refractory materials). Being designed by the DREAM Project.	4-6	Not specified in literature.	MEDIUM
System optimisation	Reduce product weight	Manufacture of ceramic products	Reducing the mass of material of product such as bricks will reduce the fuel required for firing and drying.	7-8	Not specified in literature.	MEDIUM
System optimisation	Oxygen enrichment technology	Production of cement clinker; Manufacture of ceramic products,	Oxy-fuel combustion system separates oxygen and nitrogen from the air using an air separation unit. Pure oxygen is fed into the combustion chamber. The resulting gases from combustion are then trapped and stored. The use of oxygen-enriched combustion air in the clinker burning process allows an increase in the energy efficiency, production capacity or substitution of fossil fuels by low calorific value or (alternative) fuels.	7	Integration of energy flows between the additional units and the cement plant	MEDIUM

Pathway group	Pathway	Mineral industry activity	Descriptions	TRL	Main barriers	GHG reduction*
Carbon capture	Re-carbonation / Carbon dioxide Storage by Mineralisation (CSM)	Production of cement	Re-carbonation is the process whereby concrete re-absorbs some of the CO_2 that was released during clinker production. The purpose of (CSM) is to fix CO_2 to metal oxide as thermodynamically stable carbonates. Potential metal oxides are magnesium and calcium silicates (e.g. serpentine, olivine, wollastonite)	6-7	• Large material transport and storage requirements • High energy demand for the mining, transportation, and preparation of the mineral; through this the CO_2 removal efficiency is significantly reduced • Slow reaction rate of carbonation • Limiting factor: availability of alkalinity • Very high costs compared to geological storage.	HIGH
Carbon capture	Calcium looping	Production of cement clinker	The calcium looping process is based on the equilibrium of calcium carbonate to calcium oxide and carbon dioxide at different temperatures and pressures. In a carbonation process, calcium oxide is put in contact with the combustion gas containing carbon dioxide to produce calcium carbonate. The exothermic carbonation could take place at temperatures between 600 and 700 °C in a so-called carbonator.	3-7	• Still in the stage of research and development • Sorbent deactivation • High mass streams have to be handled • Make-up of sorbent required (deactivated CaO can be utilised in the clinker burning process).	HIGH Capture about 95% of total emissions (including process and fuel CO_2 emissions). Potential for partial negative emission technology when combined with alternative fuel mix containing biomass.
Carbon capture	LEILAC - Low Emissions Intensity Lime & Cement.	Production of lime, Production of cement clinker	Based on technology called Direct Separation, which aims to capture the process emissions. Re-engineering the existing process flows of a traditional calciner, indirectly heating the limestone via a special steel vessel. This system enables pure CO_2 to be captured as it is released from the limestone.	7-8	• Not specified in literature.	HIGH Capture over 95% of process emissions or 57% reduction of total emissions.
Carbon capture	Limestone reduction through electrolysis	Production of lime	The CO_2 produced in the transition from limestone to lime is further reduced in the electrolysis process inside molten carbonate resulting in CO or pure carbon.	3	• The process could be economically viable at larger scale through valorisation of CO as feedstock in chemical processes.	MEDIUM

** Indication of the GHG emission reduction potential: high (>70% reduction) / medium (30-70% reduction) / low (<30% reduction) – see section 3.2.1.*

3.7.2. Wider environmental impacts

The wider direct and indirect environmental impacts of the decarbonisation pathways used in the production of minerals are provided in Table 3.13 below. The symbols and the overall approach are described in section 3.2.2. Overall, the information available is limited, mainly due to the low maturity of technologies.

Table 3.13 Wider direct and indirect environmental impacts in the **mineral industry**

Subgroup	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	**Water**	**Energy use and efficiency**	**Resource efficiency/ waste generation**	**Soil, land use and biodiversity**	
Alternative feedstock	Raw material substitution / new binders	-/+ Dependent on the characteristics of the alternative feedstock.	0 No emissions to water	-/+ Dependent on the characteristics of the alternative feedstock.	+ Resource efficiency is achieved through the reduction of use of raw materials. Reduction of waste generation is also achieved when by-products are used.	0 No impact expected.	-/+ Dependent on the characteristics of the alternative feedstock.[45]
Alternative feedstock	Novel Cement	+ Reduced air pollution when fly ash or blast furnace slag are used in the process.	+ Reduced risk of water pollution when fly ash or blast furnace slag are used in the process.	? No information found	+ Resource efficiency is achieved when fly ash or blast furnace slag are used in the process.	+ Reduced risk of soil contamination when fly ash or blast furnace slag are used in the process.	? No information found
Alternative feedstock	Adding biomass to clay	-/+ Reduced atmospheric pollution due to a reduced use of fossil fuel for firing. The addition of biomass residues or sludge from wastewater treatment to	+ Reduced risk of water pollution due to a reduced use of fossil fuel for firing.	+ Biomass and other organic materials are used as pore forming agents in the manufacturing of bricks and expanded clay aggregates. Adding	? No information found	+ Reduced risk of soil contamination due to a reduced use of fossil fuel for firing.	? No information found

[45] A study will be conducted by CEMBUREAU to determine potential sources of alternative waste raw materials and clinker replacement materials from different industries.

Subgroup	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
		the clay can increase emissions of heavy metals and volatile organic compounds during firing.		finely divided biomass to clay reduces fossil fuel requirements for firing.			
Alternative fuel	Biomass (waste) / low carbon fuels	0 Dust emissions from the clinker burning process remain unaffected by using wastes as fuels. the use of suitable waste only has a minor influence on metal emissions from the clinker burning process. The inorganic exhaust gas constituents NOx, HCl and HF remain unaffected by the choice of the material/waste.	0 No impact expected	- Thermal energy demands can increase when using waste fuels with a higher moisture content, coarseness or a lower reactivity compared to, e.g. fine ground, dry and/or high calorific fuels.	+ Resource efficiency achieved due to the valorisation waste, such as sewage sludge, animal meal, waste sawdust, etc.	0 No impact expected.	+ Emissions avoided from incineration of waste or landfill.
Alternative fuel	BiOxySorb	+ Flexible and low-cost control of SOx, HCl and Hg emissions.	+ Lower risk of water pollution, particularly from Hg.	? No information found	? No information found	+ Lower risk of soil contamination, particularly from Hg.	? No information found
Alternative fuel	Hydrogen	See details in the cross cutting pathways section					
Alternative fuel / Electrification	Electrification of kilns; Electric melting	+ The complete replacement of fossil fuels in the furnace	0 No impact expected	+ Reduces energy consumption by 40% due to uniformly	0 No impact expected	0 No impact expected	-/+ Highly dependent on the energy source of the

wood.

Subgroup	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
		eliminates the formation of combustion products at the installation level. The absence of combustion in electric melting means that the waste gas volumes are extremely Low.		absorbed heat, shorter processing times, lower maintenance costs.			electrification. Power generation from coal, oil, gas, nuclear, hydro and other renewable sources all have very different environmental issues associated with them.
Alternative fuel / Electrification	SOLPART project	+ Elimination of air emissions, during the operation phase.	-/+ Reduced risk of water pollution, but potentially a higher consumption of water for the cleaning of mirrors or lenses.	+ Reduced consumption of energy from conventional sources.	? Highly dependent on the exact characteristics of the solution.	- A lot of land is required for installing the solution.	? No information found
Alternative fuel / Electrification	Hybrid kiln	-/+ Reduction of atmospheric pollution due to a lower use of primary fuels. However the overall impact depends on the source of energy used for electricity generation.	0 No impact expected	? No information found	0 No impact expected	0 No impact expected	-/+ Highly dependent on the energy source of the electrification.
Alternative process	CER-Wave project	+ Reduced atmospheric pollution due to improved energy efficiency.	? No information found	+ A reduction in energy consumption up to 10%.	? No information found	0 No impact expected	0 No impact expected

Subgroup	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
Alternative process	Vertical roller mills and roller presses	+ Reduced atmospheric pollution due to improved energy efficiency.	0 No impact expected	+ Reduction of electricity consumption (70-75% compared to ball mill)	0 No impact expected	0 No impact expected	0 No impact expected
Alternative process	High efficiency separators	+ Reduced atmospheric pollution due to improved energy efficiency.	0 No impact expected	+ Reduction of electricity consumption	0 No impact expected	0 No impact expected	0 No impact expected
Alternative process	Fluidised bed kiln	+ Reduction of NOx emissions.	0 No impact expected	+ Reduction of heat use by 10–12%	0 No impact expected	0 No impact expected	0 No impact expected
Alternative process	Field Assisted Sintering Technology (FAST)	? No information found	0 No impact expected	+ Lower temperature for sintering.	0 No impact expected	0 No impact expected	0 No impact expected
Recycling	Material recovery and recycling	See section on waste management					
Recycling	Thermal cement recycling	0 No difference in air pollution compared to primary production	0 No impact expected	- Use of thermal energy	+ Resource efficiency achieved due to the valorisation of waste cement.	0 No impact expected	+ Reduced emissions and pollution from primary / virgin materials
Recycling	Mechanical cement	-	0	-	+	0	+

Subgroup	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
	recycling (Smartcrusher)	Dust emissions from treatment operations	No impact expected	Increased energy use for recycling processes	Resource efficiency achieved due to the valorisation of waste cement.	No impact expected	Reduced emissions and pollution from primary / virgin materials
System optimisation	Closed-loop heat pump	+ Reduced air emissions achieved from the emissions abatement systems.	0 No impact expected	+ Increased energy efficiency due to the maximisation of heat recovery	0 No impact expected	0 No impact expected	0 No impact expected
System optimisation	Design for energy efficient Kiln	+ Reduced air emissions achieved from increased energy efficiency.	0 No impact expected	+ Increased energy efficiency	0 No impact expected	0 No impact expected	0 No impact expected
System optimisation	Reduce product weight	+ Reduced air emissions achieved from reduced amounts of fuel required for firing and drying.	0 No impact expected	+ Reduction of electricity consumption	+ Higher resource efficiency (less raw materials per output).	0 No impact expected	+ Reduced need of transportation due to the lower mass of materials.
System optimisation	Oxygen enrichment technology	+ Reduced air emissions achieved from the reduced use of fossil fuels.	+ Reduced risk of water pollution due to a lower use of fossil fuels.	+ The use of oxygen-enriched combustion air in the clinker burning process allows an increase in the energy efficiency,	0 No impact expected	+ Reduced risk of soil contamination due to a lower use of fossil fuels.	0 No impact expected
Carbon capture	Recarbonation / Carbon	+	+	-	+	+	0

Subgroup	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	**Water**	**Energy use and efficiency**	**Resource efficiency/ waste generation**	**Soil, land use and biodiversity**	
	dioxide Storage by Mineralisation (CSM)	Naturally the lime included in the mortar, absorbs CO_2. The wider air emissions depend on the characteristics of the building where the lime is used. In general, no emissions occur from this process.	Reduced risk of water pollution due to lower atmospheric emissions.	Increase in thermal energy by 2,550 MJ/t clinker. Increase in electrical energy by between 300 to 700 kWh/t clinker.	Reduction / valorisation of materials and products	Reduced risk of soil contamination due to lower atmospheric emissions.	No impact expected
Carbon capture	Calcium looping	+ Capture about 95% of total emissions (including process and fuel CO2 emissions).	+ Reduced risk of water pollution	+ Energy consumption: The energy from the carbonation reaction – due to the high gas temperature – can be used for electricity generation	? No information found	+ Reduced risk of soil contamination	? No information found
Carbon capture	LEILAC - Low Emissions Intensity Lime & Cement.	+ Capture over 95% of process emissions or 57% reduction of total emissions.	+ Reduced risk of water pollution	0 Thermal and electrical energy consumption is not expected to change significantly, in cement or lime plants with LEILAC, except for the new compressor mentioned earlier.	0 No significantly new types of materials or chemicals are expected to be required. Oxygen generation will not be required.	+ Reduced risk of soil contamination	? No information found

3.8. Chemical industry

3.8.1. Decarbonisation technologies

The chemical industry consists of many different and complex energy-intensive activities leading to direct and indirect GHG emissions, as set out in 2.2.2. The sector's GHG emissions have decreased over the past decades and are expected to further decline.

Decarbonisation technologies are available for the chemical sector at different stages of development (from research to industrial scale application). Many of the **cross cutting technologies**, described in section 3.4, are applicable to the chemical sector, in particular the use of alternative fuels (biomass and hydrogen), electrification of heat and processes, system optimisation, energy efficiency improvement options and carbon capture technologies. In addition to these cross cutting technologies, there are a range of sector specific decarbonisation technologies which have been identified in the literature.

Several pathways in the chemical industry relate to the use of **alternative feedstock** or materials. **Biomass** for example can be used as an alternative to some of the petroleum feedstock. Biomass as an alternative feedstock is widely reported as an important pathway to reduce dependency on fossil fuels for the sector of organic chemical production. However, it has been reported that the use increases energy intensity of production and that there is uncertainty around the supply for a further uptake. In addition to biomass, the sector has high potential for the use of CO_2 as input to some of the chemical production processes, i.e. chemical **valorisation of CO_2**. Various CO_2 conversion technologies (e.g. catalysts, membranes, process technologies) can for example be used to produce methanol or other alternative fuels for the transport sector as well as for the production of methane and other chemicals via so-called 'Power-to-X- technologies' (also used for chemical energy storage). There is, furthermore, a growing trend of using **recycled materials** (e.g. chemicals, plastics, syngas) back into the production process, avoiding the need for virgin materials. Various types of recycling processes are available, including chemical and mechanical recycling, pyrolysis and depolymerisation.

As per the cross cutting technologies, **fuel switching** (including biomass and hydrogen) as well as the **electrification of heat and processes**, such as electric crackers (or e-crackers), are important decarbonisation options for the chemical sector in general, given the large share of GHG emissions resulting from combustion processes. Furthermore, direct electrification of chemical processes can be applied, for example the use of plasma technologies for valorisation of alternative carbon feedstock.

The list of specific decarbonisation technologies presented in Table 3.14 (and more details in Appendix A) also includes **process innovations** or production process optimisations, such as the production of ethylene via the low carbon Methanol-to-Olefins (MTO) process, the use of oxygen-depolarised cathodes (ODC) and catalytic crackers.

Hydrogen production technologies and the associated (direct or indirect) GHG emissions are important to consider as part of fuel switching options (see above), but also in relation to the production of ammonia. **Green hydrogen production**, i.e. electrolysis of water to hydrogen and oxygen driven by renewable electricity, offers a high potential for a further decarbonisation of the sector, compared to the conventional steam methane reforming process.

For the chemical sector in particular, a collaboration with other sectors or **industrial symbiosis** offers a lot of potential for further decarbonising the chemical industry. Examples include the production of urea from residual steel gases and the use of CO_2 emissions from cement plants or power plants for chemical synthesis.

Innovations in the entire value chain as well as new business models have also been reported as potentially impacting the GHG emissions from the chemical sector. An example of this is changes in the demand for fertilisers, directly impacting the GHG emissions related to the production process of fertilisers.

Finally, **carbon capture technologies** (in addition to the valorisation of CO_2 – see above) have been reported for the chemical industry, offering potential in particular in clusters with other industrial sectors and activities. As an example, Carbon4PUR[46] technology has a GHG reduction potential of 70% of process energy in the polyol producing industry, including 15-36% reduction of petrochemical epoxy compounds.

The main pathways for the chemical industry are presented in Figure 3.9, for the production of petrochemicals, ammonia and fertilisers, and for the chemical activities in general.

Figure 3.9 Main decarbonisation pathways for the chemical industry

Chemical sector - General

- Alternative fuels (low carbon fuels/hydrogen) and electrification of heat and processes
- System optimisation and improving energy efficiency
- Synergies with other sectors - industrial symbiosis
- Value chain innovations and new business models

Petrochemicals

- Alternative feedstock and process innovations: biomass, recycled materials and CO_2 valorisation (incl. Power-to-X)
- Recycling: chemicals / plastics
- System optimisation and improving energy efficiency: catalytic technologies, chemical separation systems
- Carbon capture technologies

Ammonia and fertilisers

- Green hydrogen for ammonia production
- Alternative processes: Solid State Ammonia Synthesis (SSAS)
- System optimisation and improving energy efficiency
- New business models and consumption reduction

A detailed list of the technologies identified for the chemical industry is presented in Appendix A and a summary of the sector specific decarbonisation technologies provided in Table 3.14.

46 https://www.carbon4pur.eu/

Table 3.14 Specific decarbonisation technologies identified for the **chemical industry**

Pathway group	Pathway	Chemical activity	Descriptions	TRL	Main barriers	GHG reduction*
Alternative feedstock	Biomass	Organic chemicals	The use of biomass as an alternative to petroleum feedstock. Biomass may require pre-treatment processes and can be transformed to chemicals through routes such as: • Catalytic processes • Pyrolysis (incl. catalytic pyrolysis) • Enzymatic processes Biomass such as biological municipal waste, forestry and agricultural waste, grass miscanthus, other energy crops and microalgae can be processed to produce organic chemicals such as ethanol.	3-9	Limited availability of sustainable biomasses for future uptake. Currently significantly more expensive than fossil fuels and likely to continue.	HIGH The reported GHG reduction varies across the literature. It is dependent on the type of biomass, logistics and product being manufactured.
Alternative feedstock	Carbon (valorisation of CO_2 or more widely – CCU)	All	Thermocatalytic, electrocatalytic and photo-electrocatalytic processes can utilise CO_2 as a carbon source in the production of chemicals and polymers. It is proven technology for the production of polyols, where a 10kt/a unit has commenced operation in 2018.	1-9[47]	Significant investments; some sustainable materials with new properties have to overcome market penetration; competing against established processes.	HIGH Innovative CO_2 conversion technologies can contribute to reducing the use of fossil carbon sources and import dependency.
Alternative feedstock	Recycled chemicals and materials	Organic chemicals	Improved chemicals recycling technology for plastics and polymers create new sources of raw materials (see details on recycling options below).	6-9	Technically possible to recycle materials and use as feedstock, though need for improved recyclable by design.	MEDIUM

[47] The TRL range reflects the wide range of processes and products falling under the pathway of chemical 'valorisation of CO_2', covering more established techniques (e.g. thermocatalytic processes – production of polymers) as well as techniques at very early stages of development.

Pathway group	Pathway	Chemical activity	Descriptions	TRL	Main barriers	GHG reduction*
Alternative fuel	Low carbon fuels	All	The use of biomass, syngas as an alternative energy source for heating and processes (see details in the cross cutting pathways section)	8-9	Limited availability of sustainable biomass.	MEDIUM
Alternative fuel	Hydrogen	All	Use of hydrogen as an alternative fuel (see details in the cross cutting pathways section)	5-8	Sufficient supply of green hydrogen; infrastructure for storage.	HIGH
Alternative energy source / Electrification	Direct utilisation of electrons and alternative energy forms Power-to-X	All	Power-to-gas; Power-to-chemicals (methane, ammonia etc). Power-to-X concepts, where excess power at peak loads is used to synthesise (using electrolysis) chemical energy carriers for energy storage or to produce chemical feedstock (building blocks). Power-to-Ammonia: processes converting nitrogen and hydrogen to ammonia used as a product or for energy storage purposes	4-7	Elements of the conversion resemble technologies which are used commercially elsewhere, although at very different scales. Integrated processes have only been demonstrated at pilot scale. Challenges relate to a further scale up of the technologies and the higher production cost than fossil-based route due to high OPEX.	HIGH
Alternative fuel / Electrification	Electrification of chemical processes	All	Adoption of electricity driven processes such as: • Electrical heating, cooling, and pumping • Electric furnaces and ovens • Steam production • Electric cracking • Induction heating • DI-electric heating	3-7	Electricity prices have been identified as a key barrier. For plastics manufacturing such technology will require major development work.	HIGH High temperature heat accounts for a significant part of the CO_2 emissions from the chemical sector. Development of renewable electricity-driven steam crackers has the potential to cut CO_2 emissions by as much as 90%.
Alternative process / innovation	Low carbon ammonia	Ammonia and fertilisers	Low-carbon ammonia synthesis refers to an alternative, low-carbon hydrogen production, where hydrogen is produced through electrolysis. Hydrogen can be produced from water electrolysis via several key technologies: • Alkaline water electrolysis	7	Breakthrough will be required for the generation of hydrogen at significantly lower energy demand and for providing significant excess hydrogen from renewable energy sources.	HIGH If excess hydrogen from renewable sources can be provided for these processes, a significant GHG reduction is

Pathway group	Pathway	Chemical activity	Descriptions	TRL	Main barriers	GHG reduction*
			• Polymer electrolyte electrolysis • Solid oxide electrolysis		Electrolysers need to prove stability for operations under pressure (30 to 40 bars). In addition, development of electrodes with low noble metals and other rare elements content.	possible. For ammonia, a 30% implementation rate to replace the fossil routes by 2050, would reduce emissions by 200 $MtCO_2$ eq.
Alternative process / innovation	CH_4 Pyrolysis - Hydrogen production	All	Hydrogen is a key feedstock in the manufacturing of chemicals (e.g. ammonia and methanol). Hydrogen can be produced by natural gas pyrolysis. Methane and other lower hydrocarbons are decomposed in a high temperature pyrolysis process generating hydrogen and solid carbon.	4-5	A large-scale demonstration plant of this new process is expected by 2030.	MEDIUM/HIGH If the energy comes from renewables hydrogen can be produced without CO_2 emissions. Based on the thermodynamics the energy demand of methane pyrolysis is 87 % lower compared to water electrolysis.
Alternative process / innovation	Catalytic cracking[48]	Organic chemicals	The cracking process breaks long-chain hydrocarbons into light hydrocarbons. Several more energy efficient options have been highlighted, including the use of catalytic cracking.	7-9	Catalytic cracking processes are becoming common at refineries; however, it has been noted that the viability of natural gas crackers is a limitation.	LOW Catalytic cracking is estimated to reduce CO_2 emissions by 15-40%.
Alternative process / innovation	Methanol-to-Olefins (MTO)	Organic chemicals	Ethylene production via low carbon Methanol-to-Olefins (MTO). Production of olefins from natural gas via methanol, replacing the current process of steam cracking of naphtha or ethane.	7-8	Methanol currently produced from natural gas would need to be formulated from electrolysis. Improvements needed on efficiency and MTO catalysts.	MEDIUM

[48] The pathway has been reported in literature within the chemicals sector however the process is believed to be applicable to activities grouped under Energy Industries relating to refining of mineral oil and gas.

Pathway group	Pathway	Chemical activity	Descriptions	TRL	Main barriers	GHG reduction*
			Methanol can be produced by green hydrogen and captured CO_2.			
Alternative process / innovation	Oxygen-depolarised cathodes (ODC)	Inorganic chemicals	Replacing membrane cells in chlor-alkali electrolysis process with oxygen depolarised cathodes provides an energy saving of about 30% compared to other processes as the process is able to operate at a lower voltage.	7-9	Plants running on conventional membrane technology can be partly or entirely converted to NaCl-ODC technology.	MEDIUM Up to 25-30 % less energy consumption than conventional membrane-based technology
Alternative process / innovation	Advanced separation technologies (membrane /distillation technologies)	Organic chemicals	More efficient separation technologies such advanced distillation technologies (e.g. heat integration distillation columns, high gravity, and (bio) reactive distillation), membrane technologies, adsorption technologies, advanced filtration systems.	3-8	Distillation system configuration, design, modelling and control issues; Fouling of the membrane is a common materials design issue.	LOW Energy efficiency saving provides 8% reduction in CO_2 emission compared to current distillation processes.
Alternative process / innovation	Solid State Ammonia Synthesis (SSAS)	Ammonia and fertilisers	Direct electrochemical synthesis of ammonia; process combining electrolysis with Haber-Bosch process.	1-2	Achieving a rate of production for SSAS is one of the limiting factors.	MEDIUM
Recycling	Chemical recycling of plastic waste	Organic chemicals	Chemical recycling breaks down plastics into monomers, oligomers or simpler molecules, creating new feedstocks for plastics production. Attractive option for plastics that are not suitable for mechanical recycling. (example of specific technologies listed below)	4-9	Need for improved recyclable by design and improved pre-treatment technologies. Barriers also relate to cost competitiveness and scale up.	MEDIUM
Recycling	Microbial technology	Organic chemicals	Biotechnological processes, applying microbes and enzymes for waste recycling.	4-7	Identification and engineering of range of enzymes and microorganisms that can be applied on bulk production polymers with variable physicochemical properties;	MEDIUM

Pathway group	Pathway	Chemical activity	Descriptions	TRL	Main barriers	GHG reduction*
					Cost competitiveness and scale up (key upstream and downstream purification issues).	
Recycling	Plastic waste to feedstock	Organic chemicals	Convert waste plastics to feedstock for products such as olefins. This can be achieved through: • Pyrolysis, • Gasification.	4-8	High energy-intensity required due to high process temperatures;	LOW
Recycling	Plastic waste to monomers - Depolymeri-sation	Organic chemicals	Depolymerisation is used to convert back sorted plastic waste to their monomer building block.	5-8	Need for improved pre-treatment steps and robustness of process to deal with the potentially high content of impurities of materials. Large volume of solvent and significant energy is required for solvent recovery.	MEDIUM Sources state between 11-50% emission reduction from virgin crude oil processing. Avoidance of 2 kg CO_2 eq/kg waste is possible).
System optimisation / energy efficiency	Process efficiency improvements	All	Several process efficiency options can improve output from the sector. The options are: • Optimised nitrogen management, particularly in fertiliser productions, • Improved process control of operations, • Process intensification/ process integration by creating synergies across process steps, • Novel catalysts and solvents and catalysts to improve efficiency and yields, • New reactor design.	7-9	Options depend on the activity and specifics of the site.	LOW
Carbon capture	Carbon capture (CCS/CCU)	Organic chemicals; Ammonia and fertilisers	Capture of CO_2 from combustion gases, and subsequent geological storage (CCS) or use of CO_2 as a feedstock for chemicals production (CCU – see CO_2 valorisation options). Example: deployment of CCS on process emissions from the steam methane reforming process to make ammonia or hydrogen (i.e. on high purity CO_2 stream).	3-8	Whilst carbon capture is applied in fertiliser production, the storage of carbon has not been used in the EU on an industrial scale.	HIGH

** Indication of the GHG emission reduction potential: high (>70% reduction) / medium (30-70% reduction) / low (<30% reduction) – see section 3.2.1.*

3.8.2. Wider environmental impacts

The wider direct and indirect environmental impacts of the decarbonisation pathways used in the production of minerals are provided in Table 3.15 below. The symbols and the overall approach are described in section 3.2.2. As in the case of the technologies deployed in the production of metals and chemicals, the information available is limited, mainly due to the low maturity of technologies.

Table 3.15 Wider direct and indirect environmental impacts in the **chemical industry**

Pathway group	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
Alternative feedstock	Biomass	-/+ Dependent on the type of biomass	0 No impact expected	- Process can require higher energy demand	+ In most cases, biomass derives from waste and in such cases an increase in resource efficiency is achieved.	0 No impact expected	-/+ Indirect impacts are linked to the source of biomass that is used (waste, forestry…). It also depends on the specific characteristics of the process that is considered and whether biomass could be integrated in the cracker. If it derives from waste, there is the question of availability of the feedstock and eventual competition. If biomass is produced there is concern about the amount of arable land required (indirect) for a high-volume, bio-based chemical feedstock, and potential competition with food production.

Pathway group	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
Alternative feedstock	Carbon (valorisation of CO_2 or more widely – CCU)	-/+ Overall, a reduction of atmospheric pollution is achieved due to a reduced use of fossil fuels. Nevertheless the technology requires hydrogen which can be associated with an increase of atmospheric pollution.	0 No impact expected	- Energy consumption: high levels of energy are required to reanimate CO_2 at the end of its lifespan so that it could be used as a chemical raw material.	+ Thermocatalysts for the direct conversion of CO_2 to polymers can effectively contribute to carbon circularity and a lower environmental footprint of polymer production.	0 No impact expected	+ Reduction in the demand for virgin materials
Alternative feedstock	Power-to-X	+ Process emissions are typically lower compared to conventional routes (fossil sources)	0 No impact expected	-/+ The total energy demand of the low-carbon process is substantially higher than for the conventional route (factor 3). However, the difference is less pronounced, if the feedstock is included in the energy demand of the fossil process.	+ Valorisation of carbon	0 No impact expected	+ Enabling the introduction of renewable energy in the chemical industry and providing options for renewable energy storage
Alternative feedstock / recycling	Recycled chemicals and materials	-/+ Emissions from processes such as pyrolysis and gasification	0 No impact expected	- Recycling processes can require high temperature / energy	+ Resource efficiency achieved.	0 No impact expected	+ Avoiding the use of raw materials. Valorisation of waste and avoiding materials to be incinerated or landfilled.

wood.

Pathway group	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
Alternative fuel	Hydrogen	See section on cross cutting pathways					
Alternative fuels / Electrification	Electrification of chemical processes	+ Reduction of emissions compared to gas/oil fired systems. Low NOx emissions. Positive if renewable sources of energy are used.	0 No impact expected	-/+ No significant impact on energy efficiencies	0 No impact expected	- Need to redesign the process to use electricity.	-/+ The operation of one cracker requires 250 windmills, and this would not secure electricity constantly. If there is no adequate wind the electricity could derive from polluting energy sources.
Alternative process / innovation	Low carbon ammonia	+ If excess hydrogen from renewable sources can be provided a reduction of atmospheric pollution (together with GHG) can be achieved.	- Increase in water consumption for the green hydrogen production (electrolysis)	+ Energy savings reported of approx. 10% (compared to methane steam reformation)	0 No impact expected	+ Positive if renewable sources of energy are used.	-/+ Impacts related to the production of green hydrogen (supply and infrastructure).
Alternative process / innovation	CH_4 Pyrolysis - Hydrogen production	+ Formation of CO/CO_2 is avoided and only solid carbon is obtained as reaction by-product. If excess hydrogen from renewable sources can be provided a reduction	0 No impact expected	-/+ Energy efficiency of 58 %, which is comparable to SMR when the separation of CO2 is taken into account	0 No impact expected found	0 No impact expected found	0 No impact expected found

Pathway group	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
		of atmospheric pollution (together with GHG) can be achieved.					
Alternative process / innovation	Catalytic cracking	- Increased atmospheric pollution due to higher energy consumption.	- Higher risk of water pollution due to increased atmospheric pollution.	- Methanol-to-olefin technology requires 500% increase in energy compared to convention naphtha process.	? No information found	- Higher risk of soil pollution due to increased atmospheric pollution.	0 No impact expected found
Alternative process / innovation	Methanol-to-olefin reactions	+ Lower atmospheric pollution due to the substitution naphtha or ethane with natural gas.	+ Lower risk of water pollution due to decreased atmospheric pollution.	? No information found	? No information found	+ Lower risk of soil contamination due to decreased atmospheric pollution.	0 No impact expected found
Alternative process / innovation	Oxygen-depolarised cathodes	+ Lower atmospheric pollution due to reduced energy consumption.	+ Lower risk of water pollution due to decreased atmospheric pollution.	+ Up to 25 % less energy consumption than conventional membrane-based technology	? No information found	+ Lower risk of soil contamination due to decreased atmospheric pollution.	0 No impact expected found

Pathway group	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
Alternative process / innovation	Membrane technologies	+ Lower atmospheric pollution due to improved energy efficiency.	+ Lower risk of water pollution due to decreased atmospheric pollution.	+ Improved energy efficiency	? No information found	+ Lower risk of soil contamination due to decreased atmospheric pollution.	0 No impact expected found
Recycling	Microbial technology	? No information found	? No information found	? No information found	+ Resource efficiency achieved due to the valorisation of plastic waste.	? No information found	0 No impact expected found
Recycling	Syngas from waste plastic	? No information found	? No information found	? No information found	+ Resource use: If the recycling rate increases to 50% by 2050, the demand for raw ethylene would reduce by 8% simply from the recycling increase.	? No information found	0 No impact expected found
Recycling	Depolymerisation	? No information found	? No information found	? No information found	+ Resource efficiency achieved due to the valorisation of plastic waste. Nevertheless, significant energy is required for solvent recovery.	? No information found	? 0 No impact expected found

Pathway group	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
System optimisation / energy efficiency	Process efficiency improvements	+ NH_3 emissions are prevented.	0 No impact expected found	+ Improvements in energy efficiency and reduction of energy use	+ Overall resource efficiency is achieved.	? No information found	0 No impact expected found
Carbon capture	Carbon capture (CCS/CCU)	See section on cross cutting pathways					

3.9. Waste management and other activities

3.9.1. Decarbonisation technologies

In this section the IED Annex I activities 5 (waste management) and 6 (other activities) are covered. Waste management consists of activities relating to disposal or recovery of hazardous waste, waste incineration plants, non-hazardous waste, landfills and temporary or underground storage of hazardous waste. Other activities under IED Annex I include production of pulp, paper or cardboard, wood-based panels, treatment of textile fibres, tanning of hides and skins, food production and intensive rearing of animals, disposal or recycling of animal waste, production of carbon (hard-burnt coal) or electrographite and preservation of wood products with chemicals.

This groups of activities are very diverse in terms of raw materials, production or treatment processes, products and hence also the type and level of GHG emissions resulting from these activities (see section 2.2.2). Many of the GHG emissions from the activities are related to the production and use of energy, generated either on or off site. Therefore, a number of common aspects or pathways for further decarbonisation options applicable across most of these activities could be identified (covered by some of the cross cutting decarbonisation technologies). In particular, these options include:

- **Fuel switching** – the use of low carbon fuels, including biomass and hydrogen, for the generation of energy for heating and processes. Many of the activities already use a degree of low carbon fuels, such as biomass or gas based boilers, though there is potential for a further uptake and conversion of fuels.
- **Electrification** – the use of electric heating and electricity driven processes. This also includes existing electricity use where a decarbonisation of the power sector will lead to a decrease of indirect GHG emissions for the productions and processing activities.
- **System optimisation and energy efficiency improvements** – upgrading the existing processes with state-of-the-art technologies, and process improvements leading to energy efficiency gains, are applicable to most of the activities covered in this section and can lead to important GHG emission reductions.
- **Process innovations** – for some of the sectors, several novel process technologies have been identified that could lead to further decarbonisation of the activities. Specific innovative or breakthrough techniques are presented in Table 3.16 for the production of pulp and paper, and for the food processing sectors.

For many of the sectors, and in particular waste management and production of pulp and paper, **recycling of materials and by-products** will be an important pathway leading to further changes in the processes and impacts on GHG emissions. The European paper industry delivered a 72.5% paper recycling rate (CEPI, 2018) and in its 2050 roadmap the industry stated that in the future fibres will be used and recycled in an optimal way, with the highest possible value added at each stage. In more general terms, waste streams are expected to change in composition in the future and the uptake of different feedstock and material inputs across all sectors will create different waste products. There will be a need for waste treatment activities to adjust accordingly. Consequently, operation of existing waste processing activities will change. Examples of pathways leading to a higher uptake of recycling and material recovery, which also can have impacts for the waste management sector, are presented in the sections above, e.g. for the chemical industry (plastic recycling) or mineral industry (recycling of by-products).

Finally, although carbon capture could in theory lead to a further decarbonisation of many of the sectors falling under this section, it is considered that CCS is not a primary solution for the individual activities.

However, in the situation where installations are clustered and infrastructure is in place, carbon capture, e.g. from pulp and paper production, can offer a further possibility. The latter highlights the importance of **industrial symbiosis**, not only for CO_2 emissions, but also regarding synergies for by-products and waste streams.

In terms of more specific decarbonisation pathways and technologies, the information analysed in this project focussed on waste management and on the energy intensive sectors of pulp and paper making; production of food and drink; and the intensive rearing of poultry or pigs.

Table 3.16 Specific decarbonisation technologies identified for the **waste management and other activities**

Pathway group	Pathway	Activity	Descriptions	TRL	Main barriers	GHG reduction*
Alternative feedstock	Biomass	Pulp, Paper or cardboard, wood-based panels; Food production	Use components of wood: • to replace existing fossil and non-renewable sources • for new industrial products Renewable feedstock: new products for sustainable agriculture, forestry, and the ocean, i.e. plant- based raw material meat replacement, vegetable oils, and algae. Potential on biomolecules, biocatalysts and bacterioplankton.	5-8	Limited availability of sustainable biomasses.	MEDIUM / HIGH Bio-chemicals: CO_2 abatement potential over the period 2015-2050 Food: Reduction in consumption, CO_2 emissions, and contribution to animal welfare Overall GHG emission reduction : 50-97%
Electrification	Electrification of heating	Pulp, Paper or cardboard, wood-based panels; Food and drink production.	Generation of low carbon electricity and heat by using solar and wind energy (i.e. some paper mills have roof-top photovoltaic). Electrify the heating demand to generate heat in pulp, paper, and food production through: • Heat pumps • Electric ovens • Industrial ovens (cooking and backing) The sector would provide a buffer and storage capacity for the grid, storing energy as hydrogen or pulp.	3-5	High electricity prices. Necessary efforts to reduce capital expenses and increase the output temperatures. Limited potential for fine paper.	MEDIUM Industrial ovens (food): Emission reduction 5-70%. Industrial ovens (pulp and paper): Emission reduction 4-70%. Free-emission process. Eliminating the use of fossil fuels and cutting NO_x and SOx emissions.
Electrification	Eliminate air compressed	Pulp, Paper or cardboard, wood-based panels	Switch or eliminate compressed air where possible and favour electric motors.	9	Not specified in literature.	LOW
Alternative process / process innovations	Electro-chemical recovery processes	Waste treatment	Electrochemical processes can be used as an alternative process to recover valuable materials, including catalysts, metals, critical raw materials to minimise waste and reduce CO_2	3-5	Corrosion- resistant and inexpensive electrode materials for efficient processes	MEDIUM

Pathway group	Pathway	Activity	Descriptions	TRL	Main barriers	GHG reduction*
Alternative process / process innovations	BIOFOS – Bio-catalysis technique[49]	Waste treatment	Biogas consisting of methane and CO_2, produced from waste treatment is passed through a biocatalyst which hydrogenates CO_2 to bicarbonate. The remaining gas stream is grid-grade biomethane. (It is believed this technology could also be used in post-combustion CCS pathways for other fuels)	5	Not specified in literature.	LOW
Alternative process / process innovations	New physical recycling technologies	Waste treatment	New techniques for physically sorting scrap metal include fluidised bed sink float technology, colour sorting, and laser induced breakdown spectroscopy (LIBS).	5-7	Not specified in literature.	LOW
Alternative process / process innovations	Water consumption	Pulp, Paper or cardboard	Waterless paper production through two technologies: dry pulp and cure- formed paper to reduce water consumption. Reduction of water use when drying through flash condensing with steam using minimum water	1-4 1-5	The optimal development of DryPulp compound requires R&D Approx. 10 years for flash condensing before becoming commercially available	MEDIUM 50-55% CO_2 emission reduction
Alternative process / process innovations	High consistency forming	Pulp, Paper or cardboard, wood-based panels	The process pulp entering the forming stage has more than double the normal consistency. This measure increases forming speed and reduces dewatering and vacuum power requirements.	7	Not specified in literature.	LOW CO_2 reduction: 3%

49 https://biofos.dk/

Pathway group	Pathway	Activity	Descriptions	TRL	Main barriers	GHG reduction*
Alternative process / process innovations	Neo-carbon food[50]	Food and drink production	Microbial process enabling protein production with minimal requirements separating food production from agricultural land use.	1-2	Not specified in literature.	HIGH
Recycling	Waste – recycled paper	Pulp, Paper or cardboard	New recycling technologies to avoid wetting and drying, upgrading, etc. This technology focuses on reducing energy use and improving quality of recycled paper by removing impurities to produce a good pulp.	1-8	Not specified in literature.	MEDIUM CO_2 abatement potential over the period 2015-2050 (energy efficiency): 7 Mt.
Recycling	Water efficient industrial food production	Food and drink production	Improved recycling of water in the food industry, i.e. DRIP – Danish partnership for Resource and water efficient Industrial food Production[51]	4	Not specified in literature.	MEDIUM
Recycling	Black Liquor recovery	Pulp, Paper or cardboard	Black liquor recovery and gasification used in pulp mills to generate energy in the form of steam and on-site electricity.	7-8	This technology is developed but is not used in practice.	LOW CO_2 emission reduction is approx. 10%
System optimisation	Drying technologies	Pulp, Paper or cardboard	Several drying options to use in paper manufacturing and to increase energy efficiency: • Using supercritical CO_2[52] • Dry sheet forming • Hot pressing • Impulse drying Steam	7	Many of these techniques are common in other industries but not yet adopted by the paper and pulp sector.	MEDIUM Supercritical CO_2: 15-45% abatement potential Steam: 50% abatement potential

[50] http://neocarbonfood.fi/
[51] https://www.kt.dtu.dk/english/research/prosys/projects/drip
[52] For drying or removing contaminants without heat and steam using high pressure temperature substituting steam-heated cylinders

Pathway group	Pathway	Activity	Descriptions	TRL	Main barriers	GHG reduction*
System optimisation	Material efficiency	Pulp, Paper or cardboard, wood-based panels	Increase material efficiency through production of light weight products, such as paper by selling surface instead of weight (up to 30% material reduction per surface unit) and nanocellulose use	4-9	Not specified in literature.	MEDIUM
System optimisation	Process efficiency	Pulp, Paper or cardboard, wood-based panels	Technologies to reduce energy use in pulp, paper mills production (non-exhaustive list): • Integrated bio- refinery complexes • Deep Eutectic Solvents (DES) • Valorisation of pulp/paper making waste streams • Predictive maintenance programme (utilities, wires) • Control of utilities: steam system, air compressor, vacuum pumps, lighting, water systems and pumps, agitators • High consistency forming • Efficient screening and dispersers Optimise steam turbine control	1-4 Utilities: 7-9	In 15 years, the Deep Eutectic Solvents could be at industrial scale market	MEDIUM Deep Eutectic Solvents for pulp could achieve a CO_2 reduction of 20%
System optimisation	Heat exchanger for poultry houses	Intensive rearing of poultry[53]	The heat exchanger saves up to 80% of the energy needed in the poultry houses while at the same time reducing ammonia emissions by 30-40% (through controlling the moisture content in the air). In the poultry sector, air-air heat exchangers are mainly applied.	9	The cost of the equipment is relatively high. The ventilation design becomes a limitation when retrofitting in naturally ventilated existing houses.	HIGH

[53] The IRPP BREF includes techniques (BAT) to prevent or control (ammonia and methane) emissions from animal housing, storage of manure and manure processing. These techniques (such as anaerobic digestion of manure, recovery of biogas, manure additives and landspreading techniques) have not been included in the summary tables. (Source: IRPP BREF, 2017: https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/JRC107189_IRPP_Bref_2017_published.pdf).

Pathway group	Pathway	Activity	Descriptions	TRL	Main barriers	GHG reduction*
System optimisation	Manure cooling in pig farms	Intensive rearing of pigs[53]	A sustainable hydraulic system is used to cool the slurry manure. The surplus heat can be used for heating the buildings and in some cases make the farm self-sufficient with heating and cooling – and independent of external heating supply.	8-9	Manure cooling is not effective for large slurry volumes.	MEDIUM
System optimisation	Near-zero-emission stall housing system	Intensive rearing of pigs	A near-zero-emission stall pig housing system through which the formation and release of aerial pollutants can be reduced to close to zero. This is achieved by a combination of different measures concerning slurry management, building design, and ventilation. The system leads to reduced ammonia emissions and also enables energy savings through integrated ventilation and heat recovery.	8-9	Applicable to new systems. Compared to standard systems, the building costs per piglet are expected to be lower.	MEDIUM The integrated ventilation and heat exchange concept enables significant energy savings. Ammonia, odour and dust emissions are reduced to a very low level.

** Indication of the GHG emission reduction potential: high (>70% reduction) / medium (30-70% reduction) / low (<30% reduction) – see section 3.2.1*

3.9.2. Wider environmental impacts

The wider direct and indirect environmental impacts of the decarbonisation pathways used in waste management and other activities are provided in Table 3.17 Table 3.13 below. As in the case of the production of minerals, metals and chemicals, the information is limited particularly in technologies that have not been developed at the market scale.

Table 3.17 Wider direct and indirect environmental impacts in the **waste management and other activities**

Pathway group	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	**Water**	**Energy use and efficiency**	**Resource efficiency/ waste generation**	**Soil, land use and biodiversity**	
Alternative feedstock	Biomass	? No information found	? No information found	? No information found	+ Replacements of existing fossil and non-renewable sources with biomass deriving either from waste or raw biomass	+/- Land use: There is concern about the amount of arable land required for a high-volume, bio-based chemical feedstock, and potential competition with food production. Sludge from wastewater treatment is increasingly being used for biogas production and could provide 5-10% of the energy use at a paper mill that uses recovered fibre.	? No information found
Electrification	Electrification of heating	+ It would decarbonise papermaking through the adoption of more efficient technologies that use electricity rather than fossil fuels to generate heat. Ending the use of fossil fuels will also totally cut NOx and SOx emissions.	+ Lower risk of water pollution due to decreased atmospheric pollution.	+ The sector could also provide a buffer and storage capacity for electricity, offering a means to store inexpensive surplus energy from the grid generated from intermittent renewable energy sources such as solar and wind power. It would do this by using electricity when it is	? No information found	+ Lower risk of soil contamination due to decreased atmospheric pollution.	? No information found

Pathway group	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
				inexpensive to produce and store Thermo-Mechanical Pulp (TMP) and hydrogen (H_2), using the latter to generate power during periods of high electricity prices or selling it to external users.			
Electrification	Eliminate air compressed	+ Lower emissions if the electricity is generated from renewable resources.	0 No impacts expected	+ Less energy used	+ Less resource used	0 No impact expected	-/+ Impacts relate to the source of electricity
Alternative process / process innovations	Electro-chemical recovery processes	? No information found	? No information found	? No information found	+ Recovery of valuable materials, including (catalysts, metals, and critical raw materials) and reduction waste.	0 No impacts expected	0 No impacts expected found
Alternative process / process innovations	BIOFOS – Bio-catalysis technique[54]	? No information found	? No information found	? No information found	+ Energy efficiency achieved through waste treatment.	0 No impacts expected	0 No impacts expected

[54] https://biofos.dk/

Pathway group	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	Water	Energy use and efficiency	Resource efficiency/ waste generation	Soil, land use and biodiversity	
Alternative process / process innovations	Neo-carbon food[55]	+ Reduction of vacuum power requirements	+ Reduction of dewatering requirements	? No information found	? No information found	? No information found	? No information found
Recycling	Waste – recycled paper	+ Lower atmospheric pollution due to reduced energy use	+ Water savings achieved.	+ Reduced energy use	+ Resource efficiency achieved.	? No information found	? No information found
Recycling	Water efficient industrial food production	? No information found	+ Water savings achieved.	? No information found	? No information found	? No information found	? No information found
Recycling	Black Liquor recovery	? No information found	+ Water savings achieved.	? No information found	+ Resource efficiency achieved.	? No information found	0 No impacts expected
System optimisation	Drying technologies	? No information found	? No information found	+ Increased energy efficiency	? No information found	? No information found	0 No impacts expected
System optimisation	Process efficiency	+	?	+	+	?	0

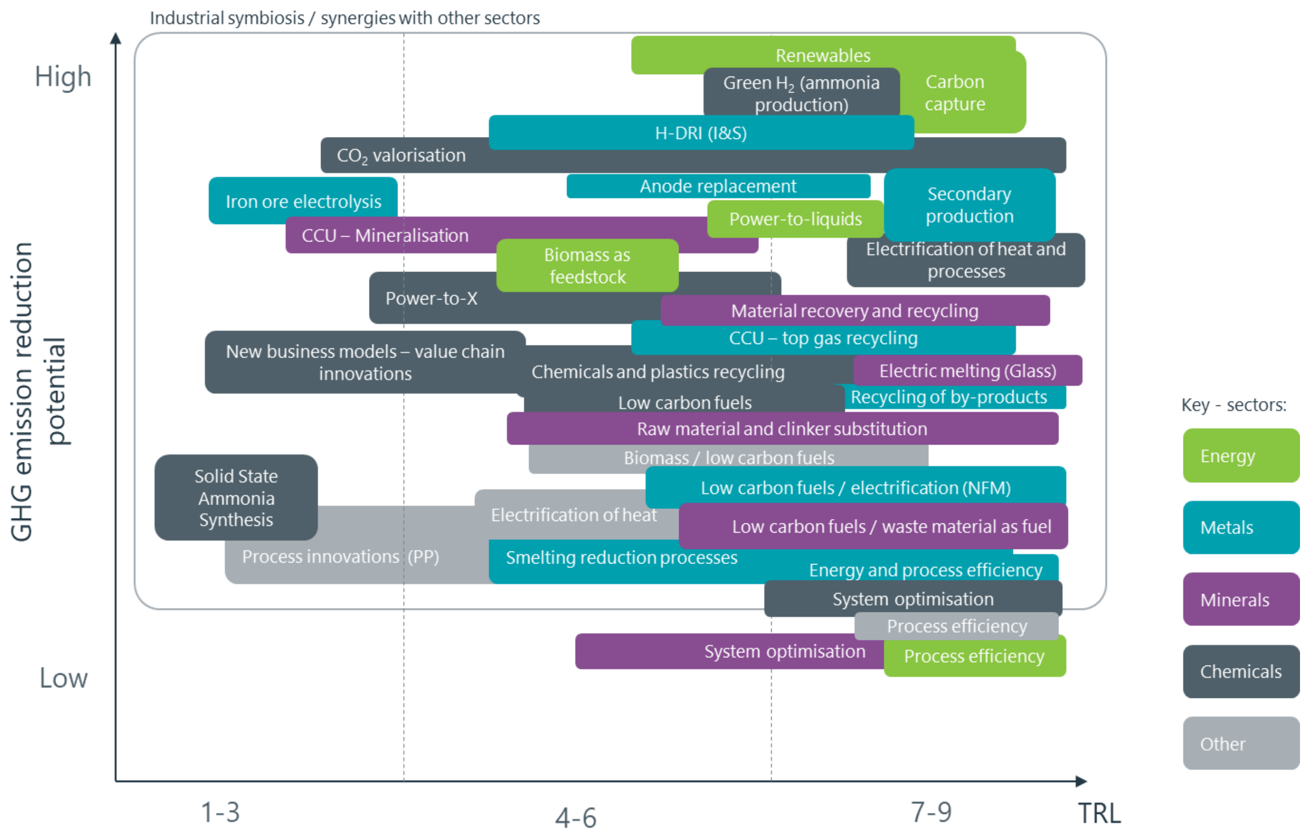
[55] http://neocarbonfood.fi/

Pathway group	Pathway	Direct environmental impacts					Indirect environmental impacts
		Air	**Water**	**Energy use and efficiency**	**Resource efficiency/ waste generation**	**Soil, land use and biodiversity**	
		Reduction of atmospheric pollution due to enhanced energy efficiency.	No information found	Energy efficiency achieved	Resource efficiency achieved.	No information found	No impacts expected
System optimisation	Heat exchanger for poultry houses	+ Reduction of ammonia emissions by 30-40%.	? No information found	+ The heat exchanger saves up to 80% of the energy needed	+ Resource efficiency achieved.	? No information found	0 No impacts expected
System optimisation	Manure cooling in pig farms	+ Reduction of atmospheric pollution due to enhanced energy efficiency.	+ Reduced risk of water pollution	+ Energy efficiency achieved	? No information found	+ Reduced risk of soil pollution	0 No impacts expected

3.10. Conclusions

The sections above provide an overview of the main decarbonisation options, grouped per sector under the scope of the IED. The main options, their level of readiness (TRL) and potential for GHG emissions reduction are summarised in Figure 3.10. Some of the categories presented in Figure 3.10 refer to a single technology with potentially high implications for the sector (e.g. low carbon ammonia production or the direct reduction of iron ore using hydrogen), whilst others in this figure combine several technologies, such as the valorisation of CO_2 in the chemical industry or the system optimisation options in the various IED sectors.

Figure 3.10 Main identified decarbonisation options, their TRL and GHG emission reduction potential



The details of each category (descriptions, TRL and GHG reduction potential) are presented in the sector sections of this report. From the identification of these technologies, a number of general observations and conclusions can be drawn.

First of all, when gathering information on decarbonisation options for the industrial activities, there is a high variety in the **type of technologies and their potential impact on GHG emission reductions**. When referring to decarbonisation, reference in literature as well as by stakeholders was made to either the high level pathways, such as green hydrogen or carbon capture and use, whilst in other instances already well-established practices were provided, such as energy efficiency measures, insulation of equipment, or combustion optimisation. Not only is there a big difference in terms of the potential impact on GHG emissions between those types of options, but the timeline for uptake of these measures is also completely different. Many of the more high level pathways are often still in the early stages of development, with TRLs below 5 or 6. This often implies that (i) information on these, likely promising, options, is more scarce, (ii) their application at an industrial scale, and if relevant, to other activities than those currently being tested, has not been proven, and (iii) the time for uptake of these options is still uncertain and will require further evidence. The study attempted to capture the entire spectrum of measures, however, with a focus on those technologies leading to the highest impact in the longer term.

There are clear differences in options available between industrial sectors. In sectors such as iron and steel or the production of organic chemicals, innovative process technology changes are available, potentially leading to a step change in terms of GHG emissions from those activities by 2050. This is somewhat reflected by the various decarbonisation roadmaps produced mainly for those sectors with the highest potential for future, more **innovative technologies**, such as cement, metals processing and the chemical industry. This is different from activities where the majority of GHG emissions are not related to process emissions, but rather originate from the **combustion of fossil fuels** for the generation of energy to the processes. In these examples, such as many of the food production or the pulp and paper production activities, the potential for further reduction of GHG emissions is very much relying on the continued decarbonisation of the energy sector, both on site and off site, i.e. indirect emissions. The number of options available for these sources of emissions are smaller, though could have a high potential. Many industries have already taken steps to reduce these emissions, for example by the use of renewable energy sources, switching to electricity driven processes and recovery of energy (heat) for the processes.

The majority of the technologies identified in this study are related to the reduction of **CO_2 emissions** (either from combustion of fossil fuels or from the processes). This is obviously a key aspect for the required deep decarbonisation of the industry sectors by 2050. However, several activities also generate significant levels of **non-CO_2 GHG emissions**. Examples include emissions of methane (CH_4) from waste management or handling of manure and emissions of polyfluorocarbons (PFCs) from primary aluminium production. Although options are available and have already been implemented to reduce these emissions, controlling and further reducing them will remain important in the longer term, i.e. towards 2050.

Apart from some process (and activity) specific decarbonisation options, there are several important themes or **pathways applicable to many sectors** which are expected to contribute to a significant decrease in GHG emissions by 2050. These options have been categorised in the study as 'cross-cutting technologies' and cover options such as fuel switching (biomass, hydrogen), electrification or carbon capture technologies. It is important to note that the implementation of some of these options are somewhat out of the control of the operators. In particular, industrial symbiosis, which requires multiple sites to collaborate in order to exchange resources (including waste, by-products, energy, etc.), involves improvements and decisions at many levels, including planning, regulatory, transport/logistics. Similarly, evolutions in segments of products value chains, other than those under the scope of the IED, could potentially drive or necessitate changes in the production process with an impact on the associated GHG emissions of production. One example of this are changes in business models of fertilisers leading to a decrease of the demand. Reducing or even avoiding the use nitrogen rich fertiliser by other use models will impact the production. Such changes, important regarding the decarbonisation of the industry, are not always controlled by individual sites.

Regarding the **wider direct environmental impacts** of the identified decarbonisation options, overall the deployment of decarbonisation options would have a positive direct impact on **air emissions**, particularly of NOx and SOx. Only certain technologies might lead to an increase of certain pollutants, for example, the use of biomass as feedstock in energy industries is associated with an increase of NOx and NH_3 but a decrease of unburned hydrocarbons and CO emissions. Nevertheless, **uncertainties exist in relation to certain decarbonisation options** where emissions are subject to the specific characteristics of the technologies and the process. This is particularly relevant for certain renewable energies, namely biomass and hydrogen. Specifically, air emissions resulting from the combustion of biomass differ depending on the purity and composition of the biomass. Furthermore, emissions to air related to hydrogen production depend largely on the source used for the generation of electricity and the associated emissions. The same applies to technologies that involve electrification of processes..

The risks associated with the **contamination water and soil deriving from conventional technologies** in general are also reduced with the introduction of decarbonisation technologies. This is achieved mainly through the reduction of atmospheric pollutant emissions and **reduction of pollutant deposition** that is caused through the pollution of the precipitation into water bodies and soils. With a few exceptions (i.e. certain technologies on waste management), the use of water is not affected directly by the decarbonisation options. In certain cases the technologies might generate additional impacts on water (e.g. eutrophication from hydropower facilities) or increased water use (e.g. for washing in SOLPART).

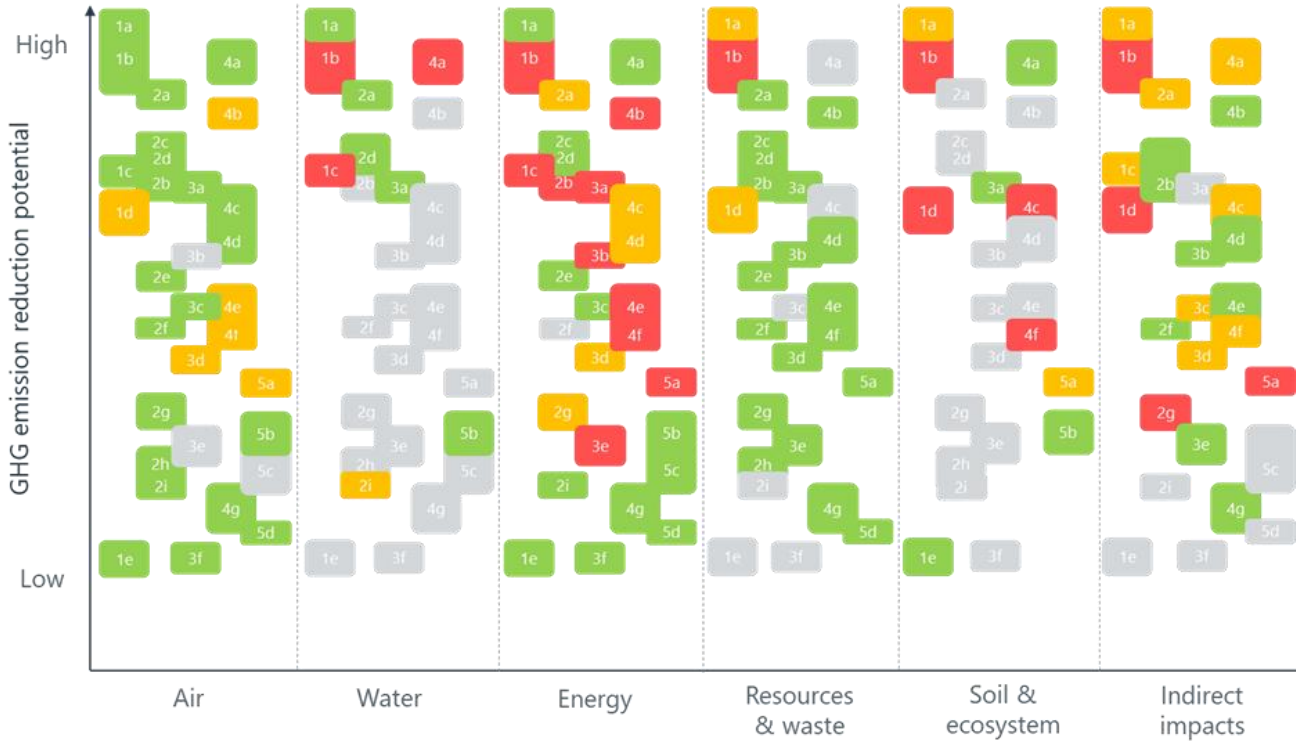
The decarbonisation options are also linked to a reduction of **energy use and to improvements in energy efficiency.** In most cases the decarbonisation achieved is a direct result of improvements of the energy performance. However, certain exceptions exist, for example in the use of power to-liquid as alternative feedstock or the use of ammonia as an alternative fuel.

Significant **resource savings** are achieved mainly when waste is used as an alternative fuel (presuming there are no other treatment options) or feedstock. Nevertheless, these savings mostly refer to the reductions of raw materials directly in the process (e.g. as a fuel) without considering additional infrastructure for the deployment of these technologies. For example, the use of hydrogen can lead to a significant reduction of fossil fuel use but in parallel, the development of the required infrastructure may additional resources (e.g. for additional pipes that need to be thicker).

The **indirect impacts** relate mainly to the production or transportation of alternative fuels and feedstocks but also to the whole value chain involved in the manufacturing process of the technologies. In relation to the alternative fuels and feedstock the impacts might be higher compared to the conventional materials (e.g. for the transportation of hydrogen through pipes or trucks). The same also applies for the manufacturing of certain technologies such as windmills that might require more material and land per MW. Nevertheless, such impacts are expected to be reduced as the technologies are advancing and the effectiveness of the required logistics are improving. In addition, impacts associated with the transportation of biomass are greater than those from conventional fuels, as biomass is less energy dense and has to be collected from dispersed locations. More land is needed if raw biomass is used instead of waste unless if the comparison is done against the use of coal or shale gas that also require a large size of land for the extraction and production processes. Similarly, in relation to CCS, negative environmental impacts are associated with the development of energy infrastructure or with the extraction and transport of additional fossil fuels.

An overview of the wider environmental impacts for the main decarbonisation options, as presented in Figure 3.10, is provided in the figures below. The figures summarise the assessment of the wider environmental impacts, based on the underlying details presented in section 3. Figure 3.11 provides an overview of the wider environmental impacts of the main decarbonisation options for all sectors and environmental aspects under the scope of the study, plotted against their potential for GHG emissions reduction. This overview is broken down in Figure 3.11 and Figure 3.12 for the individual sectors and environmental aspects, respectively.

Figure 3.11 Assessment of the wider environmental impacts for the main decarbonisation options and their potential for GHG emissions reductions across all sectors and environmental aspects under the scope of the study

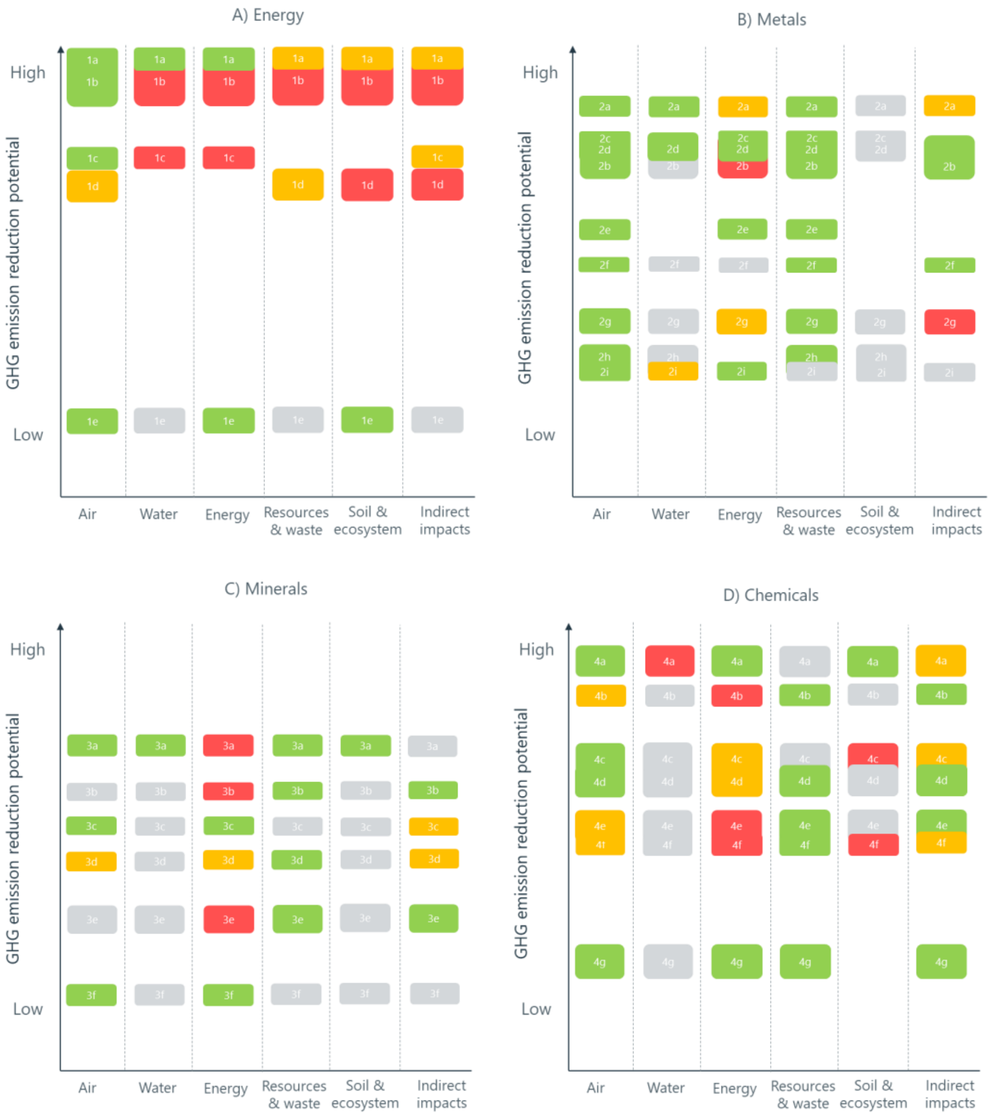


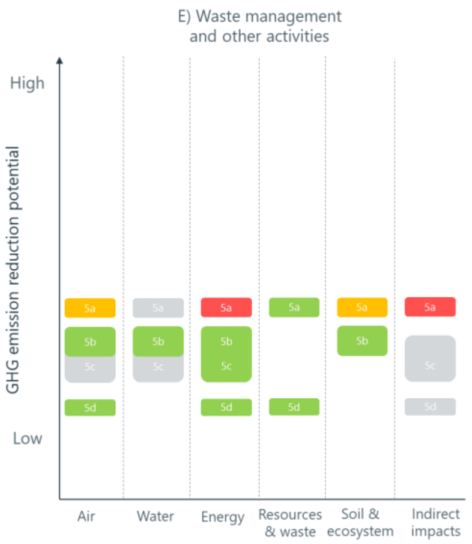
Key:

- xx Positive environmental impact(s)
- xx Negative environmental impact(s)
- xx Positive or negative environmental impact(s) – depending on certain conditions
- xx No effect or impact(s) expected

1a	Energy – Renewables	2g	Metals – Low carbon fuels	4a	Chemicals - Green H_2 (ammonia production)
1b	Energy – Carbon Capture	2h	Metals – Smelting reduction	4b	Chemicals – CO_2 valorisation
1c	Energy – Power-to-liquids	2i	Metals – Energy and process efficiency	4c	Chemicals - Electrification of heat and processes
1d	Energy – Biomass as feedstock			4d	Chemicals – Power-to-X
1e	Energy – Process efficiency	3a	Minerals – CCU	4e	Chemicals – Chemicals and plastics recycling
		3b	Minerals – Material recovery and recycling	4f	Chemicals – Low carbon fuels
2a	Metals - H-DRI (I&S)	3c	Minerals – Electric melting	4g	Chemicals – System optimisation
2b	Metals – Secondary production	3d	Minerals – Raw material and clinker substitution		
2c	Metals – Anode replacement	3e	Minerals - Low carbon fuels / waste material as fuel	5a	Waste & Other - Biomass / low carbon fuels
2d	Metals – Iron ore electrolysis	3f	Minerals – System optimisation	5b	Waste & Other – Electrification of heat
2e	Metals – CCU – top gas recycling			5c	Waste & Other – Process innovations
2f	Metals – Recycling of by-products			5d	Waste & Other – Process efficiency

Figure 3.12 Assessment of the wider environmental impacts for the main decarbonisation options and their potential for GHG emissions reductions split by industrial sector: A) Energy, B) Metals, C) Minerals, D) Chemicals, and E) Waste management and other activities





Key:

- xx Positive environmental impact(s)
- xx Negative environmental impact(s)
- xx Positive or negative environmental impact(s) – depending on certain conditions
- xx No effect or impact(s) expected

1a	Energy – Renewables	3c	Minerals – Electric melting
1b	Energy – Carbon Capture	3d	Minerals – Raw material and clinker substitution
1c	Energy – Power-to-liquids	3e	Minerals - Low carbon fuels / waste material as fuel
1d	Energy – Biomass as feedstock	3f	Minerals – System optimisation
1e	Energy – Process efficiency		
		4a	Chemicals - Green H_2 (ammonia production)
2a	Metals - H-DRI (I&S)	4b	Chemicals – CO_2 valorisation
2b	Metals – Secondary production	4c	Chemicals - Electrification of heat and processes
2c	Metals – Anode replacement	4d	Chemicals – Power-to-X
2d	Metals – Iron ore electrolysis	4e	Chemicals – Chemicals and plastics recycling
2e	Metals – CCU – top gas recycling	4f	Chemicals – Low carbon fuels
2f	Metals – Recycling of by-products	4g	Chemicals – System optimisation
2g	Metals – Low carbon fuels		
2h	Metals – Smelting reduction	5a	Waste & Other - Biomass / low carbon fuels
2i	Metals – Energy and process efficiency	5b	Waste & Other – Electrification of heat
		5c	Waste & Other – Process innovations
3a	Minerals – CCU	5d	Waste & Other – Process efficiency
3b	Minerals – Material recovery and recycling		

Figure 3.13 Assessment of the wider environmental impacts for the main decarbonisation options and their potential for GHG emissions reductions split by environmental aspect: A) emissions to air, B) water use and pollution, C) energy use and efficiency, D) resource use and waste generation, E) soil pollution and ecosystems, and F) indirect environmental impacts

1a	Energy – Renewables	2g	Metals – Low carbon fuels	4a	Chemicals - Green H_2 (ammonia production)
1b	Energy – Carbon Capture	2h	Metals – Smelting reduction	4b	Chemicals – CO_2 valorisation
1c	Energy – Power-to-liquids	2i	Metals – Energy and process efficiency	4c	Chemicals - Electrification of heat and processes
1d	Energy – Biomass as feedstock			4d	Chemicals – Power-to-X
1e	Energy – Process efficiency	3a	Minerals – CCU	4e	Chemicals – Chemicals and plastics recycling
		3b	Minerals – Material recovery and recycling	4f	Chemicals – Low carbon fuels
2a	Metals - H-DRI (I&S)	3c	Minerals – Electric melting	4g	Chemicals – System optimisation
2b	Metals – Secondary production	3d	Minerals – Raw material and clinker substitution		
2c	Metals – Anode replacement	3e	Minerals - Low carbon fuels / waste material as fuel	5a	Waste & Other - Biomass / low carbon fuels
2d	Metals – Iron ore electrolysis	3f	Minerals – System optimisation	5b	Waste & Other – Electrification of heat
2e	Metals – CCU – top gas recycling			5c	Waste & Other – Process innovations
2f	Metals – Recycling of by-products			5d	Waste & Other – Process efficiency

Significant uncertainties exist particularly in relation to technologies deployed for the production of the minerals, chemicals and metals. The data gaps derive mainly from the low maturity of the decarbonisation options which have been often developed in the context of small scale or pilot projects. For technologies with a relatively higher maturity (i.e. cross-cutting technologies and waste management options), the environmental impacts are highly dependent on their exact of characteristics and conclusions could not be drawn. For example, the impact of the electrification of processes depends on the type of energy source used for the generation of electricity that might be associated with impacts on land use (e.g. in the case of wind energy and solar panel installations) or atmospheric emissions (e.g. in the case of geothermal energy).

4. Potential contribution of IED installations to the circular economy

4.1. Introduction

A Circular Economy (CE) ensures that materials are retained within the closed loop of the economy – materials are not lost as waste, but recycled within the system. As installations under the scope of the Industrial Emissions Directive (IED, 2010/75/EU) use significant quantities of materials, it is important that they contribute to the CE. Many produce waste that is disposed of, making this material flow to be linear, but more are making efforts to change to a circular model, where unwanted material is used for other purposes (e.g. a by-product) or can be recycled by others.

The 2015 Circular Economy Action Plan (COM(2015) 614) (CEAP) stated that "The transition to a more circular economy, where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimised, is an essential contribution to the EU's efforts to develop a sustainable, low carbon, resource efficient and competitive economy". Thus, the maintenance of the value of resources is critical, i.e. that they continue to circulate in the economy (Farmer, 2019), and industry has an important role in this. Following this, the Commission Communication 'A new Circular Economy Action Plan: For a cleaner and more competitive Europe'(COM(2020)98, 11.3.2020) emphasised the need to address circularity in specific industrial sectors, as well as support for high quality recycling within toxic-free material chains. The Commission's Communication (COM(2019)640, 11.12.2019) on the European Green Deal also emphasised the need to mobilise industry for a "clean and circular economy" and, in particular, resource intensive sectors, some of which are IED sectors. Further, the Communication on a New Industrial Strategy for Europe (COM(2020)102, 10.3.2020) stressed the need for transformation in Europe's industry, although the emphasis in this case was more on product transformation, rather than process. Thus, the role of industry as a key player in delivery a CE in Europe has been stressed repeatedly in recent EU strategic policies on the CE.

It is also important to note that the recent Commission proposal for the 8th EAP (COM(2020)652, 14.10.2020) includes thematic priority objectives on accelerating the transition to a CE, along with a toxic-free environment and promoting sustainable industrial production – all of which are relevant to the issues raised in this study.

The importance of the role of industry in the CE has also been emphasised by other EU institutions. For example, the European Parliament Committee on the Environment, Public Health and Food Safety's draft report on the 2020 CEAP (2020/2077(INI), 12.10.2020) raised a number of recommendations relevant to the contribution of industry to the CE. It encouraged the Commission to introduce product-specific targets for recycled content, which would affect choices on material inputs to installations. It also stressed the importance of high quality recycling and the need for non-toxic material cycles, which would support the supply of good quality secondary materials for installations. It also recognised the barriers in the implementation of existing EU policy to a functioning internal market for secondary raw materials, such as a lack of common standards.

Many (but not all) industrial sectors are regulated under the IED. Therefore, it is important to consider not only how well those sectors are contributing to the CE through circular material flows, but also how the directive itself supports these processes.

Resource and energy efficiency have been a key objective since the IPPC Directive (the precursor to the IED) was adopted in 1996. Resource efficiency, however, did not have the focus of attention in the early years of implementation which it might have had (attention mainly focused on pollution reduction, appropriate BAT-AELs, etc.). The specific objective of circularity of materials for the CE is not explicit within the IED (as opposed to resource efficiency). However, it can be viewed as part of the primary objective of the directive –

protection of the environment as a whole. It is, therefore, important to explore what IED requires in relation to the CE, in its text, in adopted BAT Conclusions and in the practical implementation decisions of operators and regulators.

This study aimed, therefore, to provide an understanding of the "**possible untapped potential of IED installations to contribute to the circular economy**", based on expert interviews and literature. It explores what works well and what not, i.e. looking at both the positive and negative elements. Key issues are how well IED installations are contributing to the CE, whether there is potential to do more and how, and the wider role of the market and other policies. Other aspects of the interactions between IED and the CE were addressed in a more extensive study for the Commission by Ricardo and Vito (2019). This section sets out the results of our analysis.

It is important to note that the CE has a strong link to decarbonisation. This requires either that the material circularity requires less energy consumption than the production of virgin materials (or occasionally more energy) or that the energy used is decarbonised. As an example, at a global level, EMF (2019) states that a "circular economy approach could reduce global CO_2 emissions from key industry materials by 40% or 3.7 billion tonnes in 2050". Therefore, progress on supporting IED installations to contribute to the CE can also support their wider contribution to the decarbonisation of society (and thus link to the other major theme of this project described in the earlier sections, as for example illustrated by the recycling and material recovery pathways in some of the industrial activities).

4.2. Methodology

The methodology used in this work was based around two types of information gathering: a literature review and interviews with stakeholders.

The literature review has focused on recent material. This literature has included information identified by the project team (including recent BREF developments) and material supplied by interviewees. During interviews, a particular emphasis was put on asking not only for studies and reports that were relevant to this work, but also for data on material flows. This resulted in a good number of inputs. although quantitative data have been limited. Some sectors have compiled some data on some material flows, but there are often limitations (e.g. to some MS or specific materials).

It was not possible within the scope of this project to examine every IED industrial sector and activity. It was agreed not to include the waste sector as, while it is a critical sector for operation of the CE, its relationship to material inputs and outputs is quite different to other industrial sectors using materials and producing products. Also sectors such as the rearing of pigs and poultry and slaughterhouses were excluded as their operations are highly constrained on health/hygiene grounds and much of the material that they do use and produce is renewable. In conclusion, 13 major and contrasting industry sectors were included in the analysis[56]. The study includes relevant material uses and outputs by installations, although water reuse was not included as this is conceptually different to most other materials, being both renewable and the relevance of which is highly dependent on whether installations are in water rich or water scarce areas. It is also important to note that considerable development on EU policy on water reuse has already taken place since 2011.

[56] Energy sector, Refineries, Iron and Steel, Non-ferrous metals, Chemicals, Food and Drink, Cement, Lime and Magnesium Oxide, Surface Treatment with Solvents, Pulp and Paper, Rendering, Ceramics, Glass and Textiles.

A draft list of interviewees to be contacted was developed by the project team and discussed and amended by the Commission. The list included industry, MS officials (including competent authorities), NGOs and academic/research specialists. During interviews further recommendations for interviewees were also sought, e.g. to explore issues that an interviewee did not feel competent to address. The scope of the issues to discuss in interviews was also agreed with the Commission. These were tailored to different interviewees depending on their areas of expertise. During interviews, the approach taken was always to explore the issues that the interviewee seemed to have the most experience about and where they had information to provide. In total, 25 interviews were undertaken, often with more than one interviewee in each interview.

Task 4 takes account of an earlier report on "IED Contribution to the Circular Economy" undertaken for the Commission by Ricardo and Vito, published in May 2019. Task 4 does not seek to replicate this earlier, and much larger, project. Some issues in Task 4 are already included in the Ricardo and Vito report (on material flows, hazardous substances and BREFs), whereas other issues (regulatory approaches in Member States (MS)) are covered only briefly. In this report, where appropriate, key points from the Ricardo and Vito report are noted as the context for the findings here.

4.3. Results

4.3.1. Introduction

This section sets out the findings from the information gathering activities. It summarises the data, other information, views, and conclusions from the sources consulted. In exploring the CE and the IED, it is important not to confuse "IED" and "IED installation". This is critical both in trying to understand if the IED as a regulatory instrument has affected the performance of the activities it regulates as well as thinking about possible future changes.

The IED as an instrument has its limitations – what it regulates and where it regulates. These limitations are not always clear, but arise from:

- The text of the IED itself;
- The interpretation of specific issues within BREFs and BAT Conclusions; and
- The regulatory approaches and decisions in MS (what to include or not include).

What IED does or does not contribute to the CE in itself is, therefore, explored in this report for each of these points.

IED installations also undertake many decisions of operation not driven by the IED. The most obvious of these are core business factors (costs, market changes, etc.). There are also other areas of EU law affecting their activities (REACH, waste law, product safety, food safety, industrial accidents, etc.). There will also be national and local policies providing further opportunities and constraints. This may affect both what is taking place on a site as well as issues on materials within the wider value chain.

Thus, IED installations may alter performance with regard to circular material flows, but this may or may not be due to the IED as an instrument. Indeed, where the IED is coherent with such changes, it may not be evident whether IED implementation is helping to drive the change in the installation or is simply reflecting the change. This also affects recommendations for the future – what are the best mechanisms to deliver change in material flows for installations and what is appropriate for the IED as an instrument and in its practical implementation to support this.

These issues are explored further below, but it is important to ensure this distinction is recognised up front.

4.3.2. Understanding what the Circular Economy means regarding industry/IED installations

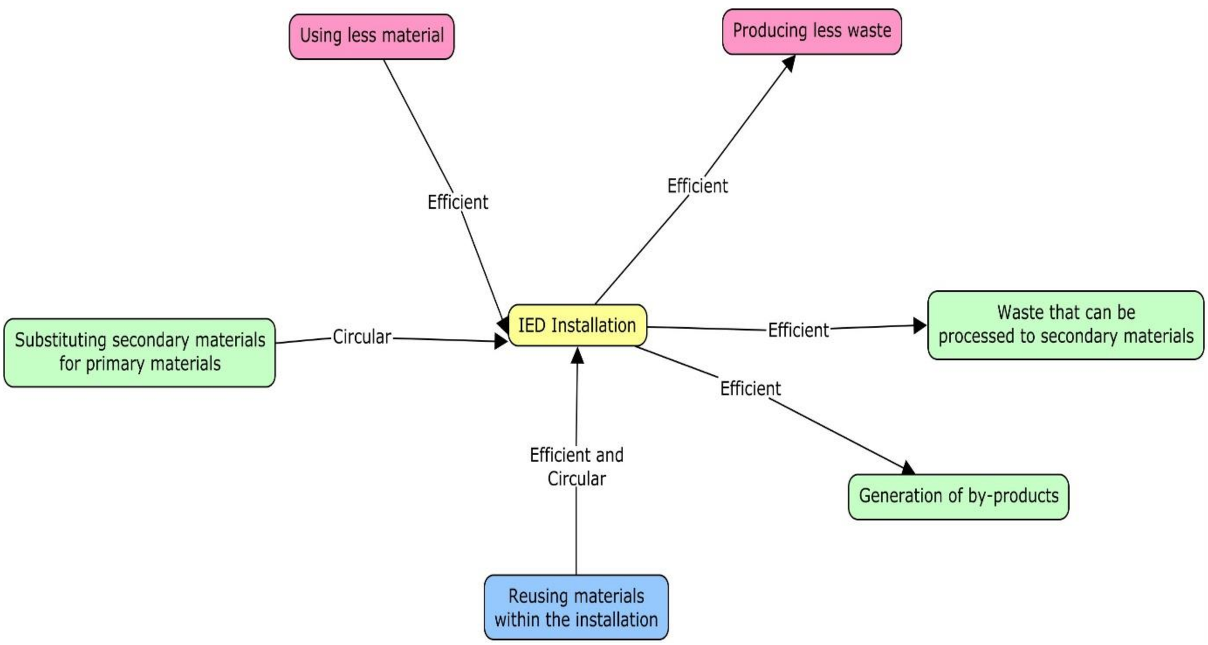
As the whole context of the work of Task 4 concerns the context of the IED and IED installations in the CE, it is useful to begin by examining any evidence and views concerning what this means conceptually.

An important conclusion from interviews and the literature is that issues concerned with making materials in industry more circular may not be labelled as "circular" or "circular economy" and it is, therefore, useful to identify where actions, such as reuse, occur or are encouraged as evidence of circularity. As Cullen (2017) notes, "in a perfect CE, the quantity of materials in "closed loops" must be conserved", with no material losses from the closed loop of the economy as a whole. Cullen also notes that it is important to take account of the energy requirements to conserve materials in a closed loop.

The IED explicitly requires that installations use resources efficiently and this has been addressed to different degrees within BREFs (Ricardo and Vito (2019) and also more below). Efficient use of resources is also at the heart of the EU Circular Economy Action Plan (CEAP). Efficiency, which is usually in the economic interest of the operator, is not, however, necessarily circularity (it could mean a more efficient linear system), but it might be assumed that resource efficiency is a pre-requisite for circularity. To a large extent this is probably true, but it is not true in all cases.

The following figure presents an overview of this distinction between efficiency and circularity for IED installations. Using less material as an input and producing less waste as an output (both per unit of production) are both examples of efficiency in material use. Using secondary materials instead of primary materials as an input and producing outputs that are either directly by-products or waste that others can convert to secondary materials are examples of circularity in material use. Within an installation the recycling of "waste" material for reuse within the installation is both efficient and circular.

Figure 4.1 A simplified view of efficiency and circularity in material flows for IED installations



A further issue to consider with regard to the CE is the use of waste material (processed or unprocessed) as a fuel for combustion. Partly driven by price, but also as a means to reduce net carbon emissions, in some sectors this has become more common as a substitute for fossil fuels. However, in the overall societal consideration of the CE, there may be ways to retain some of that material value in the economy. Therefore, whether some of this use of waste as a fuel is consistent with the objectives of the CE is questionable, or, at least, worthy of further analysis.

Overall, in contributing to the CE, IED installations should become more efficient in their material inputs and outputs and the material inputs and outputs should be as circular as possible. The "as possible" is critical and this chapter explores a variety of constraints that operators face in this regard.

There are occasions where it might make sense for an installation to use more resources in order for those resources to retain their value in the overall economy for a longer period than would otherwise be the case. EMF (undated B) stresses that a focus only on efficiency can make products more brittle, with shorter lifespans and difficult to recycle. A move away from a throwaway society has to address this. Therefore, new material models should lead to new business models and new process decisions. This point is relevant to the manufacture of final products (which only a sub-set of IED installations do). Therefore, decisions on the resource performance of an installation (whether this is considered in a BREF or by an individual permit decision making process) should take account of broader life cycle issues of products, including robustness (length of life), repairability, recyclability, etc.

It is also important to note that interviewees stressed the diversity of situations across industry with some, such as iron and steel, with very long-established use of by-products, whereas others, e.g. plastics, still developing ways to use the waste materials. Further, the answers to circular material flows may lie in wider value chains, such as working with consumers and changing business relationships. This places IED installations in context and the IED as an instrument in its context.

4.3.3. Material flows and the untapped potential

Introduction

Understanding material flows is important in order to inform decision making. If little secondary raw material is used, why is this and what might be done to improve the situation?

Some studies have been undertaken on material flows related to industry. The JRC has undertaken analysis seeking to develop indicators for material flows (Talens Peiro et al., 2018). These indicators are for the overall EU economy. However, in doing this, it is necessary to consider inputs and outputs from industry (not limited to IED regulated industry). However, it is difficult to get a clear picture with the information presented in the report. The JRC study also sought to explore the nature of such indicators, so it focused on a few specific elements. Thus, it does not assess total material flows for different components of the economy, such as industrial activities. The study focuses on the end-of-life recycling rates in society, rather than the performance of industry per se. The EU Industrial Minerals Association (IMA, 2013) produced a report on recycling of materials, including within industry. It focuses on a few selected minerals. However, when considering recycling, it sometimes examines products, rather than the mineral, e.g. on lime, it examines steel recycling. This makes interpretation of the results difficult. Nonetheless, it is possible for some minerals. Thus, bentonite is used in production of iron and steel and in paper making; the IMA concludes that the recycling rate for the former is 70% and the latter 72.5% (2016). However, these figures are due to recycling of iron and steel and of paper respectively. Therefore, again, a focus on an individual mineral is useful if the objective concerns policies for that mineral, but with regard to industrial performance, the figures for recycling by industrial sectors is largely a matter of the ability of society to collect and recycle material to feed back to industry.

Similarly, Eurostat statistics on the contribution of recycled materials to raw materials demand[57] is presented for specific minerals and it is not possible with these data to assess the performance of specific industrial sectors.

The Ricardo and Vito (2019) report includes some data on the use of resources by different sectors (Chapter 3.1.2). These data are almost entirely derived from the EXIOBASE database and, therefore, are quite old (showing trends from 1995 to 2011). Not only do these data not reflect any responses to recent CE policy, they also do not reflect any response to IED as an instrument (but may reflect implementation of IPPC).

It can be seen that studies like these on individual minerals or materials might be useful in understanding the effectiveness of the wider CE, but when looking at individual installations or industrial sectors, a more focused approach is needed.

This section explores material flows for a number of IED sectors. The results are gained from the literature and interviews and include both quantitative and qualitative information. In some cases quantitative information is significantly lacking. The aim is not simply to understand what the material flows are, but why they are like they are. Thus, different opportunities and constraints will be noted (and several of these are explored in more detail in subsequent sections). Understanding these opportunities and constraints is important in determining the untapped potential for the CE.

It is important to stress at the start that a key finding in the study has been the limited amount of information available. Attempts to gather sector-wide information have been partly successful. There are some examples either for some materials or for some companies. Also, an issue raised by some interviewees is that of commercial confidentiality. It was, therefore, sometimes acknowledged that some data were known, but could not be provided. This was also a concern from non-industry stakeholders (regulators and NGOs) and reflected similar issues within recent BREF TWG discussions. The principal concern from industry is that material flows are a key determinant of business efficiency and, therefore, are key commercial indicators. As a result, the information presented here is limited and is presented in the form of examples. However, the information does enable a number of conclusions to be reached.

The information is presented below according to different industry sectors.

Energy sector

For this sector material use involves considerable combustion of materials (solid, liquid fuels, etc.), which represents a large end use of materials. This is energy consumption and better addressed within wider energy/climate policy. Material inputs are not, therefore, an untapped potential with regard to circularity of materials, except potentially where waste is combusted and the materials are not recirculated into the economy. The main information included here, provided by industry, concerns the production and use of the materials resulting from combustion process.

For the energy sector, the total production of coal combustion products (CCPs) in the EU is more than 140 Mt (120 Mt from ash and the remainder as desulphurisation products) (Skidmore and Feuerborn, 2017). 40 Mt are from the EU 15. The higher production in the rest of the EU is due to the levels of coal use in energy production. The utilisation rate for CCPs in raw material and construction materials and for reclamation is 92% for the 40 million tonnes from the EU15, but data for the rest of the EU are not available (Table 4.1). Examples of the utilisation for different CCPs and uses are given in Table 4.2 to Table 4.4. Note that these

[57] https://ec.europa.eu/eurostat/databrowser/view/cei_srm010/default/table?lang=en

tables provide data on the distribution of use of CCPs in other applications. They do not include the CCPs that are not used (see below on their untapped potential).

Table 4.1 Production of coal combustion products in the EU in Mt (Source: Skidmore and Feuerborn, 2017)

	EU 15	EU 28
Ashes	30.1	>84
Desulphurisation products	10.3	>20
CCPs Total	40.4	>102

Table 4.2 Utilisation of Fly Ash in the Construction Industry and Underground Mining in Europe (EU 15) in 2016 (total 11.4 million tonnes) (Source: ECOBA, 2016)

Use	Percentage
Concrete addition	40.8
Blended cement	17.0
Cement raw material	16.6
Road construction, filling application	16.4
Concrete blocks	5.5
Other	3.7

Table 4.3 Utilisation of Bottom Ash in the Construction Industry and Underground Mining in Europe (EU 15) in 2016 (total 1.4 million tonnes) (Source: ECOBA, 2016)

Use	Percentage
Concrete blocks	47.8
Road construction, filling application	37.0
Cement/concrete	13.6
Other	1.6

Table 4.4 Utilisation of Flue Gas Desulphurisation (FDG) Gypsum in the Construction Industry in Europe (EU 15) in 2016 (total 7.1 million tonnes) (Source: ECOBA, 2016)

Use	Percentage
Plaster Boards	58.6
Self-levelling floor screeds	19.0
Projection plaster	10.5
Set retarder	7.5

Gypsum blocks	4.0
Other	0.3

Almost all of the remainder of the CCPs in the EU 15 are used for reclamation activities and as utilisation is high, there is little untapped potential. However, clear data for the rest of the EU are lacking. There are definitely some quality issues for CCPs for utilisation in different applications. CEN standards have been adopted for many of these[58]. Szczygielski, (undated), therefore, argues for consideration of "a transformation of properties of the anthropogenic minerals during the process of power generation, so they can meet requirements for various products" and, in particular, that they meet the wide range of CEN standards which already list CCPs as raw materials or construction products. For example, different types of processes in coal combustion plants produce different qualities of CCPs. Semi-dry flue-gas desulphurisation results in a product with variable quality and much is landfilled, in contrast to wet systems which are able to produce usable gypsum.

There is also cross-border transport of ashes in the EU. It is important to note that the volumes of trade have not declined as coal combustion has declined (possibly as MS with declining coal combustion have sought CCPs from elsewhere for the construction industry). This is relevant to discussion later in this report on consistency of approaches between MS on by-product and waste management. The need to replace the supply of CCPs in the EU15 due to their decline in production, has also led to the "mining" of CCPs produced in the past, which were landfilled as waste. The value of the CCPs is greater than the costs of such extraction.

It is also important to note the changes to the energy sector and the implications for circular material flows. The historic focus has been on use of solid, liquid, and gaseous fuels and management of waste (fly ash, gypsum, etc.). With the increase in renewables, materials issues such as recycling of wind turbines that are at the end of their lives or of photovoltaics and batteries is increasingly in the spotlight. These are very different material issues, but are not relevant to IED.

On markets for CCPs, Harris et al. (2019) summarise the standards used around the world, noting that the different legal frameworks refer to CCPs variously as waste, non-hazardous wastes, solid waste, inert waste, or resources, by-products or products and their use, as a result, varies. This variation is clearly a challenge in the marketing of these materials at international level. Further, this variation in standards may affect the wide range in rates of utilisation of CCPs: Japan 96.3%, EU15 94.3%[59], Korea 85%, China 70%, other Asia 67% and US 56%.

Therefore, in considering the untapped potential for use of CCPs, different points should be noted:

- Utilisation of CCPs in the EU 15 is very high, but not quantified for the rest of the EU.
- Cross-border transport shows increasing use of CCPs from Central and Eastern European Member States as coal use has declined in the EU 15, so indicating presumably some unused potential within those Member States.

[58] EN 13282 Hydraulic road binder, EN 14227 Hydraulically bound mixtures, EN 14227 Part 10++ Soil treatment, EN 12620 Aggregates for concrete, EN 13043 Aggregates or bituminous mixtures and surface treatments, EN 13139 Aggregates for mortars, EN 13242 Aggregates for unbound and hydraulically bound materials, EN 13055 Lightweight Aggregates, TC 104 Concrete, TC 51 Cement and Lime, TC 227 Road construction, TC 154 Aggregates.
[59] Note the small difference in earlier estimate for use of CCPs in the EU15.

- There is increasing effort being given to "mining" old landfill sites to extract deposited CCPs, so indicating that there is a market for their use.
- Decisions made on flue-gas treatment techniques used in combustion plants have a bearing on the ability of other sectors to use the CCPs.
- Other factors such as CEN standards and possible waste law affecting movement of CCPs may be a factor.

In looking at the EU as a whole there is, in conclusion, untapped potential for CCPs (though this is not quantifiable), but this picture is very different across the MS, where some have very high utilisation rates (as noted above the untapped potential for CCPs in the EU 15 is, at most, 8% of total production). Looking to the future, the decline in combustion of coal will be a major factor in the availability of CCPs and their use.

Refinery sector

The refining industry is looking to substitute feed stocks, but this is not driven by IED. Many refineries are using biobased materials and waste to manufacture products. There are plans to increase this, particularly waste from agriculture, forestry and municipal solid waste (MSW) and specific refineries have explored plastic waste, cooking oil, etc., as material sources. However, it has not been possible to quantify these developments and it seems unlikely that the level of substitution is significant. It would also not be appropriate to suggest that the unsubstituted virgin material (crude oil) feedstocks are an "untapped potential". Replacing all of this crude oil with bio-based materials could have significant consequences for the waste sector and potentially impact on land use (see also the wider environmental impacts of this decarbonisation pathway in earlier sections of the report). These may be undesirable and would link to the wider discussion on the bioeconomy, which is beyond the scope of this study. It is also questionable whether some of the material combusted would be better recycled and retained within the material cycles of the economy.

Refineries generate some waste that cannot be used or that is recovered in the installation, e.g. using catalysts. CONCAWE (2017) reported that total waste production by the refining sector in 2013 was 1.2 million tonnes, of which 43% was classified as hazardous. 94% of refinery wastes in 2013 were disposed of within the country of origin, with only spent catalysts were exported outside the EU. Recycling of refinery wastes in 2013 accounted for 34% and landfill 20%. In 1993 the figures for recycling and landfill were 21% and 40%. Other disposal included energy recovery (which declined from 1993 to 2013). Overall, between 1993 and 2013 waste to landfill from refineries reduced to only 0.5 kg for every tonne of throughput. 34% of the 1.2 million tonnes of waste produced in 2013 was recycled, which represents some material recovery. Although only 20% is landfilled, it may be assumed that some of the waste sent to energy recovery may be able to be subject to material recovery. Note that given the hazardousness of some of this waste, recovery of materials from the untapped potential would likely be costly. Therefore, there may be some untapped potential for the CE from this sector on waste outputs, but it has not been possible to quantify this, nor determine what material recovery is technically possible.

Iron and steel sector

The iron and steel sector in the EU produces around 160 million tonnes of steel per year and uses around 100 million tonnes of ferrous scrap (secondary raw material) a year, coming from the waste sector[60]. Steel

[60] https://www.eurofer.eu/issues/environment/circular-economy/

production processes use primary and secondary raw materials and reuse material in installations, so there is internal circularity.

Cullen et al. (2012) noted that globally the recovery rate for steel end-of-life scrap is greater than 80%. Importantly they examined the internal recycling of scrap within steel production. Historically significant quantities of scrap were produced during forming, casting, and fabrication processes, with most of this recycled. However, improved processes have reduced the amount of scrap produced (e.g. average yield for continuous casters today is 97%, an improvement over the older technology of solid ingot casting followed by an extra rolling step, which has a yield of about 91%). Thus, material efficiency has improved. However, understanding the quantities is not straightforward. Eurometaux (2016) noted that MS calculate their recycling rates differently, creating inconsistencies. Also it is important that the outcomes of recycling are clear with regard to which materials or substances are recovered and can substitute for primary material for input into new products.

The limitations of using ferrous scrap concern quality and quantity, in particular the grade of steel that clients require to be produced. Stainless steel or alloys for the aerospace industry need high quality steel so not all scrap can be used. However, other steel products can be produced using low quality scrap as input material. Overall, there is often not enough scrap to meet the demands of the sector. However, some very low-grade material still cannot be used, and this tends to be exported to third countries that are able to process this material due to the lower production costs. In theory, if the quality of scrap could be improved (increasing copper quantity and reducing unwanted material), more scrap might be used in EU. This improvement of quality would be an issue for waste collection and processing due to the economies of scale and due to the need for improved separate collection (so is not usually captured within the IED).

Although use of secondary material is important to reduce primary material use, improved recycling of materials within an installation can also reduce material use. NEPA (2018b) reports on an example of action taken by Sidenor, a steel production plant in the Basque region. It launched a "Refractory Close Loop Project" to reduce part of its 5,000 tonnes/year refractory waste, save money and maintain or increase steel quality. This included increasing high quality magnesite recycling rates from 8% to 75%. There are still waste challenges, but, apart from material benefits, the recycling has saved €0.8 million per year in materials. The success factors identified were:

- A new business model where suppliers needed to commit for improvement (achieving 50% of the results).
- Optimisation of furnace oven control parameters making it possible to monitor process parameters in detail.
- Availability of highly skilled and experienced refractory experts and commitment of interdisciplinary team members.
- Following up by the permitting authority.

In conclusion, the sector readily uses secondary material as a source for iron and steel production. It could use more, if it were available. The limitations are in the wider waste collection system, rather than any untapped potential in the sector. Low grade scrap is exported to be recovered elsewhere, so technically this is untapped potential, but the economics of recovery do not justify its recovery in the EU.

On material outputs, there are a lot of cogenerated residues, either waste or by-products. Most are functional to the production process, e.g. from dust filters or slag. These require internal procedures to recover and recycle materials, but many are sold as by-products to road construction, cement production, water purification or others uses. Table 4.5 presents data on the use of ferrous slag in the EU in 2016. It can be seen that 5% of ferrous slag was sent to landfill. This could represent an untapped potential. However, as described later in this section, there are pressures on the current use of slag in MS such as Sweden due to the presence of hazardous substances in the slag. This pressure may reduce the amount used.

Table 4.5 Utilization of ferrous slag in 2016 in the EU (total 40 million tonnes) (source: Eurofer)

Use	Quantity (tonnes)
Road construction and hydraulic engineering	14,000,000
Metallurgical use and interim storage	4,400,000
Cement, concrete, additions	20,700,000
Fertilizers	500,000
Other (e.g. mineral wool, water treatment)	2,000,000
Final deposit to landfill	2,600,000

Non-ferrous metals sector

Wyns and Khandekar (2019) undertook an examination of the sector with regard to climate neutrality, including the extent of secondary material use as a key factor in contributing to this. The sector encompasses a wide range of base metals as well as precious, speciality and rare earth metals. It is important to note that the quantities of metals processed in the EU vary significantly. Total primary production of non-ferrous metals in 2016 was 7.4 Mt. Of this, copper was 2.3 Mt, aluminium 2.2 Mt, zinc 1,7 Mt, lead 436 kt and nickel 211 kt. By total mass, this accounts for most of the total production, with other metals representing low production volumes. This affects an understanding of any untapped potential of secondary material use – small volumes of rarer metals may be a significant potential, but the same volume for copper, for example, might not be considered significant.

It is also important to note that the sector in the EU has strong links with global trade; material circulation for many metals has to be considered in this context. For example, the EU accounts for 1% of global mining production for base metals, but primary smelting and refining accounts for 6% of the global volume (indicating the importation of ore/recycled material). In contrast, the EU sector accounts for 24% of global recycling. As a result, 50% of Europe's domestic supply of base metals comes from recycled sources. Overall, the sector is currently able to extract and recycle about 20 metals to reasonable amounts and achieves very small recovery rates for several other metals. For some metals, e.g. aluminium, recycling is far less energy intensive than primary production and is, therefore, highly attractive (Cullen and Allwood, 2013).

It should, however, be noted that the recycling and processing activities involves a wide range of smelting, transformation, refining, and recycling operations, some of which are IED installations and some not, but companies co-operate to collect and extract different metals. For example, the Flanders "metal valley" has a number of different companies that specialise in the extraction of different metals. Some also co-operate in the exploration of new techniques for metal extraction from waste. This means that improving recycling and recovery of a metal may require action by more than one actor and one or more of these actors may not be captured by regulation under the IED.

There are challenges to the recycling of non-ferrous metals in the EU. The wide range of metals is used for an even wider range of applications, such as buildings, transportation, electronics, energy generation and transmission, connectivity and strategic sectors such as defence. For some uses, there are high recycling rates (such as collection of waste from businesses rather than consumers). The quality of waste from business also tends to be higher. There are high recycling rates from construction (95%), end-of-life vehicles (90%) and lead batteries (99%). However, rates of recovery from waste electrical and electronic equipment (WEEE) are only 35%. There is significant leakage, including in illegal waste shipment abroad. In 2017 the EU exported 2.07 Mt of scrap and imported 0.91 Mt (copper, nickel, aluminium, lead and zinc). This is a significant net loss to the European recycling economy. Much of this was sent to markets such as China. There is, therefore, potential to increase metal recovery in the EU if collection and enforcement were to be improved.

The following table provides information on the recovery rates of different metals. There are some additional metals recovered, but the rates are below 1% due to technical and economic constraints. The recycling means that about 50% of base metals production in the EU is from secondary material (globally excluding the EU this is only 18%), done via secondary production, using recycled metals.

Table 4.6 Recovery rates for different metals in the EU (source: Wyns and Khandekar, 2019)

Metals	Recovery rates in the EU (%)
Chromium, titanium, manganese, cobalt	Above 50
Gold	20
Silver	55
Platinum	11
Palladium	9
Iridium	14
Rhodium	9
Ruthenium	11
Molybdenum, magnesium, iridium, tungsten, cadmium, antimony, mercury	1-25

There are challenges to the recycling of non-ferrous metals in the EU. The wide range of metals is used for an even wider range of applications, such as buildings, transportation, electronics, energy generation and transmission, connectivity and strategic sectors such as defence. For some uses, there are high recycling rates (such as collection of waste from businesses rather than consumers). The quality of waste from business also tends to be higher. There are high recycling rates from construction (95%), end-of-life vehicles (90%) and lead batteries (99%). However, rates of recovery from waste electrical and electronic equipment (WEEE) are only 35%. There is significant leakage, including in illegal waste shipment abroad. In 2017 the EU exported 2.07 Mt of scrap and imported 0.91 Mt (copper, nickel, aluminium, lead and zinc). This is a significant net loss to the European recycling economy. Much of this was sent to markets such as China. There is, therefore, potential to increase metal recovery in the EU if collection and enforcement were to be improved.

It should also be noted that there are considerable quantities of metals that are in long-term use in products (such as buildings). These will become available for recycling in the future. As a result, it is expected that the volumes of aluminium scrap in the EU will increase from 4.5 Mt in 2015 to 9 Mt in 2050 and copper scrap will increase from 1.6 Mt to 2.7 Mt over the same period (Wyns and Khandekar, 2019). They suggest three actions to achieve higher levels of metals recovery:

- Reduce the amount of scrap exported (legal and illegal), as well as invest in recycling of new end of life products, such as photovoltaics.
- Improve the recycling of end of life products to ensure metals are not lost.
- Improve the techniques for recovery of metals from WEEE – from better sorting and treatment to extraction – as it is an energy intensive process.

The sector is exploring new technologies (hydrometallurgical, pyro, etc.) to recover greater volumes of metals and new metals from waste streams. As a result, the current capacity to extract metals from received waste is unlikely to represent future capacity (even if the quantities and nature of the waste does not change). Secondly, as noted above, there are significant quantities of waste not retained for recycling by the sector. If measures are taken to restrict loss of this waste (especially illegal activities), then this would increase the volumes of metals extracted.

The collection of additional waste represents untapped potential within European society, but not untapped potential due to decisions by IED operators. The development of new techniques for extraction would represent future new potential, rather than existing untapped potential for secondary material use.

The sector also produces waste. This is generally of two types – slag from extraction of metals from ore and sludge from WWTPs. The slag can be used for different purposes, largely in construction (processed by grinding), such as buildings, roads, etc. Some is used in other sectors, such as cement manufacture. It is important to note that slag contains trace amounts of metals, some of which may be classified as hazardous. The uses of slag may ensure that these substances are not released into the environment. However, as policies for a non-toxic environment are developing (see also the section on ferrous metals and the section on national policy), constraints may arise on the use of such slag (at least in some applications). Sludge from WWTPs in this sector also tends to contain significant quantities of metals and other contaminants. Some installations can internally recycle some of this material, but most goes to landfill. In conclusion, there is possibly some untapped potential for extraction of material value from WWTP sludge if new techniques for extraction are developed. Regarding slag, there may be future challenges to retain the levels of use of the material at the current rates.

Chemicals sector

The chemicals sector is a diverse sector. The sector produces consumer chemicals, petrochemicals, basic inorganic chemicals, polymers (including plastics), speciality chemicals and more. The sector is covered by several BREFs and the operation of individual installations can shift radically over time (e.g. with the changes involved in batch production). Given the limitations of this study, this section provides information on the sector as a whole and, within the sector, specific information on plastics production.

With regard to the CE, the most relevant issues are those concerned with resource use. The sector is able to use a variety of waste and/or secondary raw material inputs, e.g. concentrated acids that have become weaker during use, or by breaking down waste polymers (e.g. plastics) into their constituent molecules, thus providing new raw materials.

Few studies have examined the chemicals sector as a whole. For example, CEFIC (2020) in its presentation of facts on the European chemical industry lists several environmental issues, but all of these concern emissions to air (GHGs or other pollutants) and none concern material use, waste, etc. Levi and Cullen (2018) examined material flows of chemicals in the economy more widely, but concluded that doing this was hampered by the lack of any sufficiently detailed, globally balanced and publicly available map of materials in the chemical sector. However, Accenture (2017) did examine the sector as a whole by conceptualising the potential of a closed loop for chemicals in the EU, with the sector producing products and then being used and recovered in different ways to be reprocessed by the sector. It concluded that up to 60 percent of the molecules provided by the European chemical industry to customer industries and end-users could be re-circulated if all available measures were optimised. To do this, it would include three important steps:

- Improved product design to enable products to be reused (or chemicals easily recovered). Some of this is within the control of sector (but a product quality/standard issue, rather than an IED issue), but much product design is by manufacturers receiving material from the sector and is not under the IED in any case.
- Mechanical recycling to collect, separate and prepare material recovery. This is undertaken by different parts of the waste sector, rather than the chemicals sector.
- Chemical recycling where the recovered materials are broken down, such as breaking up long-chain hydrocarbons into precursors via processes such as catalytic cracking or plasma gasification. This would be done by the chemicals sector.

Therefore, some actions to further chemical recycling in the EU are within the control of the sector, while others are not. Further, of those actions within the potential control of the sector, some are not captured by regulation under the IED.

Accenture (2017) compared the potential quantities that could be recovered and the results are presented in the following table. Chemical recycling would recover about 20% of the total potential. At one level this represents untapped potential by the sector. However, realising its potential requires the materials to be recovered and separated by the waste sector (and others) in the first place. Thus, the untapped potential can only be realised once other conditions are put in place.

Table 4.7 The potential recovery of chemicals in the EU for the CE using different methods (source: Accenture, 2017)

Action	Potential mass of chemicals that can be recovered (Mt/annum)
Product design leading to reuse	17
Mechanical recycling recovery chemicals	19
Chemical recycling	8

Accenture (2020) did further research on the material pathways of different chemicals produced by the chemicals sector, which suggested that these figures might be revised. They concluded that of the 140 Mt/annum of chemical products produced in the EU 28, only 101 Mt/annum reached their end of use endpoint. Further, of this 101 Mt, 70% is not accessible for recovery as the chemicals are either retained in a product or they are dispersed into the environment. Accenture (2020) concluded that only 31 Mt/annum was accessible (and 22 Mt/annum of this is currently incinerated or landfilled). This suggests the potential (if all incinerated and landfilled material was recovered) is slightly lower than suggested by Accenture (2017), but it is possible that improved product design may improve the figures. In any case, the untapped potential for chemical recovery by the sector (if the sector is supplied with the material), while important, is less than 10% of the annual total production.

With regard to plastics, Plastics Europe (2019b) published quantitative information on the production, use and recycling of plastics in Europe. The chemicals sector produces around 61 Mt/annum of plastic raw material. Of this, 4.9 Mt are recyclates. This is passed to those making plastic products (such as small injection moulding companies) which produce 55.2 Mt/annum. Note that some of the raw material is exported and plastic manufacturers import some plastic raw material (but much remains in Europe). Consumption of plastics by consumers is 55.4 Mt/annum. Currently much remains in products, but the waste sector collects 29.1 Mt/annum. Of this, 7.7 Mt goes to landfill, 12.4 Mt to EFW and 9.4 Mt to recycling (some of which is exported). More recent figures published by the Circular Plastics Alliance (Circular Plastics Alliance, 2020b) are that 21 Mt of plastic waste are collected each year from the biggest plastics-using sectors in Europe (agriculture, automotive, construction, packaging, electronic and electric). From this, 9.2 Mt of plastic waste were sorted for recycling, 7.5 Mt were sent to recyclers in Europe and from this, 5.2 Mt of recyclates for use in new products was produced each year.

From this it can be concluded that, from the perspective of the life cycle of plastics in Europe, there is untapped potential for European society as a whole to recover material and recycle the polymers. However, it is not clear what the direct untapped potential is for the chemical sector. It is worth noting that a greater focus on EU plastics waste management is being driven by the response to the China waste ban (European Commission, 2018). Expectations are for much greater volumes of plastics being recycled within the sector. This suggests more material will be made available to the chemicals sector. This is an untapped potential, but not necessarily one in the control of the operators of the chemicals sector installations.

It is also important to note that 46% of recyclates in the EU28 plus Norway and Switzerland are used in building and construction applications (Plastics Europe, 2019b) that require high-performance and durable products, although other uses include packaging and the agriculture sector. Therefore, recycling of material is not equal across different plastic products and potential markets need to be considered.

It is worth noting that an action to be taken by the Circular Plastics Alliance (established by the European Commission) is to explore the untapped potential for plastics recycling (Circular Plastics Alliance, 2020a). Much of this will concern waste collection and processing, but it may also consider the opportunities and constraints within the chemicals sector to process material received. However, for recycling of plastics, better information is needed on the content of the plastics and products and traceability needs to be expanded with respect to content and previous use (Royal Swedish Academy of Engineering Sciences, 2020). Chemical recycling (plastics broken down at the molecular level) makes more plastics recyclable and provide high-quality recycled material.

The European standard EN 15343:200712 (Annex D, p17) addresses plastics recycling traceability and assessment of conformity and recycled content. It thereby provides support to key circular economy considerations such as sourcing and quantified recycled content. In addition to this standard it is important to check if certain chemical substances are contained within the recycled materials. Legislation exists to limit certain substances in products (e.g. substances of very high concern in REACH, and specific hazardous substances in RoHS), but the current situation shows that some product manufacturers wishing to use recycled materials such as plastics have corporate approaches that are choosing to go beyond legislation. An example of such a standard is CEN/TS 16861:2015 (Annex D, p11) on recycled plastics and determination of selected marker compounds in food-grade recycled PET[61].

Finally, with regard to material outputs, the chemical sector produces very little waste. Where "unwanted" material outputs occur alongside products, these are generally either recycled within the installation itself or they are made available as by-products. Some are used for energy recovery. The only waste more commonly arising from this sector is sludge from waste water treatment plants. In conclusion, there is little untapped potential for the CE from this sector regarding the material outputs.

Food and drink sector

For the food and drink sector, it is important to note that, due to strict hygiene and food standards, the sector is largely unable to use secondary materials directly as it is essential that operators have confidence in the high quality of materials used. This does not mean that secondary material does not enter the sector, but this would be via transformation in other sectors. For example, plastic waste processed into constituent polymers by the chemicals sector may be used as "new" plastic packaging by the food and drink sector, but this essentially concerns the ability of the chemicals sector to recycle material, rather than the food and drink sector. Therefore, it would not be appropriate to state that there is untapped potential for use of secondary materials as material inputs for this sector.

For the sector, limited data have been obtained on waste arisings and what is done with these. The following two tables provide examples from the UK and Belgium. In the UK, food waste arising at manufacture is about 16% of the total food waste production and this reduced by around 395,000 tonnes between 2011 and 2018 (a 21% reduction) (WRAP, 2020). The table shows that the majority of waste is processed into usable material

[61] It is also important to highlight the information contained on specific substances in the ECHA SCIP database - information on Substances of Concern In articles as such or in complex objects (Products) established under the Waste Framework Directive.

and only a small fraction is sent to landfill. The latter has been helped by the requirements on biodegradable waste established in the Landfill Directive.

The data for Belgium (source: Fevia, the Belgian food industry association) examine the material outputs from the sector. Of the total material output of 24,703,000 tonnes, most is food. In addition, most of the material that cannot be processed as food is converted to animal feed. A small amount goes to other uses and, again, only a tiny fraction has to be treated as waste. Interviews indicated that this pattern was found more widely in the EU. It shows that little material from the sector is treated as waste. However, while material outputs are used for other purposes, these are end uses, rather than circular.

In understanding the untapped potential, a further conceptual consideration needs to be explored for this sector. At the start of this section, we stated that, for material outputs, activity consistent with the CE would be to help retain materials within the economy (reprocessable waste, by-products, etc.). However, the materials contained in the products are not maintained in the economy – they are consumed. Even at highest quality (food waste being converted to human food), the material is consumed. This makes a hierarchy of uses (e.g. comparing consumption to composting) more conceptually difficult. There is some thermal recovery and very limited landfilling. These materials may represent some untapped potential (e.g. to provide material for agricultural fertilisation). However, some of this loss may be required as hygiene standards may prevent material use (e.g. if some contamination occurs), so the exact untapped potential is not clear.

Table 4.8 Food waste utilisation for the manufacturing sector in the UK compared to total food waste (source: WRAP, 2020)

	Food waste utilisation – UK Manufacturing sector (Mt)	Total food waste in UK (Mt)
Food	0.8	>6.4
Redistribution and animal feed	0.65	>1.0
Anaerobic digestion, composting	0.44	>1.9
Thermal recovery and landspreading	0.11	>4.4
Disposal (landfill and sewer)	0.002	>3.2

Table 4.9 Material outputs from the food sector in Belgium (source: Fevia)

Ranking by Fevia from sustainable to non-sustainable material destination	Estimated production (kt)	Percentage of total
Food	18,500	74.9
Feed	4,500	18.2
Non-food raw material (biobased economy)	500	2.0
Fertiliser	400	1.6
Secondary useful application (e.g. use as building material, energy)	800	3.2
Incineration or landfill	3	<0.1

Cement sector

European cement production was around 190,000 kt in 2018. The industry uses waste as a resource input both for material inputs and energy.

Concerning materials, about 5% of the raw materials used in the production of clinker in Europe consists of recycled material and ashes from fuel, totalling about 9 Mt per year. The main recycled material inputs come from fly ash from coal-fired power stations and slag from blast furnaces. For cement processes, it is very important to ensure material inputs meet minimum quality requirements. The sector has tended to ensure this by establishing its own quality controls, with some processing of received material (removing metals) and laboratory testing of materials (toxic metals, radioactive substances, etc.). Ideally the sector would benefit from quality agreements with suppliers.

The sector does not receive waste cement from construction and demolition (C&D) waste as an input as this is not technically appropriate. However, concrete is 100% recyclable as aggregates. If all concrete C&D waste in Europe were recycled, this could supply 10% of total demand for aggregates for all applications, but this level of recycling is not technically possible yet (CEMBUREAU, 2020).

However, some of the sources of materials that are used are from sectors that are declining, such as coal-fired energy production. Thus, it is questionable whether the current levels of secondary material use can be maintained (at least from sources within the EU). It would, therefore, not be appropriate at this stage to conclude that there is further untapped potential in this regard.

The other aspect of co-processing by the cement sector is the use of different types of waste as an alternative to fossil fuels in combustion for energy generation. These wastes include used tyres, wood, unrecyclable plastics, chemicals and some MSW. Over many years this has formed a focus of debate on permitted emission levels, etc. Indeed, the BAT Conclusions for this sector (Commission Implementing Decision 2013/163/EU) provide considerable detail on the quality of such waste to be used as fuel, but do not question whether this is consistent with the best use of those materials. This trend is driven by two factors – a pressure to reduce GHG emissions and economics (for waste companies compared to other disposal routes). A report by Ecofys (2017) showed a wide variation in such co-processing of fuel across the EU, but concluded that the average substitution rate of fossil fuels by waste was 43% and this could increase in future to 60%.

From the perspective of the CE, such co-processing for energy generation may be questioned. Is the combustion of such waste consistent with the maintenance of these materials within the EU economy?[62] It is important to note there is a wider debate on the appropriate levels of incineration/EFW consistent with the CE in waste management in the EU. Sectors using significant quantities of waste as a fuel may refer to such sources as “non-recyclable” waste. However, it is not clear that all such sources are not recyclable. Furthermore, technical developments will result in new ways to recycle waste and maintain material value.

It is not possible in this study to analyse the types of waste used as fuels by the sector, nor the likely future ability to retain these materials in an EU CE. However, it can be concluded that there is some potential for the sector to contribute to the CE by not using some of this waste as a fuel in the future. Of course, this raises questions about GHG emissions and decarbonisation (see the earlier sections of this report where the use of alternative/waste materials replacing fossil fuels is identified as a decarbonisation pathway for the sector).

62 Note that the use of waste as a fuel in the sector is promoted in the European Circular Economy Stakeholder Platform as part of the CE. Whether it is the best use of this waste, or not, it cannot be described as “circular” in terms of material use.

With regard to waste arisings from the sector, cement kilns produce low levels of waste. The BAT Conclusions address one of the more important waste arisings, dust, and this may be recycled back into the production kilns as internal material circularity. Some might be blended with finished cement products. However, there can be issues with the quality of dust (e.g. metals) and this has to be taken into account. However, overall there is little untapped potential regarding waste arisings for the CE within this sector.

Surface treatment with solvents

In this study it has not been possible to quantify the use of secondary materials as an input to this category of installations. This does not mean that secondary materials are not used. However, where waste solvents are recovered (from these installations or other sources), if they are recycled into usable solvents, this tends to be within the chemical industry or dedicated waste treatment plant and users may not necessarily distinguish purchases from primary material sources. Solvent recycling can also lead to savings of up to 90% of carbon dioxide emissions (ESRG, undated).

Installations produce waste solvents. The draft STS BREF (JRC, 2019d), on reducing such waste, focuses largely on the use of high-efficiency techniques (and on toxic contaminants in waste solvents). These reduce material consumption, waste and emissions. An issue largely specific to the use of organic solvent is that one cause of the loss of material is the evaporation of solvents into the air. Of course, this is the cause of VOC emissions and much attention has been given to the adoption of techniques to reduce these in the STS BREF. ,It is important to highlight that these technical improvements over the years are not only consistent with the protection of air quality, they also retain solvents as materials and, therefore, contribute to the CE.

Waste solvents can be recovered and recovery has improved significantly since the adoption of the Solvent Emissions Directive in 1999 and provisions taken forward within the IED. It is important to note that, as with some other materials, "recovery" is used to refer to both recovery of energy through combustion and recovery of the solvent for use in other applications. The latter is consistent with the CE. Some techniques, such as with heat set printing, can include recovery of solvents through condensation. Many smaller installations may collect such material, but do not want to perform recovery themselves. Some larger printers do use the recovered solvents in combustion, such as for heating in drying processes. Some larger installations have a distillery as a secondary process to recover the solvents for reuse.

There is concern that full material recovery as a secondary activity within an installation may not be economic (at least in some cases). Therefore, material recovery would need to be undertaken by others, such as the chemical sector, which would depend on the economics for those installations (along with consistent quantities, known composition, etc.).

Data on overall amounts of waste solvents produced and recovered show that there is potential for increased material recovery. JRC (2018a) found that total spent solvents in 2014 were 2,320 kt. Of this, 1,780 kt were treated; 520 kt was used for energy generation and 650 kt used for other recovery purposes. In conclusion, there is, therefore, some untapped potential to ensure that all waste solvents are provided to those that can recover them as materials (beyond what currently occurs), but the extent of this gap has not been possible to quantify.

Pulp and paper sector

The pulp and paper sector has a different relationship to the CE than many other sectors considered in this section. This is for two reasons:

- The primary material used is a renewable resource (unlike other sectors which are dominated by non-renewable resources).
- The sector produces waste, but this waste production is increased when it uses recycled material. This relationship between secondary material use and waste production is different to other sectors.

The use of a renewable resource, wood, raises questions about the sustainable management of forests, carbon neutrality, etc., which are beyond the scope of this study. The share of wood used by the pulp and paper industry from the EU reached 84.2% in 2019 (the remainder was imported). Of wood consumed, 24% is residues from saw mills and wood working industries, which represents a significant share of secondary material input.

The sector is important in the recycling of paper and board. In 2019[63], members of the Confederation of European Paper Industries (CEPI) produced around 90 Mt of paper and board and 38 Mt of pulp (CEPI, 2019), of which 54.6% were based on recycled fibres – compared to 53.1% in 2018. However, it is important to note that not all paper collected for recycling can be recycled and the quantity collected includes materials that are not recyclable. The share of unusable materials depends on the actual sorting and collection of used paper and this varies between MS. Thus, the volume of recycled fibres actually used to produce new paper is lower than the volume of paper fit for recycling.

The production process for paper recycling is the same as the process used for paper made from virgin fibres, except that recycled paper has to be sorted and cleaned first. For certain papers (e.g. printing and writing paper and hygienic products) ink has to be removed. Waste paper is 'slushed' into pulp and large non-fibrous contaminants (e.g. staples, plastic) are removed. The fibres are cleaned and the pulp is filtered and screened several times before papermaking. Depending on the grade of paper produced, virgin pulp may be added. Papers such as newsprint and corrugated materials can be made from 100% recycled paper.

Waste paper is currently recycled in Europe at a rate of 72% (2019) (EDPR, 2019) (and paper-based packaging is recycled at a rate of 84.6%). These rates may increase, but the potential additional amount of secondary material generated within the EU is limited. It might be possible to import waste paper, but this may raise questions of transport impacts. In relation to supply within the EU, the limitation is external to the control of the operators of the installations.

The sector produces waste. The majority of this waste arises from the processing of waste paper for recycling (Monte, et al., 2019). The different wastes produced include sludges from fibre processing (e.g. de-inking), lime muds, as well as ash from combustion processes used for drying. Further, production of virgin pulp not only produces less waste, the waste is also less contaminated. The sludge waste produced has a high water content. A preferred method of disposal is through incineration, but the drying of the sludge to make this suitable can require energy. Other options may include pyrolysis, gasification, land spreading, animal bedding, composting and reuse as building material. There is also research into further use of waste sludge, such as conversion bioplastics, bio-hydrogen gas and fish feed.

The generation and, in particular, disposal and/or end-use of waste from the sector varies across the EU. It is also relevant to note that some end uses, such as in agriculture, are not part of circular material use per se, but they may be the best option given that organic matter should be introduced to land and this waste from a renewable resource is as good as any. However, there is clearly research on potential new uses for the unwanted material and, therefore, there is potential for more circularity of materials arising from the sector. Some of this may be in the control of the operator (i.e. by-products from the installation itself), while for other waste it will depend on the users of that material.

Rendering sector

The rendering sector is one of the oldest industrial recycling sectors in Europe; its material inputs are waste. There has long been a need to process unwanted cadavers and, since the 19th Century, the first industrial

[63] https://www.cepi.org/paper-industrys-recycling-performance-reaches-highest-level-ever-in-2019/

cookers have been used to do this. From this, fats and proteins have long been produced and used for many purposes. As a result, regulation at national level goes back many years (e.g. to 1917 in Germany). The quantities of material input into the sector in the EU are (EFPRA, 2016):

- 328 million cattle, sheep, goats, and pigs are slaughtered each year in the EU. 6 billion poultry are slaughtered each year in the EU. 34% of pigs, 42% of cattle and 25% of poultry is not used for human consumption and is rendered.
- Additionally, 2.4 million tonnes of fallen stock is removed from farms in the EU each year and rendered.

In conclusion, given the nature of the sector, there is no untapped potential regarding material inputs.

Almost all of the material taken in by the industry is processed to valuable by-products. There can still be some small amounts of waste, such as when it processes animal material in plastic packaging, but this remaining material can be used in energy recovery. The by-products produced are fats and proteins and were until the late 1990s mainly used in feed or for technical applications like soap, surfactant, and detergent production. Today they can be used for different purposes depending on the risk/hazard category they fall into (see later discussion on related health legislation). The quantities produced in the EU are listed below (EFPRA, 2016).

After rendering, 12 Mt of material is produced each year which is **low risk**. This is used for:

- 186,000 tonnes of edible fats fit for human consumption.
- 1.67 Mt of pet food.
- 575,000 tonnes of oleochemicals (fats and lipids) for use by the chemicals industry. These are used as ingredients for household goods such as cosmetics, lubricants, and cleaning products.
- 950,000 tonnes of animal feed (Processed Animal Protein (PAP) have 10% of the GHG emissions of soya meal).
- 99,000 tonnes of fish feed. In the EU, use of PAP in aquaculture was restricted until 2013. Since then, non-ruminant PAP has been permitted. Rendered animal fat and oil have been available to use in aquafeed for many years without any restrictions.
- Fertiliser (rich in phosphorous).
- Liquid fuel (biodiesel).

After rendering, 5 Mt are **high risk**. This is used for:

- Liquid fuel (biodiesel).
- 1 million tonnes of solid fuel.

In conclusion, the sector produces a small amount of waste (e.g. from plastic packaging). This could be viewed as an untapped potential for material recovery, but this would need to be undertaken during waste processing or possibly within chemical installations able to manage waste plastics. Given the nature of the inputs (waste packaged food) and hygiene standards, there are limitations in what the sector may do to affect the quality of the waste produced. Therefore, the ability to realise any untapped potential will depend on the technical (and economic) characteristics of the sectors receiving the waste. For safety reasons, incineration may be the most appropriate destination for such waste.

Rendering has been a service and production business for decades. On the one hand, highly perishable goods are collected and removed from farms and from the meat industry; on the other hand, it produces valuable products for several markets. Contrary to the old system of uncontrolled or controlled burying (e.g. by knackers) with unwanted emissions to air, soil and water, this system creates safe products useable in different markets. The obligatory processing of that material has become more relevant (even though historically this was always the case), subject to a number of strict EU health regulations.

It should be noted that the SA BREF (2005) for the rendering sector is now 15 years old and feedback indicates that it is "only basically referred to" by operators. Its conclusions, therefore, are not a major driver to change in the industry. However, the review of the SA BREF started in 2019.

Ceramic Sector

The ceramic sector is a diverse sector manufacturing a range of different products. Cerame-Unie (2020b) emphasises the importance of ceramic products within the CE as they have high durability and require little or no maintenance. Also given the inert nature of fired clay, ceramic products can be reused, recycled or recovered after their end-of-life. Overall, the sector uses a wide variety of secondary materials from many other industrial sectors in its manufacturing and has adopted practices to reduce waste to very low levels, mostly through the recycling of waste material within the production processes themselves, but also through the production of by-products for other sectors.

Cerame-Unie (2020a) explored secondary material uses and waste outputs for different ceramic sectors. In summary these are:

- **Bricks and clay blocks**: secondary scrap material can be reused in the process, such as the dust from the grinding of clay blocks to produce new clay blocks. Some of the pore-forming agents used to optimise thermal insulation properties are secondary raw materials from waste organic sources, e.g. saw dust, rice husks or sunflower seed shells. Ash products, industrial minerals, etc. and minerals can be also used in the production process as secondary raw materials. Broken clay blocks can also be crushed and used in the production of concrete blocks.
- **Wall and floor tiles**: Cerame-Unie (2020a) highlights a Spanish manufacturer which has developed a new type of ceramic tile, incorporating a high content of ceramic waste. Other process wastes from power plants or glass manufacturing are also considered. Also, the manufacturing processes enable the recycling of all types of ceramic wastes. Results have reduced waste production by 20% (along with energy savings). In Italy, a manufacturer is developing ceramic tiles made from 70% to 85% of recycled materials from urban and industrial wastes. These tiles have similar or improved mechanical properties with respect to traditional tiles.
- **Refractories**: manufacturers can produce products that contain between 20% and 80% of recycled material coming from various industries (e.g. iron, steel, metallurgical industries, alumina, ceramic, cement). Materials are then sorted, crushed, dried and possibly milled by the manufacturer.
- **Sanitaryware**: porcelain shards are crushed and ground before being sent as by-product materials to the feldspar extractive industry. Plaster moulds are used as by-products by the gypsum extractive industry for quarry restoration or production of aggregates.
- **Tableware:** manufacturers are developing solutions to reintroduce material residue in the production process. A manufacturer in Germany recovers up to 98% of solid material residue, reintroduced as secondary raw material in the production process.
- **Expanded clay:** up to 100% of expansion clay additives and 10-15% of virgin clay can be replaced by alternative materials derived from other industry sectors. E.g. a Belgian manufacturer uses iron oxides from the steel industry as additives. Additives come from oil refineries, vegetable oil producers, bio-diesel, steel production, industrial and municipal waste water works, mineral wool, etc.

- **Clay pipes**: a manufacturer is producing clay pipes which are 100% recyclable and consist of about 40% secondary raw materials on average. Scrap from other clay production such as tiles and sanitaryware can be used as secondary raw materials.

In the public consultation to support the evaluation of the IED (European Commission, 2019b), Associação Portuguesa da Indústria de Cerâmica e Cristalaria stated that the delivery of the CE should recognise that this might lead to increased emissions, although the extent of this is not clear.

In conclusion, on material inputs, the sector is using considerable secondary material inputs and recycling material internally. It also uses much virgin raw material. The limitations seem to be within the supply chain – collection of waste material to be used and consistency of supply quality. Therefore, when considering the potential for installations themselves to increase secondary material use, there is little untapped potential, but they could absorb more material if changes were made elsewhere in the economy.

On material outputs, sector interviews indicated that there is very little waste produced. Almost all non-product material is reused internally within installations. Occasionally there is some semi-fired material that cannot be internally reused, but this is usually sent to other ceramics installations. Overall, on material outputs there is no significant untapped potential to increase material circularity.

Cerame-Unie (2020b) highlights the issue of market limitations due to legal interpretations, in particular that MS have developed their own criteria with regard to by-products and end-of-waste criteria, meaning that secondary raw material can have a certain value in one MS and can be considered as waste in another. Cerame-Unie (2020c), therefore, argues that an internal EU market is needed as material sources and the manufacturers are not always close to each other and, therefore, a smoother exchange of waste for reuse or recycling will strengthen the functioning of the EU internal market for secondary raw materials.

As a result, the sector emphasises the importance of security of the supply chain, as well as the quality of the secondary material received from others and does not see the IED as a driver for CE actions, but rather the economics of material supply and costs of waste disposal.

Glass sector

The glass sector is a major EU industry, with EU production accounting for around a third of total global glass production. Production declined sharply after the economic crisis, but has now returned to around 36 Mt per year. Container glass (bottles, etc.) accounts for 62.1 % and flat glass for 29.2 %. All other glass types together amount to 8.7 %. Around 3 Mt of this were exported and around 4 Mt imported from outside the EU[64].

Glass is a highly "circular" material, and in theory is infinitely recyclable. Waste glass (cullet) is readily utilised by the sector. For most purposes the only limitation in use of waste glass is its availability. Glass bottles collected for recycling accounted for about 12 Mt (currently around 73% of glass bottles are recycled and the aim is for recycling rates to reach 90% by 2030[65]). However, the majority of recycled glass is from glass bottles, while, in contrast, recycling of flat glass is low. Recycling, therefore, only accounts for a proportion of total production and further recycled materials could be readily absorbed by the sector. There are some specialised glass products where the quality of the glass (with respect to contaminants, etc.) has to be rigorously met. In such cases, production using primary raw materials may be preferred. However, as

64 https://www.glassallianceeurope.eu/en/industries

65 https://packagingeurope.com/eu-glass-packaging-industry-to-boost-collection-for-recyclin/

recycling quantities are still below overall production, such restrictions are not a limitation on the ability of the sector to absorb increasing quantities of waste glass.

The sector also produces little waste. Production will result in broken and other material that cannot be sold. However, this is easily recycled in the installation.

In conclusion, the sector does not seem, in itself, to be able to increase its circularity of materials, i.e. it has little, if any, untapped potential. The limitation is outside the scope of the installations themselves, being on the ability to collect and supply waste glass from different types of consumers.

Textiles Sector

There is considerable focus on the textiles sector with regard to its role in the CE. This addresses quite diverse issues, including “fast fashion”, mixing of fibres, loss of microplastics in washing, etc. Some of these issues concern manufacturing, but many concern design, markets, consumers, etc. Thus studies on the consequences of the CE for textiles cover a range of issues, but tend to not focus on inputs and outputs to manufacturing processes themselves. For example, von Bahr et al. (2019) provide an important exploration on policies surrounding sustainability of textiles, but in considering cleaner production, focus on policies relating to the production of plant material, rather than manufacturing itself.

The focus on waste textiles in policy and studies is almost entirely on collection and processing of waste textiles from domestic and commercial sources. Such processing would prove potential inputs of secondary material to manufacturers. However, it is important to note that there are significant technical challenges in recycling some materials. For example, Morely et al. (2019) note the challenges of use of blends in textile production and, therefore, of separating materials during recycling. This is an issue of product “quality” rather than IED regulation. Some recycling is so specialised that available facilities are found only in a few MS. For example, although Sweden has (and is) putting considerable emphasis on the textiles sector and the CE, much collected waste textiles have to be shipped to Germany for processing.

For this sector, the manufacturing processes for textiles are so integrated into the wider issues of textiles and the CE that it has not been possible to reach firm conclusions on the untapped potential for the IED installations. Interviewees, in particular, stressed that both the ability of manufacturers to use secondary materials and to enable their waste to be recycled was dependent on the capacity of the textile recycling facilities. As inputs to installations, Morely et al. (2019) highlight the challenge of scaling up of textile recycling – both in separation of different fibres and in sufficient quantity to form sufficient supplies to operators. This not only applies to recycled fibres for use in the textiles manufacturing sector, but also for use as feedstock into other sectors (such as the chemicals sector). Thus, at one level more reuse and recycling of textiles is possible in the wider CE which installations would benefit from, but this is not an untapped potential that the installations themselves can act on.

Summary on material flows

The following tables summarise the untapped potential for secondary material use and waste regarding the contribution of IED installations to the CE. There are major differences between sectors on both issues. Some quantitative information is available, but much of the consideration of untapped potential depends on the context of movement of material before it arrives at an installation and after it leaves (quality, price, other policies, etc.). These are developing contexts and, therefore, the summary is qualitative. These issues are explored further in the following sections. Conclusions on material flows are set out in the conclusions section.

Table 4.10 Summary of the untapped potential for secondary material use in different IED sectors

Sector	Untapped secondary material use
Energy	The sector combusts some waste from other sources and this material is not recirculated to the economy. Therefore, this represents untapped potential for material retention. However, any combustion of waste needs to be considered in the wider energy/climate policy context.
Refining	Some recycled material (plastics, waste oils, etc.) may be used for combustion. This would prevent such materials from re-entering the economy and is an untapped potential. Where such materials are from renewable sources, this needs to be considered in the wider energy/climate policy context.
Iron and Steel	The sector uses secondary material as a source for iron and steel production. The limitations are in the wider waste collection system, rather than any untapped potential in the sector.
Non-ferrous metals	The sector is largely limited by the availability of waste for recovery of metals. Collection of additional waste represents untapped potential within European society, but not untapped potential due to decisions by IED operators. The development of new techniques for extraction would represent future new potential, rather than existing untapped potential for secondary material use.
Chemicals	Many parts of the chemicals sector are able to recycle chemicals from products. However, studies of mass flows of chemicals show that only a small proportion of those produced are sent back to installations for recovery (e.g. 61 Mt of total plastic production, using 4.9 Mt of recycled plastic). If more material were to be collected, it could be absorbed by the sector. The sector can, therefore, contribute more to the CE if other parts of the CE are made more effective.
Food and Drink	The strict hygiene standards exclude use of secondary materials directly into the sector. However, such materials may be indirectly used (e.g. plastic packaging created in the chemicals sector using recycled plastic). In conclusion, there is no untapped potential for secondary material use in the sector.
Cement, etc	About 5% of the raw materials used in the production of clinker in Europe consist of recycled material and ashes from fuel combustion. There is limited scope to increase this from other sectors, but there may be potential to increase use by the sector of the limited amount that is produced. The sector combusts a range of different types of waste (from renewable and non-renewable sources). The average substitution rate was 43% of fossil fuels by waste as a fuel and this could increase to 60%. This does not allow recirculation of the waste materials in the economy and this is an untapped potential that should be explored alongside objectives for carbon emissions.
Surface Treatment with Solvents	It has been difficult to determine inputs of secondary materials to the sector, but there is certainly recycling of solvents internally. Untapped potential is unclear and may be better done by the primary producers of solvents.
Pulp and Paper	Around 54% of production is based on recycled paper and board. Recycling rates in the economy are at 72% (84% for packaging). Some material is not suitable and the processing of recycled material produces more waste than virgin material. The sector could absorb further recycled material, but this untapped potential would need to be realised by waste collection and sorting sectors.
Rendering	The sector's material input is all secondary material. Therefore, there is no untapped potential.
Ceramics	The sector uses considerable secondary material inputs. Further quantities could be absorbed if material were to be better gathered (e.g. in construction and demolition waste) and material quality assured. However, this is not within the control of operators. Therefore, of itself the sector has little untapped potential.
Glass	The sector produces 36 million tonnes of glass per year, one third from recycled material. Glass recycling is 73% and will increase to 90%. Some glass recycling is limited by contaminants within it. The untapped potential is not at the level of the IED installations, which can absorb further secondary material if it were to be supplied. The limitations are within consumer behaviour and the waste sector.
Textiles	The sector is so integrated within wider textile production, waste collection and limitations on recycling that it has not been possible to reach a conclusion on the specific untapped potential of IED installations on material inputs.

Table 4.11 Summary of the untapped potential for material recovery from waste by different IED sectors

Sector	Untapped waste potential
Energy	Untapped potential for coal combustion products (though this is not quantifiable – possibly up to 8% in the EU 15), but this picture is very different across the MS, with likely much higher untapped potential in Central and Eastern European Member States.
Refining	The sector produces 1.2 million tonnes of waste, of which 34% is recycled and 20% sent to landfill. Other destinations include energy recovery. Much of the unrecovered waste is hazardous, but does represent further potential for material recovery in the future.
Iron and Steel	Slag is widely used for different purposes (and in some cases has been for many decades). 5% of slag is sent to landfill and this may represent an untapped potential. However, there is a challenge in some MS to current uses of slag due to policies restricting use of materials with hazardous substances, so the theoretical untapped potential might increase rather than decrease.
Non-ferrous metals	Regarding slag, there may be future challenges to retain the levels of use of the material at the current rates, due to policies restricting use of materials with hazardous substances. So, on this issue there is little if any untapped potential. There is possibly some untapped potential for extraction of material value from WWTP sludge if new techniques for extraction are developed.
Chemicals	The sector produces very little waste. "Unwanted" material outputs are generally either recycled within the installation itself or they are made available as by-products. Some are used for energy recovery. The only waste more commonly arising is sludge from WWTPs. In conclusion, there is little untapped potential for the CE from this sector regarding the material outputs
Food and Drink	Only a very small amount of food waste from the sector goes to landfill. Other waste is used for animal feed, energy recovery, etc. Food is conceptually different as waste in that it is consumed as a product and not recycled. In any case the untapped potential in this sector is minimal.
Cement, Lime Magnesium Oxide	There is almost no waste from the sector (unwanted material is recycled within the installation. There is little untapped potential regarding waste arisings to identify for the CE within this sector.
Surface Treatment with Solvents	There is some untapped potential to ensure that all waste solvents are provided to those that can recover them as materials (beyond what currently occurs), as opposed to energy recovery (if this is not the best option), but it has not been possible to quantify the extent of this gap
Pulp and Paper	Recycling of paper creates much more waste than virgin material, so waste volumes increase as recycling increases. A variety of waste is produced. Some is used for energy recovery, landspreading, etc., which removes material from the economy, but may be the best option for what is a renewable resource. However, research is continuing on new uses, such as bioplastics. Therefore, there is some likely future untapped potential, but it is not possible to quantify this and it is not clear what would be under the control of IED operators themselves.
Rendering	The only waste generated is possibly from plastic packaging. This is incinerated and probably should not be further recovered due to contamination with old food waste and human health risks. Therefore, there is no untapped potential from this sector.
Ceramics	The sector produces very little waste. Almost all unwanted material is either recycled internally or used by other industries. There is little untapped potential for improved material circularity regarding material outputs.
Glass	The sector also produces little waste. Broken material is internally recycled. There is, therefore, little untapped potential regarding material outputs.
Textiles	The sector is so integrated within wider textile production, waste collection and limitations on recycling that it has not been possible to reach a conclusion on the specific untapped potential of IED installations on material outputs.

4.3.4. IED as a Driver

The Ricardo and Vito (2019) report makes reference to the provisions within the IED text but does not explore whether these provisions sufficiently drive or facilitate the contribution of IED installations to the CE (rather focusing on the role of BREFs and BAT Conclusions). However, in Task 4 interviewees did give views on the opportunities and limitations of the directive itself, with suggestions for improvements, as well as some issues raised in the literature.

It has not been possible to find hard evidence of the IED driving circularity as opposed to resource efficiency. Industry interviewees were unanimous in stressing that other factors have driven this, with the IED facilitating rather than driving these changes. In other words, there has been increased circular material performance by IED installations due to other policies, markets, etc., and the IED has either facilitated this or been flexible enough not to inhibit these developments. One non-industry interviewer noted that even for resource use and waste generation well over 90% of the BAT examined are narrative or limited to very specific issues (such as on hazardous substances), but also considered that such narrative BAT are not effective at driving change.

A national competent authority highlighted that the IED is limited in how the CE is supported by the IED as currently formulated, in particular Articles 11-15 and Annex 3[66]. These focus on resource efficiency in setting objectives for operations of installations (including on the elements of the waste hierarchy), contents of a permit application, issues to be included in a permit, determination of BAT, etc. According to the interviewee, the key objectives of use of secondary materials, production of by-products, general circularity and delivering non-toxic resource cycles (e.g. including objectives in the IED for substitution of chemicals) should be included alongside the resource efficiency and waste reduction objectives that are currently required, so ensuring that operators are bound by conditions relating to circularity. If this were to be done, then Article 32 should also include information exchange on CE issues, such as on secondary raw materials use.

Several industry interviewees emphasised the importance of the integrated, cross-media approach in IED as a key principle that should take account of all pollutant and material issues and so facilitate circular materials for IED installations. The integrated approach should avoid undue focus on one material or outcome against all others.

Some industry interviewees did not view the IED as a key driver of material circularity, but the legal drivers are waste law, in particular food waste (which DG SANTE leads on) (e.g. it took some time to view one output, feed, not as waste or even a by-product, but as a product). The IED does not focus on the CE and does not address key aspects of it such as the bioeconomy. These issues are highly relevant to material relationships between installations, so they are of practical relevance to industrial regulation.

As a result, interviewees found it difficult to identify cases where the IED itself has led to circular material decisions, although this is an evolving part of business practice. Instead, other policies are driving the actions of the industry. However, this does not mean that the IED could not play a greater role, including in how some aspects of the CE are integrated into BAT, although there is a challenge linking any minimum "standards" to market issues. As a result, the interviewee concluded that implementation of the IED should not be too prescriptive, allowing industry to innovate and avoid a "one size fits all" solution to complex environmental issues.

Swedish Enterprise (2020) stated that the role of the CE in the implementation of the IED could be clarified in the guidance for the BREF making process, but it also views the IED as "not the main tool to use to increase

[66] Criteria for determining BAT include the following four criteria relevant to CE: use of low-waste technology; use of less hazardous substances; furthering of recovery and recycling of substances generated and used in the process and of waste, where appropriate; consumption and nature of raw materials (including water) used in the process and energy efficiency.

resource efficiency, bearing in mind BREFs are sector specific and it is important not to create obstacles for the circular markets."

While industry responses tend to emphasise the limited role of the IED to date on driving circular material flows for industry, they do not suggest changes that might improve the role of the IED. In contrast, there are such suggestions by competent authorities.

The scope of the IED is also an issue for discussion on what it can/should cover with regard to circularity. It is site-based, but there is some scope for capturing "directly associated activities". It does not regulate issues up-stream or down-stream (such as products), but decisions on process operation directly affect these. For example, operators may reach agreements with suppliers of secondary materials on the minimum quality of those materials, but the performance of these suppliers is a commercial contractual issue and not captured within IED regulation. Industrial symbiosis, as a specific type of business relationship, can be accommodated to some extent and this would vary depending on how MS apply permits. The scope of what can be captured within permitting is not new and there is a difference between what the IED requires and what it might limit in this regard.

HAZBREF (2020) stated "The traditional scope of the IED and BREFs is the installation (gate to gate thinking), whereas CE needs to apply a life cycle thinking and a better connection of upstream and downstream processes. This requires better implementation of value chain thinking. For example, the regulation of product design and quality directly impact the content of future waste streams once these products are discarded."

A key issue not captured by the IED is product quality (subject to other EU law), but products are integral to some processes that the IED does regulate. The nature of products affects their repairability and their recyclability and changing products can change subsequent impacts (e.g. with textiles). Some interviewees have noted this limitation of the IED. While there has been some suggestion (nothing stronger than this) that it would be helpful if the IED could intervene more on this aspect, no suggestion has been made on how it would do this (what would be the nature of any regulatory decisions and how would these be actioned?). Further, many IED installations produce materials rather than products, so this issue would not be relevant for them.

4.3.5. IED as a constraint

A question to consider around the relationship between the IED and the CE is whether the IED, or some detailed requirement within it, might act as a constraint on installations adopting circular practices for materials. It is important to highlight that (with one exception below) no literature or interviewee demonstrated or stated that the directive itself somehow limits circular actions. Indeed, there was widespread positivity towards the provisions of the IED – that it facilitates circular actions by installations. It should not, however, be interpreted that the lack of barriers means that the IED is a driver (or strong driver). This is explored above.

One exception that has been raised is the provision in the IED on emerging techniques. This was noted in the IMPEL/Make it Work (2019) guidance and by an interviewee. The point is simply that the nine month limitation on exemptions to test an emerging technique is too short a time to gather sufficient information to assess the performance of the technique. It is important to note that this point is applicable to an emerging technique applying to any change (relevant to the circular economy or not). With regard to the circular economy, it may be important to have time to consider whether downstream conditions (markets, quality, etc.) for material emerging from an installation (such as a new by-product) are stable. It is not clear how widespread an issue this is, nor its exact relationship with circular economy issues. Indeed, it has not been possible to identify specific examples where the time limit in the directive concerning ETs has an impact of circular materials decisions in regulation. In any case, this issue, if relevant, is not limited to issues of the circular economy, but is about ETs in general.

Another issue is that a lack of focus of the IED on material circularity may in part be due to its emphasis to date on addressing emissions to air and water and general reduction of waste generation. In using new feedstocks based on recycled materials, contaminants may be introduced, which may exceed strict emission limit values based on the use of virgin materials that do not contain these substances. For example, recycled glass contains organic contaminants and emissions will be higher in VOCs. Recycled gypsum may contain small quantities of heavy metals. Recycling glass wool requires the use of oxidisers to tackle organic contaminants leading to increased NOx emissions. Increasing use of some secondary materials would require implementation of the IED to take a holistic approach to environmental protection. It is not possible in this section to weigh up whether a specific increase in emissions would justify increased material circularity, but simply to note that such analyses are necessary (whether in development of BREFs or within individual regulatory decisions).

In conclusion, little concrete evidence has so far emerged that the text of the IED contains any constraints on installations being circular in material use and production or become more circular in their material use and production.

4.3.6. BREFs and BAT Conclusions

The Ricardo and Vito (2019) report had a major focus on BREFs and BAT Conclusions. In particular chapter 4 explored the CE in forthcoming BREF reviews. This section reviews recent BREF and BAT Conclusions developments for different industry sectors and how they address CE issues, from resource efficiency, reuse of materials, etc.

Recent BREF and BAT Conclusion developments

A first draft of the revised FMP BREF (**ferrous metals processing industry**) was produced in 2019 (JRC, 2019b). The original FMP BREF has particular emphasis on the recycling and reuse of different residues. The 2019 draft has some changes to the management of residues or raw materials. These include:

- General considerations on BAT-AEPL calculation for material use, BAT 1, EMS with an extra residues' management plan (connected to BAT 31 a).
- On 'material efficiency' there are 6 BATc, number 11-16.
- On 'residues' there are four BATc, BAT 31-34.

Each of these is consistent with resource efficiency and waste minimisation. The revision also introduces proposed requirements regarding water use per tonne of production in Table 9.2 for hot rolling, cold rolling, wired drawing and hot dip coating. The use of consumption per unit of production is an interesting development.

The review of the **smitheries and foundries (SF) industry** BREF kicked-off in September 2019 (JRC, 2019f). The report of the meeting concluded that the review would collect water consumption / water discharge data (on the installation and process level) and contextual information to understand and compare the data in order to understand water consumption. On solid residues, the TWG decided to focus on techniques which would maximise the re-use, recovery and recycling of residues and to collect quantitative data on this through questionnaires. This was done to better address the CE aspects in this sector with the possibility to derive BAT-AEPLs if the data quality were sufficient. The TWG concluded that the following residues should be covered:

- The amounts of slags and dross generated and sent for disposal and/or for internal/external recovery.
- The amounts of filter dust recycled and/or sent for disposal.

- The amounts of refractory linings recycled and/or sent for disposal in ladles and melting furnaces.

These points highlight a focus on internal recycling and immediate external recovery. Understanding what is happening with residues such as slags as by-products is being sought in the smitheries and foundries questionnaire on: re-use, recycling, recovery (other than recycling), disposal and information on the future use. Information on the BAT candidates for material efficiency, especially in the environmental performance and operational data, will help understand future use, but some major drivers may not be captured (e.g. in relation to changing markets for slag use – see above).

On **textiles**, the review of the TXT BREF is ongoing. The report (JRC, 2018) of the kick-off meeting for the review did note that "it was important to collect information not only on the amount of waste but also on the by-products and all other contextual information which allows an understanding of the waste streams". However, in identifying specific data to collect, the specific issues listed under "waste" are limited (as agreed in the TWG discussion) to very specific waste types and only refers to collecting "contextual information" relevant to waste which includes "processes, raw materials, product specifications, waste streams and by-products, type of recovery" to "understand and compare the data collected", i.e. the specific waste data. Thus, as planned, the broader data and information needed to understand circular material use and production is not part of the information collection and analysis. The first draft (JRC, 2019c) includes two specific BAT-AEPLs on material recovery. BAT 29 (for the pre-treatment of raw wool fibres by scouring) is to recover wool grease and recycle waste water and BAT 38 (for the pre-treatment of textile materials other than raw wool fibres) is to recover caustic soda used for mercerisation. While important, overall these are limited when considering the total material use in the textiles sector and wider circular material requirements are not included.

The review of the **slaughterhouses and animal by-product industry** BREF kicked-off in June 2019 (JRC, 2019e). The report of the meeting included objectives to understand water consumption and the reasons for this. As noted earlier, this sector is largely a recycler of solid materials and produces little waste (so these were not addressed in the meeting).

On **surface treatment using organic solvents** including preservation of wood and wood products with chemicals, the revised BREF and BATc published in 2020 (Commission Implementing Decision (EU) 2020/2009) includes some techniques (optimisation of the painting process, dewatering of paint sludge, recycling of paint sludge or the water emulsion) to deliver minimisation of raw material consumption.

The FDM BREF for the **food, drink and milk industries** was revised in 2019 (JRC, 2019a) and BAT Conclusions published in late 2019 (European Commission, 2019a). These contain a range of BAT Conclusions for resource efficiency. On general BAT Conclusions, BAT 2 is "to establish, maintain and regularly review (including when a significant change occurs) an inventory of water, energy and raw materials consumption as well as of waste water and waste gas streams, as part of the environmental management system (see BAT 1)" and specific features for this are included. This BAT is accompanied by BAT 6 which is "identification and implementation of an appropriate monitoring strategy with the aim of increasing resource efficiency". This is an important development as it places an obligation on the operator to monitor and review progress for individual installations rather than a specific technical measure. The BAT Conclusions also include some specific techniques for individual sectors within the broader sector. However, these are only for three (brewing, dairies and ethanol production) of the eleven sectors included.

Although this study does not include the waste sector, it is useful to note the BAT Conclusions for **waste treatment** (European Commission, 2018a). These do not mention resource efficiency itself and reference to efficiency is largely limited to energy efficiency or the efficiency of the abatement techniques. The exception is BAT 22, which concerns substitution of raw materials by waste in treatment actions. The BAT Conclusions do not consider techniques for the treatment of waste that might affect how the materials in those wastes might be better used within the economy after leaving the installation, i.e. wider CE context.

In conclusion, it can be seen that recent revisions of the BREFs have started to include more specific actions relevant to the CE. Some of these are, however, limited to very specific actions. An exception is the food and drink BAT Conclusions and the BAT to produce an inventory of resource use and monitor this. Such an all encompassing BAT has the potential to capture diverse CE issues for installations.

The role of BREFs and BAT Conclusions

The interviews and literature have explored the potential role of BREFs and BAT Conclusions in helping to improve the performance of IED installations with respect to the CE – both what they might do better and what might be inappropriate in these documents.

NEPA (2018a) stated that the IED "could more efficiently be used as a driver for circular economy" and, in this regard, suggests two levels – more detailed guidance on best waste management and resource efficiency practices in the BREFs together with guidance in BREFs on how better to integrate CE objectives in permits.

Swedish Enterprise (2019c) stressed that the preconditions for the CE are different in different sectors so that "different solutions and measures are therefore needed for different sectors as regards both policy and instruments of control". In effect, the current development of BAT Conclusions for different sectors already treats different sectors differently and IED is not a one-size-fits-all instrument. However, there may be some common elements or approaches applicable to several sectors.

Interactions between BREFs

One issue with the BREFs is their interaction where more than one BREF applies to an individual sector. The Iron and Steel sector, for example, is subject to several BREFs, which cover different issues and are of different ages. Explicit links may be made between the BREFs, but this can be challenging in addressing the circularity of some material issues The Iron and Steel BREF itself addresses some material inputs as well as BAT regarding the processing of slags. Of course, connections can be made, but it is a challenge for circular thinking. The Iron and Steel BREF includes many BAT which include elements which together establish circular material use, without using the term "circular economy". BAT-AEPLs are provided for specific material consumption, material efficiency, recycling, resource efficiency, recovery, and waste management, which are prerequisites for circularity. BAT 6, 7, 8, 9, 11, 12, 23, 27, 30, 40, 57, 68, 82 and 93 cover objectives to reuse, minimise, recycle different wastes, residues, and by-products.

The relationship between complex sites to which several BREFs apply was raised by industry, e.g. sites with inorganic, organic, polymer, etc., processes. Each unit may be able to use materials arising from others, but this can be problematic, depending upon how BAT Conclusions are interpreted. This could be addressed in how BREFs are drafted, but it is also an issue of national permitting (e.g. there is a unit by unit permitting approach in Germany, whereas there is a more comprehensive permitting of several units in Spain and the UK).

Interviews have explored the relative roles of vertical and horizontal BREFs. Overall, most noted that while some principles might be set out in a horizontal context, the differences in material use and production across sectors are so huge that CE issues are best addressed in vertical BREFs. What is identified as BAT for one sector is not necessarily BAT for another sector. There are the differences in processes between sectors and as such of the environmental problems and key environmental issues (KEIs). Further, those arguing for specific targets relating to the CE consider this is only possible in the specific consideration of individual sectors.

Waste

It is important to stress the holistic integrated approach of the IED. Waste minimisation is a goal, as is broader resource efficiency. To this circular material use could be added as an explicit objective. However, in all cases decisions on what is appropriate should take account of other environmental objectives and the right trade off determined. Control of air and water pollution creates waste (e.g. filters) and sludge, but that is desirable. Reduction of waste may not always be desirable, but better, circular management of the waste produced is desirable.

Support for material cycles in BREFs

Some interviewees emphasised that the IED, as elaborated in detail in BREFs, has much potential to support circular material cycles, but many BAT Conclusions are narrative in character on issues such as recycling or waste reduction. As a result, the suggestion is that the IED has not been a driver. The focus has been elsewhere (air and water emissions), but there is potential to achieve more. An industry interviewee stated that a horizontal BREF on CE could set out key principles to consider. However, it would not be possible to include any material targets in such a BREF as the sectors are so diverse and material issues are so dynamic. This applies even for individual materials, e.g. recycled polycarbonates can be used by some sectors, but the food sector, for example, will have strong safety constraints on what is permitted to be in contact with food.

Some industry interviewees view BAT-AEPLs as having limited application in resource efficiency and waste generation because they vary according to many factors, not least the widely differing local differences in waste management and material availability. Further, industry interviewees were also of the view that any definition of BAT should not be so prescriptive as to prevent industry from innovating and developing new solutions.

However, in contrast, there is support for setting quantitative targets in BREFs/BAT Conclusions related to circular material use from some non-industry interviewees (NGO and competent authorities).

The HAZBREF Project (2020) suggests three approaches that could be used to integrate better CE within the BREF process:

- Production waste approach – where BATs could be introduced to improve the quantity and quality of wastes produced by an installation. Note that no such BATs have been adopted to date, so this approach would be new.
- Secondary raw material approach – where there may be BATs on use of secondary raw materials by installations, but taking account of impacts on the final materials, wastes produced.
- Product end-of-life approach – possible BATs affecting post-consumer product recoverability to bring materials back to production.

In considering how far to expand thinking within BREFs it is also useful to consider six business actions that EMF (2015) recommended to operationalise the CE:

- Regenerate – shifting to renewable materials.
- Share – keeping product loop speed low and maximise utilisation of products by sharing them among users, reusing them throughout their technical lifetime, and prolonging their life through maintenance, repair, and design for durability.
- Optimise - increase performance/efficiency of a product and remove waste in production and supply chain.
- Loop - keep components and materials in closed loops and prioritise inner loops.
- Virtualise - deliver utility virtually.
- Exchange - replace old materials with advanced materials and apply new technologies.

One suggestion raised within some interviews has been a requirement for an explicit circular materials plan within (or alongside) an EMS for each installation (e.g. MiW and IMPEL, 2019). This would be broader and more detailed than residue or materials plans currently being explored. Such a plan would require the operator to explore what materials are used and why (including market context) and how these might change to become more circular. It would also explore material outputs (waste, by-products, and products) and set out actions to make these more circular, such as chemicals substitution, symbiosis, consumer relationships, etc. It would also set out process changes needed to deliver on these actions and what this might mean for other process objectives in a permit. Guidance could be produced to support this (including within BREFs on setting "reference points", etc.). Further, IMPEL could support regulators in understanding best practice and other implementation issues (e.g. on how to take measures within such a plan into obligatory permit conditions).

Limitations from the scope of IED

Several industry interviewees stated that because market issues are critical and can both drive and constrain material flows, it is not appropriate to set a specific target for secondary raw material use or by-product production within BAT Conclusions. FuelsEurope (2020) does not consider that BAT-AEPLs could be derived nor that a "KEI" could be pre-identified due to the limitations of data and the diversity in sectors. Further, it views the IED limitation to regulation of an individual site, as opposed to wider issues (e.g. up or down stream of the installation) as limiting its ability to address circularity of materials. However, MiW and IMPEL (2019) stressed that authorities can help in exploring synergies between industries and mapping industrial clusters to support symbiosis. Performance is highly specific to installations and is diverse across the sector, being heavily dependent on individual metals. Further, as the sector is highly dependent on performance in the waste management sector and its inputs, much of this is beyond the IED and certainly beyond the control of the operator of a metal processing installation.

Huybrechts et al. (2018) concluded that value chain issues are not systematically considered during development of BAT conclusions and in IED permitting, thus affecting the overall delivery of value chains for materials. They concluded that a more systematic assessment of value chains would be delivered in three ways in BREF discussions:

- Consider "cross-sector effects".
- Determine a "value chain BAT".
- "Collaboration with upstream and downstream partners in the value chain" as a general BAT for all sectors.

However, taking a broader approach requires a full life cycle analysis (Swedish Enterprise, 2019) covering product use, repair, recovery, etc. which will identify key aspects of design and production. It is also important to note that the OECD BAT project[67] includes ongoing work on the challenges and opportunities associated with value chain approaches to establish BAT for industrial installations.

Data confidentiality challenges

Some interviewees highlighted the issue of data confidentiality in gathering information in BREF development. There is an issue between this and transparency, but material and energy efficiency are sensitive issues. The FMP TWG meeting supporting the revision examined confidential information by using anonymised numbers and special provisions during the meeting, but it is not clear if this will work more widely. This is an issue not only for understanding material use, but also for setting BAT-AEPLs.

[67] (https://www.oecd.org/chemicalsafety/risk-management/best-available-techniques.htm

Hazardous chemicals in materials

The Ricardo and Vito (2019) report included a chapter on hazardous chemicals. This largely explores the use of hazardous substances in production processes rather than where they end up (e.g. in products, waste, etc.). It noted that there are relatively few BATs associated with minimisation, elimination, or substitution of chemicals. The issue is frequently highlighted as an impediment to circular material flows.

An NGO interviewee stated that the IED could be much more explicit on the general prevention of use (avoidance) of hazardous substances i.e. substitution, with the CE. IED Annex III point 3 aims to enhance "the furthering of recovery and recycling of substances generated and used in the process and of waste, where appropriate" and this requires a consideration of the substances this contains (e.g. UBA 2016). Swedish Enterprise (2019b) argued that chemical substitution is better driven by the needs of downstream users rather than legislation. However, this would likely only apply to certain substances for certain uses and wider action on removing hazardous substances from materials would be required to deliver materials with sufficient quality for long-term circulation in the economy.

The HAZBREF Project (2020) emphasised the importance of information on hazardous chemicals. It considered the composition of the materials used in products, in by-products, and in waste. Knowing this allows for the substances to be traced and for informed decisions on what should be done within IED installations and for all further materials management through the value chain, as well as to help identify where needs for substitution are greatest. Therefore, the suggestion is for BREFs to identify the requirements for a chemicals inventory and, indeed, this has been proposed in the first draft of the revised Textiles BREF (2019). It is important to note that this would include tracing the fate of such substances into air and water emissions as well, thus providing a confirmation that all is accounted for. Indeed, it is useful to note that the Ricardo and Vito (2019) report concluded that "there is no comprehensive data source that collates information on the use of hazardous chemicals in EU industrial sectors". Note that this concerns only use, whereas it was suggested that such data on inputs would only be a starting point and that tracking on key substances is needed.

4.3.7. Practical implementation of IED

The obligations and opportunities in the text of the IED as an instrument and the requirements elaborated in BAT Conclusions are only realised in their practical implementation in the MS. Operators need to interpret these in their permit applications and regulators interpret them in their permitting decisions.

The IED is not a rigid general binding rule, but requires interpretation in individual regulatory decisions as permits are issued, reviewed, etc. These need to take account of BAT Conclusions, other issues (such as objectives in other EU law) and the overall objectives of the directive to deliver protection of the environment as a whole. This suggests some flexibility in the application of the directive, but also complexity for operators and regulators in determining what is appropriate and, therefore, compliant. This issue has been the subject of some discussion in the literature and was raised by some interviewees. However, it is important to note that while industry operators would be expected to have views on this issue, many of the industry representatives interviewed were unfamiliar with individual permit decision-making and were not able to provide detailed comments.

In some cases, it may be clear what an installation may need to do on use of materials or on waste/by-products to contribute to the circular economy. In most cases there is some, or even considerable, complexity (such as on interpreting markets, material quality, trends, etc.). Regulatory decisions on this issue, therefore, often require consideration of a variety of issues. Further, many of these issues are different from those commonly examined by permitting authorities more familiar with air and water emissions. This raises a challenge for competent authorities, in particular whether their staff have sufficient expertise and guidance. This will vary between MS and whether specialist expertise can be called on within competent authorities. In general, smaller, more decentralised competent authorities, are likely to be those with the greatest challenge. This point was explored by MiW and IMPEL (2019). In that case the guidance viewed regulatory decisions on circular material use as novel and requiring new regulatory decisions. This is a potential "risk" and competent authorities may be risk adverse, sticking to known linear economy models in their decision making. Thus, the opportunities that the IED affords for delivering the circular economy might not be realised in practice.

EPA (2018b) noted that practical implementation of the IED for the CE must be more than simply applying standard requirements. A dialogue is needed to explore opportunities, e.g. as was done for the steel sector in the Basque region, including beyond IED installations to allow for recycling activities to take place locally rather than requiring expensive long-distance transport. The IED permitting authority in the Basque region did this in different ways, including hosting joint seminars (EPA, 2018b).

The diversity of approaches to IED implementation was raised by several interviewees. In some cases, permitting authorities are more flexible to support circular material use by operators, in other cases there is more rigid application of conditions. A particular example concerns complex sites with several activities that might be subject to different BREFs, but which may be operated by the same company. In some MS each activity has its own permit, with specific conclusions on waste, by-products, etc. even if these are moved for use into a neighbouring activity. In other MS, an overall permit may be issued, taking account of the BREFs and BAT Conclusions for each activity, but making integrated decisions which take account of material flows. However, sometimes this overall permit approach is less flexible than at first sight. For example, in Sweden an overall permit for a site is issued by an environmental court, but Sweden implements BAT Conclusions via general binding rules, so each activity within the site is automatically subject to them without flexibility even though they operate within the broader site permit – there are barriers to moving materials between units on the same sites in Sweden.

Complex sites are not the only cases where single or divided permits might affect implementation. In Poland, sites where there is both steel production and waste management need two permits, but in some other MS they might require only one permit, recognising the material movements between them. Not only differences between MS can lead to inconsistencies, but also how regional and local authorities make decisions.

The flexibility in the IED regarding the setting of ELVs in permits based on BAT Conclusions was raised by MiW and IMPEL (2019). The suggestion is that the IED does allow a deviation from such conditions if a better environmental outcome could be demonstrated. An industry interviewee suggests this might be appropriate for management of waste acids (re-concentrating them on site). However, at this stage it is not clear:

- How many examples there are where ELVs based on BAT Conclusions result in sub-optimal outcomes for material cycles.
- How one assesses the consequences of an increase in emissions above the ELV against the benefits of the improved material cycles.

MiW and IMPEL (2019) explored this to some extent. They considered that circular innovations could be facilitated through one permit covering the multiple sites (e.g. as can be found in the Netherlands) rather than each one being permitted separately. They stated that bringing several facilities under one 'umbrella' permit may mean that some emissions and wastes will no longer be leaving the site, thereby easing the burden for both the regulator (in setting the permit conditions) and the operators (in complying).

An industry interviewee noted the value of industrial symbiosis and clustering of industrial activities can help encourage circular material use. However, while authorities and industry can help further by mapping infrastructure and potential material flows, the relationships between operators still need to meet market realities if materials are to be moved between entities.

There is a view from some national regulators that while waste prevention and resource efficiency are cornerstones of the IED, there is insufficient inclusion of these elements in some permits with limited information on how installations perform with regard to these issues and how they can improve. Such thinking needs to be embedded more in practical application, including on material relationships with other companies and wider industrial symbiosis. The IED can support this, but such relationships would include both IED and non-IED installations.

One interviewee argued that the limitations of the IED to sites and "directly associated activities" is a limitation in "controlling" material cycles. As a result, they stated that the IED should be extended to wider value chains, so highlighting the conclusion in the Ricardo and Vito (2019) report on value chain approaches to determining BAT and proposes that Annex I should be reviewed in relation to the functions and products of the installations to society and not be limited to individual sites. Further, the IED activities should be assessed according to how well they meet the following circularity principles:

- Slow (long life of product).
- Small (no superfluous waste).
- Local (territorial hierarchy).
- Clean (no toxic substances).
- Sustainable feedstocks.
- Perpetual (prevent downcycling).

4.3.8. The regulatory context

The previous section has examined how MS competent authorities may interpret the IED in furthering circular material use in the regulatory decisions related to IED installations. It is, however, important to stress that the relationship between the competent authorities and those operators (and decisions arising from that relationship) need not be limited to the formal implementation of the directive. In this sense, such decisions would be beyond the strict scope of the IED and might, therefore, be beyond the scope of this chapter. However, they involve the same actors and same installations and are important in considering how to support IED installations in improving their role in the circular economy. In other words, does the answer lie within the directive (as it is or revised) or in other regulatory decision making?

Within this study, however, there has been little information obtained on this issue through the interviews. Recent literature has more to offer. The 2019 IMPEL and Make it Work Guidance described how competent authorities can adopt different approaches to supporting business in becoming more circular. It states that competent authorities could produce strategies for specific regulatory regimes and it specifically highlights the IED. The guidance stresses the overall objective of the IED for protection of the environment as a whole to guide such a strategy, recommending that competent authorities examine how they are using the IED to achieve this, including with reference to the objectives of the circular economy, and alter their approaches if needed.

The guidance suggests a further alternative strategic approach, i.e. strategies or plans for particular materials, setting out business and market conditions, opportunities and constraints for those materials and then working with businesses to support circularity of those materials. This would include decision making within the IED, but also addresses issues well beyond the scope of the IED as such strategies would encompass waste management planning.

However, the guidance gives examples of strategies addressing individual businesses or business sectors (covering several companies). This assumes that competent authorities have aims beyond the core activities of implementing regulation, and have broader environmental objectives. As a result, they can work with businesses/sectors to deliver environmental objectives beyond basic compliance, while also delivering business objectives. This would include materials management, including circularity issues and take account of legislation including the IED, waste, REACH, etc. The guidance gives examples of Prosperity Agreements in Northern Ireland, which contain commitments from both NI Environment Agency and the company or organisation to deliver environmental benefits, beyond legal requirements, and commitments from the Agency to support this.

A further example is from Scotland, with its sector plans[68]. These focus on practical ways of delivering environmental, social and economic outcomes. They specify existing levels of compliance, the market context for that sector and the key issues faced by the sector and the regulator. The plans set out how to address remaining compliance issues and then what 'beyond compliance' opportunities exist and how to harness the key levers that influence that particular sector.

This section is not able to critically evaluate these approaches. However, it is important to stress that some competent authorities are examining how to support IED installations in improving environmental outcomes beyond core IED compliance, including on circular materials use. This suggests that not all of the answers to circularity of materials of IED installations lie within implementation of the directive itself, but where the boundary between regulation and voluntary agreements should be is not clear.

4.3.9. The importance of other EU law and policy

This study is not a review or analysis of the opportunities or limitations of EU law other than the IED and it certainly does not aim to analyse what changes might be appropriate in other EU law. However, many interviewees stressed the limitations in other EU law (as has some of the literature) and it is important to note these. Also, there are many calls in the literature for improved EU waste legislation and consistent application across MS (Eurelectric, 2017; Swedish Enterprise 2019; MiW and IMPEL, 2019) as well as for consistency with legislation such as REACH. Overall, there is significant evidence that the major constraint on the ability of some IED installations to increase their material circularity are issues that lie in other EU law and policy. However, some constraints are also found in national policy and, in particular, in market characteristics. These areas are the focus of the following two sections.

There was widespread concern from interviewees on the limitations of the Waste Framework Directive, and the interpretation of "waste", "by-products" and "end-of-waste". This not only concerned the specific obligations in the directive, but also the consequences of diverse approaches across MS affecting business certainty and the internal market for secondary raw materials, etc. For example, slag from the ferrous sector may be classed as waste in one MS and a by-product in another. Slag must be produced by the sector and the IED can encourage its downstream use, but what is permitted is not determined by the IED, but by waste law and, specifically, MS interpretation of that law.

Interestingly the High Level Group on Energy Intensive Industries (2019) in proposing its "Masterplan for a Competitive Transformation of EU Energy-intensive Industries" highlights the need for the sector to transform to meet the demands for both greenhouse gas reduction and the CE. However, with regard to the latter the HLG makes no reference to IED, instead highlighting the barriers within EU waste law that need to be addressed.

An industry interviewee highlighted the serious differences in interpretation of the Waste FD between MS and even within MS. For example, in Flanders there has been a long promotion of materials within the CE, but Wallonia has only just agreed that by-products for feed are not waste.

The issue of material defined as "waste" was stressed. If secondary materials are "waste", this creates a significant administrative process to get a permit for storing, handling, and reprocessing it before being able to use it as a material in the IED installation. This is beyond the IED but is a constraint that cannot be overcome by changes to the IED as an instrument or its implementation. Note that these issues arise both from the EU waste law itself and from different MS elaboration of it. As a result, the established markets for some by-products vary across the EU and operators become familiar with doing business differently

[68] SEPA. One Planet Prosperity - Our Regulatory Strategy

depending on their locations and the locations of their customers. For example, the UK uses bottom ash in the construction sector, but this is restricted in Germany, so German producers of bottom ash ship this to the UK for use.

An industry interviewee raised specific concerns on interpretation of the Waste Shipment Regulation, affecting whether waste is hazardous or not and, therefore, what can be moved across borders and the costs of doing so (e.g. if waste is moved between two MS via a third MS, but the third MS has different interpretations). Again, this is not an issue for IED interpretation, but it is a further constraint affecting the ability of IED installations to use some secondary materials.

An industry interviewee also highlighted the importance of proper implementation of legislation by MS to support circular material use by industry. Thus, ineffective implementation of the WEEE Directive, for example, allows leakage of considerable quantities of material from the EU and significantly less circular use by industry.

Another industry interviewee emphasised that legislation on food safety or legislation related to the quality of inputs (such as drinking water quality) are also very important and affect issues such as use of secondary materials (e.g. material used for packaging in contact with food).

Another area of EU law which may be a constraint is EU regulation concerning fertilising products. For example, copper production uses sulphuric acid which is recovered to be used in fertiliser production. However, it is not as clean as pure sulphuric acid, and this may now be an issue for EU fertiliser law (or at least its interpretation). This may act as a constraint reducing the use of this material.

The rendering sector provides another good example of constraints to circular material use arising from other EU law. Regulation requires the products of rendering to be assigned to a risk category (EFPRA, 2016). The lowest risk is where the material can be safely processed for further use as feed, etc. The highest risk includes material with pathogens like BSE or contaminants such as cadmium. An issue arises with a category of material which in the EU cannot be used for animal feed, but it can be used for other products. Despite the fact that this material is produced more safely than other proteins in some third countries, where they can be used in feed, this raises the question why there is a ban on export. Under EU law (Regulation (EU) No. 999/2001), due to the concern related to BSE, an industry interviewee reported that 50% of the feed grade material cannot be used for animal feed. However, the World Organisation for Animal Health (OIE) does now allow this material to be used for this purpose. As a result, the rendering industry in the EU either processes this material for use as fertiliser or it produces animal feed for use in third countries. As a consequence, the EU is exporting animal feed, but importing soya for use as animal feed internally and also importing the animal products grown using the feed exported from the EU (as well as animal products grown using feed produced from rendered material with the middle risk category processed outside the EU). This raises questions about the international context of circular material use for the EU. If the EU retained the middle category material and the protein of the 50% feed grade protein as animal feed this would increase its domestic production of protein by 15-to 20%. The regulatory context is EU health law rather than IED and it is not appropriate to comment in this report on whether the EU health law is correct in today's environment. However, it is important to note that this is a constraint on the by-products that the EU rendering industry produces and that this cannot be changed through decisions made within IED regulation.

It is also important to note the importance of the European standardisation processes (CEN). These standards may apply to by-products, such as EN 450 (fly ash for concrete) (Snop, 2019). The review processes for several CEN standards form the point of interaction between the quality that IED installations need to produce and the acceptable uses by different users. The importance of consistent international standards is highlighted by others (e.g. Inter IKEA and Ingka Group, 2020).

The complexity of legislation can lead some operators to take fewer circular decisions. A view from some regulators is that some choose to designate materials as waste, as this is easier than developing by-products (e.g. authorisation of chemical by-products through REACH) For example, some waste water treatment plants can recover oil as a by-product, but instead treat it as waste as this is less complex. Further while by-product status criteria are set out in EU law, the implementation leaves much discretion for MS, so that some are stricter than others.

In conclusion, there are many items of EU law that impact on the ability of IED installations to deliver circular material flows beyond IED itself. These provide constraints and opportunities and need to be understood in determining what should be delivered through the IED itself. Further, relationships with other EU law are continuously changing. During the course of this work, the Sustainable Finance Taxonomy Regulation ((EU) 2020/852) was adopted and proposals for delegated acts published. It is not clear what interaction with IED these might have in future, but this may need to be explored in due course.

4.3.10. National policy and legal context

As explored above, the way that MS implement the IED is one source of variation in the performance of IED installations with respect to the CE. A further variation between MS may be other national policies. Some evidence of this was identified in this study.

One issue raised by interviewees concerns the pressure in some MS, such as Sweden, for a non-toxic environment. If the national policy is to avoid the introduction of any hazardous substances into the environment, this has consequences for the use of secondary materials which may contain traces of these substances. This applies to materials derived from industry as well as from processing of other waste sources. This tension has also been experienced elsewhere (e.g. in the Netherlands).

Thus Eurelectric (2017) has raised concerns that the use of bottom ash was at risk of being classified as hazardous and no longer allowed to be used in construction in Sweden, while it is widely used for this purpose in MS such as Denmark and the Netherlands. A concern raised by several industry interviewees is that such a policy could begin to limit the use of material from industry that has been used for many decades, such as slag from metal processing in road construction (Swedish Enterprise 2019a, 2019b).

A recent Swedish Court Case ruled that the use of such slag as a base for a tarmacked area is incompatible with the non-toxic policy as the long-term sealing of the slag from rain and run-off cannot be guaranteed. As a result, authorities across Sweden are now hesitant to use slag. Further, Sweden has also imported slag from other MS for many years and a shipment of slag from an installation in Finland was stopped on the border as now "illegal". Thus, the national policy may have knock-on impacts in other MS.

The consequences of a non-toxic environment policy are explored by NEPA (2019) where several MS environmental protection agencies argue for a "non-toxic circular economy". The main focus of the argument is on chemical substitution so that "the development and use of safer and sustainable chemicals and technical solutions can be encouraged in the industrial sector". The argument mentions that "the entire life cycle of chemicals, including the use, waste and recycling stages, should be considered in the assessment and management of chemicals". The EPAs do not consider how this would reflect in regulatory tools such as the IED. However, if further policies are developed on a non-toxic environment and its link to the CE, then application of the IED may need to take account of this in the future. This will include implementation of the new EU Chemicals Strategy for Sustainability (COM(2020)667), which considers hazardous substances in materials and is explored in more detail in section 4.4 below.

The issue of the presence of hazardous substances in materials is a focus of the HAZBREF Project (2020). For some materials, the answer is not the decision on where the trade-off lies between circularity and presence of hazardous substances, but to address the problem at source. If processes (inputs, processing, waste treatment, etc.) changed so as to reduce the presence of hazardous substances in waste and by-products, the problem would be avoided. Solutions raised by HAZBREF, including better tracing of substances, are discussed elsewhere.

4.3.11. Markets

The market is critical to the CE – material inputs are a cost to operators, waste outputs are a cost, material outputs may have value. More widely developing the CE is to move from waste as a problem to materials with a value (NEPA, 2018a). As a result, several industry interviewees stressed that the "Circular Economy" is both "circular", i.e. what is technically possible for materials, and "economy", i.e. what works in the market, making economic sense for the purchase and sale of materials..

For example, for the non-ferrous metals sector, the metal price is overwhelmingly important in determining what can be practically recovered and these prices are set on the London Metals Exchange, are global in nature and have consequences for the global competitive context of EU industry. Another market factor has been energy prices, as declines in energy costs have made the extraction of both ferrous and non-ferrous metals more economically viable than it was 10-15 years ago. Further, demand may be critical factor, for example Swedish Enterprise (2019b) noted that demand in the ferrous metals sector for steel at the time of production of its report was higher than access to scrap material, so that there was not a market limitation on the use of scrap by the sector.

One issue for the iron and steel sector, which may apply to some other sectors, is that by-products may be sold in batches to users, i.e. they need to be stored on site for several months before there is a sufficient quantity to meet a user's requirements. This affects the operation of an installation and has some economic consequences.

Many industry interviewees stressed that market drivers were the overwhelming factors for CE.. For example, the crisis in construction after 2008 affected the market for coal combustion products, but as demand has since increased, there is now a major market for these products to the extent that cross-border trade in the EU is around 3 million tonnes,. It is also now imported from China and India and also extracted from older, landfilled deposits of the material in Europe.

NEPA (2018a) noted that secondary materials with a higher value are more resilient to price fluctuations, so any process that focuses on maintaining the intrinsic value of a material has a better chance of finding investment and remaining viable (e.g. metals, higher grade plastics etc.). On the other hand some materials are much more marginal and cannot compete with the cost of virgin materials on the basis of supply and demand alone.

There are also further market issues, such as sustainable building labels driving consumer behaviour and industry outputs. The wider market issues such as landfill taxes are also important (but these vary between MS). Overall, cost is the major driver. Technological availability is only a start – there are some available, such as to recycle complex polymers, that are not used due to costs and a lack of a market (e.g. that virgin materials remain more competitive). Even for major waste streams, such as glass, the fact that 90% of glass in construction and demolition waste is landfilled in the EU illustrates the over-riding driver of cost on whether secondary or primary raw materials are used.

One price issue highlighted was that of water consumption, where prices in southern Europe can be higher for industry than in the north, due to water scarcity. This is justifiable to meet objectives, such as those from the Water Framework Directive, but these differences in costs across MS need to be understood in considering the interaction between the IED and the market for specific materials.

One issue regarding markets that is commonly raised with regard to ensuring circular material use is consumer acceptance of secondary materials: "Only where the quality of the secondary raw material is comparable to that of primary material, will trust be established among consumers" and this requires "establishing of quality standards for secondary raw materials" (NEPA, 2018a). Interviewees usually raised this with regard to acceptance of secondary materials by IED installations as material inputs. Little has been raised regarding consumer acceptance of outputs such as by-products. However, Harris et al. (2019) reported that, in Germany, producers of coal combustion products formed the "Mercury Capture Initiative' to publicise implementation of BAT regarding mercury capture, so promoting the quality of these by-products for use in the construction sector.

A key market-related issue is that of materials security. One response for some manufacturers is to develop different models to secure materials. For example, in France a motor manufacturer has acquired scrapyards for vehicle dismantling to ensure those materials are available and not at risk of price fluctuations. Another model is that of product leasing, e.g. Philips leases medical machinery rather than sells it, so that they can retain the materials. This does, however, affect decisions on product design and also production processes. Some of this links to future consideration within the Ecodesign Directive as well as other market developments such as chemical leasing[69], but also about understanding material flows and process decisions within the IED installations.

There has been a clear and consistent message that markets are major drivers. Further, while MS may intervene in some ways, such as differential taxation on types of materials, there can be major economic (including global) changes that overwhelm other considerations.

4.4. Conclusions, including reflections on the untapped potential for the IED and for IED installations to contribute to the CE

Introduction

From the findings in this section, it is clear that there is no one "key" to unlock further potential of the IED and IED installations to contribute to the CE. Some categories of installations already seem to be contributing as much as is possible. For others, a range of factors may affect what materials they may use and the waste and by-products they produce. These may be technical, market-based, legislative, etc. The IED as an instrument may, or may not, be a factor in this. These conclusions, therefore, explore the extent and nature of this untapped potential.

Material flows and the untapped potential of IED installations to contribute to the circular economy

On material flows, a key conclusion, even with the limited information available, is that the performance of industrial sectors (and individual businesses in a sector) varies and that for some businesses, and possibly even whole sectors, there is good circularity of materials in the sector (within or between installations or through well-established further processing).

From the evidence gathered during this study, it is evident that determining the untapped potential of IED installations to contribute to the CE is far from straightforward. This is more than simply the issue of data availability (which is a constraint in some cases). If an installation produces waste going to final disposal, there is untapped potential as, by one definition of the CE, we should be looking to reduce that to zero. However, it is important to consider the context of such a statement. Is it part of the overall concern about waste in European society or is it about the need for IED operators to perform better? There are different commercial and legal constraints on by-products, secondary raw materials and waste that operators are facing. Therefore, if there is untapped potential, it is important to be clear who can untap it. Waste from an

[69] Chemical Leasing is a service-oriented business model that shifts the focus from increasing sales volume of chemicals towards a value-added approach. The producer mainly sells the functions performed by the chemical and functional units are the main basis for payment. https://chemicalleasing.org/what-chemical-leasing

IED installation that is easily processed by another business to usable materials is not untapped potential when viewed at the scale of society as a whole.

It is also important to note that while one might view all waste as untapped potential as theoretically one might reduce this to zero, this is not the case with the use of secondary raw materials as material inputs. Again, there are different constraints on use of these materials by installations (so, again, the question arises as to who can untap that potential). However, for many installations it is not possible to assume that primary raw materials could simply be replaced by secondary raw materials if the relevant barriers were overcome. In some cases, supply of recycled material (even if optimised) cannot meet production demands.

A critical emphasis from a (non-industry) interviewee was that IED sectors in Europe are not generally producing unnecessary waste. Waste is expensive to manage and, if there are alternatives (reduction, by-products, etc.), it would make strong business sense to reduce waste production. Much of this change has been driven by waste policies (at EU and national level) disincentivising waste production over many years. In contrast, the same cannot be said for material inputs to industry. There is the primary determinant of price for the purchased material (primary compared to secondary raw materials) and cost of processing that material (e.g. scrap metal compared to ore). Further, there are issues of material quality. However, these are economic and technical drivers. In most cases there has not been a strong policy driver (e.g. a disincentivising tax on primary materials) comparable to that seen in waste management.

The findings earlier in this section set out the conclusions for secondary material use, and untapped potential regarding waste, for different industry sectors and these will not be repeated here, but are briefly summarised in the table below. In summary these are:

- No sector is turning away available secondary material if that is of the right quality and price. Indeed, some sectors have higher costs in using such secondary materials (including waste) compared to primary material sources.
- The limitations on secondary material use may arise on the supply side: either society does not produce quantities of waste material as large as the overall production volumes or it does not collect and provide that material to the relevant IED sector. This is particularly true for mature markets, although for some developing markets, there is likely to be capacity to absorb the unused waste material that is already available.
- Within some sectors (non-ferrous metals, chemicals), techniques may be developed that will enable new materials to be recovered or materials to be recovered from waste that is currently of too poor quality. Therefore, the potential for secondary material use may increase in the future.
- The issue of combustion of waste as untapped potential needs to be explored further. Clearly combustion prevents material recovery, but there are conceptual differences between renewable and non-renewable materials and this needs to be explored within wider energy use and climate policy contexts.

Most sectors have found uses for their unwanted material. Some hazardous material is incinerated for health reasons. There are small quantities produced from some sectors and it is possible that further material recovery is possible from this. However, further sector and material specific research is needed.

Table 4.12 Summary of the untapped potential for the CE for different industry sectors

Sector	Untapped secondary material use	Untapped waste potential
Energy	Possible issue with combustion of waste.	Small in EU 15 – maybe larger in rest of EU.
Refining	Very little.	34% of waste recycled – possibly more potential for material recovery from remainder.

Sector	Untapped secondary material use	Untapped waste potential
Iron and Steel	Limitations are in supply of material – not untapped potential in the sector.	Most slag used. 5% goes to landfill, so possible small untapped potential.
Non-ferrous metals	Limitations are largely on supply of material, rather than untapped potential. However, new techniques to recover additional metals could be developed.	There is little if any untapped potential regarding slag. Possible untapped potential for extraction of material value from WWTP sludge if new techniques developed.
Chemicals	Limitations are largely on supply of material, but improved techniques may lead to additional recovery from poor quality waste.	The sector produces very little waste, so little untapped potential.
Food and Drink	The strict hygiene standards exclude use of secondary materials directly into the sector.	The untapped potential in this sector is minimal.
Cement, etc	About 5% of raw materials in the production of clinker in Europe are recycled material. There is limited scope to increase this from other sectors. However, the sector combusts waste and recovery of material from this represents untapped potential.	There is almost no waste from the sector so there is little untapped potential.
Surface Treatment with Solvents	There is some internal recycling, but untapped potential is unclear and may be better done by the primary producers of solvents.	There is some untapped potential to ensure that all waste solvents are provided to those that can recover them, but the extent has not been possible to quantify.
Pulp and Paper	Sector uses much recycled material and could absorb more, so this untapped potential would need to be realised by waste collection and sorting sectors.	Recycling of paper creates much more waste than virgin material, so waste volumes increase as recycling increases. There is some likely future untapped potential, but it is not clear what would be under the control of operators.
Rendering	The sector's material input is all secondary material. Therefore, there is no untapped potential.	There is no untapped potential from this sector.
Ceramics	The sector uses considerable secondary material inputs. Further quantities could be absorbed so, of itself, the sector has little untapped potential.	There is little untapped potential for improved material circularity regarding material outputs.
Glass	The untapped potential is not at the level of the installations, which can absorb further secondary material. The limitations are within consumer behaviour and the waste sector.	The sector also produces little waste. There is little untapped potential.
Textiles	The sector is so integrated within wider textile material cycles, it has not been possible to reach a conclusion on the specific untapped potential of IED installations,	The sector is so integrated within wider textile material cycles, it has not been possible to reach a conclusion on the specific untapped potential of IED installations,

In looking at the untapped potential, it might be assumed that material flows, as judged from a CE perspective, are progressing in industrial sectors or, at worst, remaining static. However, this is not necessarily the case. We do not have quantitative data to demonstrate a movement backwards in sustainable material use, but there are two issues raised which suggest that this is possible.

The first is the simple matter of price as a key driver or barrier to use of secondary raw materials or the ability to sell by-products. Many industry stakeholders stressed this as an important factor and that current sustainable material flows would be at risk if prices became unfavourable. They did not point out cases where there had been a retreat, so this may be a theoretical, if albeit realistic, risk.

The second concerns the consequences of national non-toxic environmental policies. These raise questions over the use of some existing by-products and could result in lower use in future and increased diversion to landfill. The evidence also found that this could have knock-on impacts in other MS. It is not appropriate for this study to comment or interpret national policies such as these. Nor is it appropriate to comment on whether or how to trade off toxicity issues and circular material use as environmental objectives. However, it is important to note that there are environmental policy pressures that are challenging some circular material flows relevant to IED installations and these might increase in the future.

Overview of opportunities and constraints affecting the untapped potential to contribute to the CE

The results of the interviews and literature review revealed a number of factors influencing whether material inputs to and outputs from IED installations may become more circular. These are summarised in the following two figures.

Figure 4.2 provides an illustrative overview of the regulatory, market and other contexts for material flows and IED installations upstream of installations, the material inputs.

The first issues to consider are the technical constraints – is the material of the right quality to meet the needs of the installation? This is common to both primary and secondary materials.

Secondly, the price difference between primary and secondary materials is a common concern for several interviewees when seeking to make more circular material decisions. Alongside these issues are legal constraints (often linked to quality issues, especially for sectors such as food and drink). There are also issues of consistency and security of supply, such as whether operators can rely on sources such as by-products and waste from other IED installations or the waste sector.

Figure 4.3 provides a schematic overview of the regulatory, market and other contexts for material flows and IED installations downstream of installations, i.e. material outputs such as by-products and waste. Waste may be subject to final disposal (so is not circular) or processed into secondary materials. Alternatively, the installation itself may produce by-products. All of these are subject to legal requirements from other EU law (chemicals, waste, etc.) and diverse interpretations at MS level. Further, there are cost constraints and the ability to sell by-products, for example, depends on markets, consumers, acceptance, etc., all of which may vary across Europe.

The mixtures of factors for both upstream and downstream material flows for IED installations includes elements which may be common for different types of installation across the EU, but interviewees have often emphasised that the combination of factors results in quite different circumstances for comparable installations in different locations in Europe and also that there have been notable changes over time. These points are discussed elsewhere in this report. However, the point to stress here is the multiplicity of potential influences. In some cases, there may be several interacting drivers and constraints and these complexities raise challenges in how to intervene to create a desired outcome (and what may be an appropriate intervention for one material or sector may not be appropriate for another). In other cases, there might be several influences, but a very limited number may be of over-riding importance.

Figure 4.2 Schematic overview of the regulatory, market and other contexts for material flows and IED installations upstream of installations, i.e. material inputs

Note: material flows are illustrated in orange, legal points in blue and market issues in yellow.

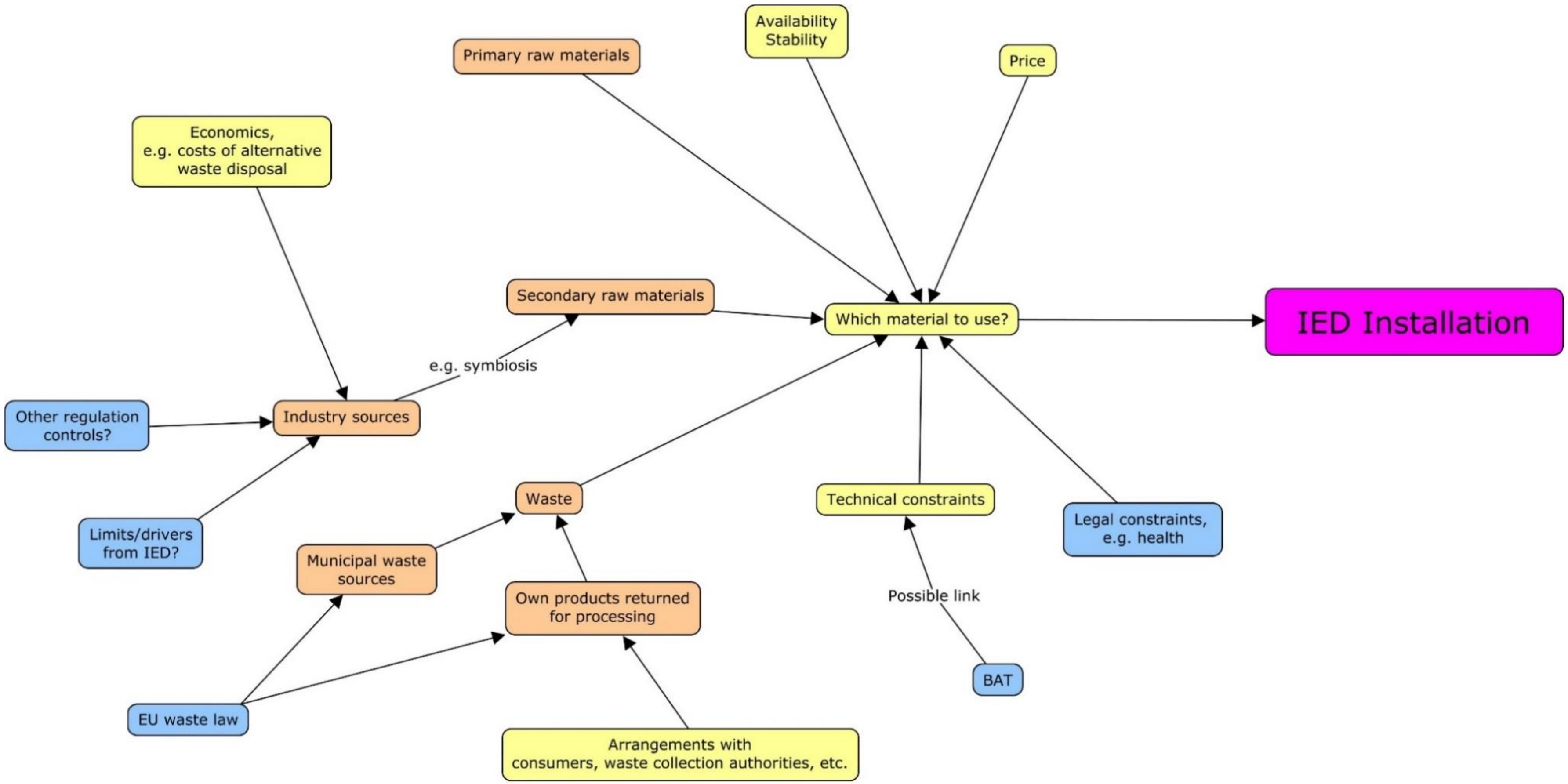
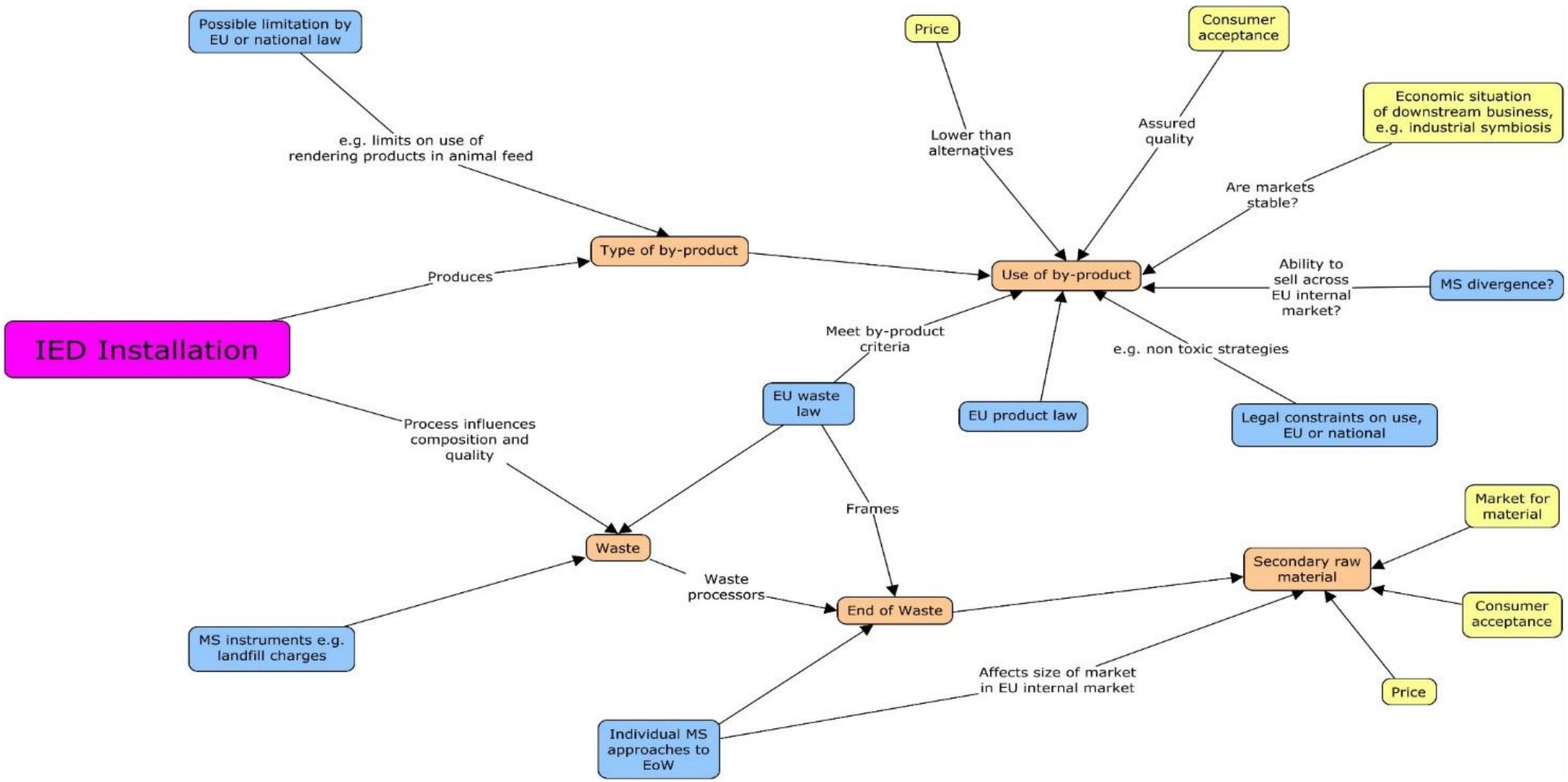


Figure 4.3 Schematic overview of the regulatory, market and other contexts for material flows and IED installations downstream of installations, i.e. material outputs

Note: material flows are illustrated in orange, legal points in blue and market issues in yellow.



IED and the untapped potential to contribute to the CE – the instrument itself

The evidence from the literature review and interviews found very few concerns over how the text of the directive itself addresses the CE. Most interviewees (from all categories of stakeholder) viewed the directive as a facilitator of action by operators to improve circular material use by installations, but it is not a driver. However, far from viewing this as a limitation of the directive, most interviewees thought that this should be expected given the range of other factors influencing material flows (as illustrated in the two figures above).

Interviewees, therefore, largely viewed the provisions within the IED regarding resource efficiency as sufficient to support actions by operators towards the CE. However, three possible issues of the instrument itself were raised in interviews.

The first was a dissenting view on the adequacy of the provisions on resource efficiency, i.e. the provisions on objectives for operations, issues to consider in permit applications and permit conditions, BAT, exchange of information, etc., in Article 11, 12, 13, 14, 15, Article 32 and Annex III. It was suggested that the wording for resource efficiency could be amended to be more explicit in support of circular material cycles. However, it was not possible to obtain further evidence of whether this would deliver additional outcomes beyond those which are possible with the current text – i.e. whether this would represent untapped potential within the directive.

A second issue raised was on the Article 15 provision for competent authorities to grant temporary derogations for up to nine months from ELVs derived from BAT Conclusions to enable an operator to test and use emerging techniques which might provide for higher level of environmental protection. It was suggested this time limit should be extended. No specific example of a circular material outcome not achieved because of the current provision was provided. Therefore, it has not been possible to identify specific limitations on circular material flows by installations from this (or what would be delivered by extending the time limitation).

Some interviewees raised the issue of the limitation in the scope of the IED – the focus on an installation, which does not capture upstream and downstream issues and thus wider value chain issues. However, while there is a desire to capture this to take a more integrated view of materials, no practical suggestions were made on how the directive could be extended in a practical legal way to do this, nor what this would mean for other EU law, such as that on waste or products. The issue of the scope of the IED has been debated for many years (from the period of adoption of IPPC), for different reasons (such as what is, or is not, a directly associated activity). Again, such issues are wider than circular material use and beyond the immediate scope of this report.

In conclusion, it is important to stress that few interviewees expressed any problems with the directive as it stands and, therefore, it was not identified that there is untapped potential for the delivery of the CE. Where suggestions for potential change were made, there is little concrete evidence of what such changes would deliver in practice. It is also important to recognise that the IED often allows considerable freedom for operators and regulators to address issues not captured by the core IED regulatory regime. For example, wider upstream or downstream issues might not be within IED, but this does not prevent such issues being part of regulatory thinking at MS level (as long as this is consistent with other EU law, such as waste law). This is considered further below, but it is important to highlight that, if there is a limitation in what the directive might achieve, the answer might not be in changing the directive, but in seeking to achieve the desired outcomes through other means.

BREFs and BAT Conclusions and the untapped potential for the CE

The Ricardo and Vito (2019) report made several recommendations relating to BREFs and the BAT Conclusions. Here, we focus on five points.

The first concerns the setting of qualitative BAT Conclusions for circular material flows. It is clear from the existing BAT Conclusions and draft revised BREFs that there are number of such BATs. Some are very specific to individual activities within a specific category of installation. Others are more widely applicable. These were generally supported by interviewees of all stakeholder types. Some indicated that further such BATs may be developed, but no specific suggestions for these were made. In conclusion, such qualitative BAT are supportive of circular material use and should be further explored and adopted as appropriate in order to facilitate the further potential of IED installations to contribute to the CE. However, we cannot recommend any specific new further examples to consider.

The second, and most controversial, option concerns the setting of quantitative BAT-AEPLs for the CE for installations (e.g. on use of secondary raw materials, production on by-products, etc.). Industry interviewees strongly objected to this. They argued firstly that it would not be possible to set targets across all sectors due to the extreme diversity in current material flows. Another option would be some targets in sectoral, vertical BREFs. Again, this was objected to, firstly because of diversity within sectors, but also because factors outside of the control of an operator determine if there are secondary materials to use (and are priced competitively) as well as whether there are markets for by-products (and having a market is a requirement for a material to be a by-product under EU law).

It should be noted that if qualitative (or quantitative) objectives are established as BAT, these may have trade-offs for other environmental impacts. For example, the glass sector could use filter dust as a secondary material input, but this contains sulphur (which could increase SO_2 emissions) and its use may require more energy. For some contaminants, such as mercury in filter dust, there are techniques to remove these, but this requires energy. The questions would be what are the most important environmental concerns and where does the balance lie? Answering these questions is well beyond the scope of this study, but it is important to note that such trade-offs may arise. A consideration of the potential of an IED installation to contribute to the CE would need to take account of the primary objective of the IED to protect the environment as a whole.

These are strong arguments, therefore, against quantitative targets. However, some other interviewees (NGOs and competent authorities) supported such targets. The argument is that, without them, industry will not move forward. Having said this, no suggestion was made of an example of a target that would prove to be a driver that does not currently exist.

Our conclusion is that there may be a role for quantitative targets in BREFs and BAT Conclusions to help unlock the potential of IED installations to contribute to the CE, but we cannot suggest specific examples. We recognise the concern that some targets would be counterproductive or irrelevant or quickly out of date as markets change, but this does not mean that all targets are inappropriate.

A third area also raised by Ricardo and Vito (2019) is on information. That report focused on exchange of information and there is a serious issue with data availability and confidentiality. JRC is looking at ways to work round this, but the closer environmental performance is linked to business performance, the more important confidentiality will be. We do not have a specific recommendation on how to address this, but some solution should be determined, or circular material flows will not be properly understood.

A further, fourth, issue raised was that of tracking hazardous substances in materials into, through and out of installations in order to provide information for those using materials and stimulating substitution, elimination, etc. As HAZBREF (2020) states "Systematic and transparent collaboration with upstream and downstream partners of the value chain improves the flow of information on hazardous substances within the chain" and supports non-toxic circulation of materials. Consideration should be given to this, at least in the BREF discussions.

Finally, one possible approach to improving circular material flows for installations would be for the EMS of each installation to be extended to include a circular materials plan. This would build on the new provision in the 2019 BAT Conclusions for the food, drink and milk industries. As described above, these included a provision (BAT 2) "to establish, maintain and regularly review … an inventory of … raw materials consumption … as part of the environmental management system" and (BAT 6) adopt a monitoring strategy for this with the aim of increasing resource efficiency. BAT 2 focuses on raw materials consumption, whereas wider circular materials management requires a consideration of inputs and outputs. Further, for good dialogue with regulators, the context of material flows needs to be made transparent – markets, costs, reliability of supply, etc. However, if an expanded circular materials plan were to be included in the EMS, this could be a positive step forward that both drives improvement from the EU level, but allows for local factors and changing circumstances to be taken fully into account. Such a requirement would provide the basis for discussion with the competent authority on positive steps forward. This could include actions on hazardous substances, creating new by-products, etc. Some of these commitments could be included in permit conditions in ways that would be hard to set out in BAT Conclusions. Such an approach would help to unlock the potential of IED installations to contribute to the CE.

Practical application of the IED and the contribution to the CE

The importance of the practical implementation of the IED through the decisions made by operators and regulators was highlighted as important in supporting circular material flows by installations. The view was expressed that competent authorities need to work positively with industry to deliver circular material outcomes. This requires action beyond a "box ticking" exercise of BAT Conclusions in permits. It requires discussion on materials being used and why and what is happening to materials produced and why. From this, process changes to deliver improvements may be made to support the CE.

This could be done in the context of a circular materials plan or within an EMS, etc. In any case it requires wider thinking than some regulators have experience with. Further, there is experience that some of this interaction is best done at company or sector level rather than at installation level. It also involves supporting industry to do more than might be required as a minimum to be compliant with the IED.

Few interviewees were able to comment specifically on such practical implementation in the permitting process. However, several expressed concern over the ability of some competent authorities to do this. Such activity takes time (which may not be available) as well as expertise (which may be limited). These concerns are commonly raised where more complex (or less prescribed) actions are required and while support tools are produced (e.g. by IMPEL), capacity concerns will be a likely constraint for, at least, some competent authorities.

Having said this, this study has identified some examples of actions by competent authorities beyond the core implementation of the IED to support the CE. Further, the Make it Work and IMPEL Guidance suggests a variety of different strategic approaches that competent authorities might take (depending on the issues to be addressed, their institutional structure, etc.). However, within the limitations of the information gathering in this report, it has not been possible to provide a critical evaluation of possible approaches.

It is important to note that, while action by competent authorities is clearly for them rather than EU level bodies, EU level bodies can support this by the development of guidance, exchange of best practice, etc. This might be done by the Commission or by others such as IMPEL.

Other EU law and national policy and their impact on IED installations and the CE

The evidence from interviewees and the literature has found strong views concerning EU waste law, in particular, as a constraint on how well IED installations perform with regard to the CE. Issues highlighted include the definition of "waste", the criteria for by-products and how end-of-waste is determined. Concerns include both the EU law and the diversity of approaches applied in MS (acting as domestic constraints and constraints for material flows in the internal market). EMF (2015) succinctly concluded "Waste regulations treat waste primarily as an environmental hazard and seek to ensure that waste managers dispose of this waste safely, rather than looking at waste as a source of valuable materials and products. As a result, redesign, recovery, reuse, and trading often face considerable administrative or legal barriers that stop or severely limit these activities." Of course, actions under the new CEAP may address these concerns.

Others noted that food safety legislation is a constraint. The importance of other product legislation was noted, but no constraints were specifically identified. Indeed, the wider approach for the Ecodesign Directive set out in the CEAP is seen as a positive development.

Alongside EU law, national law and policy can impact on what is possible for material flows in and out of IED installations. The main example has been non-toxic strategies. Such policies are a constraint. They can be accommodated in practical implementation at MS level, but they need to be taken into account if targets were to be developed at EU level.

In October 2020 the Commission published its "Chemicals Strategy for Sustainability" (COM(2020)667, 13.10.2020). It emphasises the commitment in the European Green Deal to the toxic-free environment. In this regard it includes an action that "the legislation on industrial emissions promotes the use of safer chemicals by industry in the EU by requiring on-site risk assessments and by restricting the use of substances of very high concern". This seems largely concerned with direct chemical use (with the potential to enter products), but would potentially aid in reducing contamination of some waste and, therefore, its ability to be processed to secondary materials.

There is specific emphasis in the new Chemicals Strategy on achieving safe products and non-toxic material cycles as a condition for the CE as the creation of a well-functioning market for secondary raw materials is being slowed down by, inter alia, the lack of adequate information on the chemical content of products. The Commission stated, "As a principle, the same limit value for hazardous substances should apply for virgin and recycled material." This is a point raised by several interviewees in this study. However, there may be exceptional circumstances where a derogation from this principle may be necessary, where the secondary material is used in defined and safe applications. The Commission proposes several actions to support this, including better information on the presence of substances in materials. This would also meet concerns raised during this study, particularly on operators being confident on the composition of the secondary material they receive. Note that this would focus on hazardous substances (of concern to some operators), but would not likely address other quality concerns of material inputs to installations. A specific area of actions concerns chemical pollution in natural environment. This could have resulted in sweeping actions on material inputs to the environment containing hazardous substances (as seen at national level). However, actions proposed by the Commission are limited and do not seem to affect use of by-products, etc.

Conclusions on these issues are for others to address. However, they contain some constraints on what some IED installations can deliver with regard to the CE. Where such constraints apply, in order to improve material flows, looking to do this by changing the IED or changing its practical implementation may not necessarily be the right target.

Market issues and the potential to contribute to the CE

Markets are overwhelming drivers for material flows. This concerns not only price, but consumer acceptance, etc. These factors change and are influenced by other developments (such as loss of markets for slag if it is deemed to contain toxic substances). The latter is an example of where existing markets for secondary materials may decline.

Further, when one considers the EU internal market the issue of different application of EU waste law (e.g. on end-of-waste status) is a further interaction. However, there are strong cross-border markets for some by-products, such as fly ash from large combustion plants.

Concern has been raised over market failures for the CE, especially where secondary materials are more expensive than primary raw materials. This can be an issue for some construction materials or plastics, but is not for metals. This is a matter for government intervention, such as differential taxation. At present, such intervention is largely one at MS level and, therefore, has knock-on implications for the internal market.

This report is not the place to make recommendations for appropriate market interventions. However, understanding changing markets is needed to make workable regulatory decisions in implementing the IED and to understand what their constraint is on the potential for any particular material for an installation and its relationship to the CE.

Final conclusion

In conclusion, it is important to highlight the following points:

- Many IED installations have made considerable progress in resource efficiency and the CE, reducing waste production and increasing use of secondary raw material (SRM).
- There is little untapped potential for further reduction in waste generated by many installations (there are some exceptions highlighted in the study), as waste disposal is expensive and operators will seek to avoid this. However, some efforts to improve waste quality could promote more circularity by facilitating material recovery.
- IED operators do not control the supply of secondary materials in the wider economy to feed into their installations and are typically keen to use more. For this to happen, two conditions need to be met: the material must be of a minimum quality and the price must be competitive compared to virgin materials. There may be potential for IED operators to take more life-cycle considerations into account when developing materials supply strategies. This could include consideration of material recovery rather than energy recovery of non-renewable materials. Other sustainability considerations could also be integrated in operators' parameters used for selecting supply materials.
- The IED itself has not been a significant driver in these developments. However, it has helped to facilitate them through the flexible provisions in the directive. It currently refers to resource efficiency in several articles. If it were to be amended, these could refer to circular material use to help support operators and regulators to deliver the CE.
- There is no "magic bullet" in the application of IED (such as a change in the directive, a type of BAT, etc.) to improve circular material use by IED installations. Many other factors strongly determine the performance of installations with respect to circular material use (and these should be addressed by others where possible).
- Implementing the IED with regard to the CE requires operators and regulators to consider increasingly complex information, such as understanding material markets and to think beyond the specific limits of the directive. Some competent authorities are doing this, but it would be a challenge for smaller authorities with limited capacity.
- Whilst information provided in BREFs and guidance documents is useful and largely recognised, CE improvements require operator decisions that are adapted to the specific circumstances of the plant. Thus, a one size fits all approach in BREFs is unlikely to be generally effective (except maybe in very clear and documented issues) or appropriate (as market fluctuations occur). For most issues, allowing flexibility on how operators can improve circularity is likely to be more effective, e.g. as part of the operators' Environmental Management System that could include a plan to increase the circularity of materials for the installation (inputs, outputs, opportunities, constraints, etc.). This would be usefully supported by a dialogue between the operator and the permitting authorities.
- There are many constraints (and some opportunities) in other areas of EU law and policy (waste, chemicals, food, products, etc.). Some of these areas are under review. Further, there are national policy developments that are both positively and negatively affecting the use of SRM and use of waste from installations. Ensuring integrated policy making to support the CE will be important if IED installations are to maximise their role in using secondary materials and reducing waste.

5. References

Task 1 references

Adaphos/ECCA 2019. Integrated Post-Processing Technologies in Coil Coating Lines Save Enormous Energy and Reduces Water Consumption and CO2 emissions.

Ademe 2019. Presentation of the Sectorial Transition Plans (STPs).

Akuo Energy 2019. Akuo energy presentation.

Argonne National Laboratory 2019. Water Sustainability of Renewable Fuels.

Beckers/ECCA 2019. Sustainable Coil Coatings - making sugar good for you.

Bellona Foundation 2018. An industry's guide to climate action.

Biofuels International 2020. Crop-based ethanol's path to zero greenhouse gas emissions: Towards Europe's Green Deal.

BOREALIS 2019. Borealis consideration of Reducing Carbon Footprint in Fertilizer Production.

CE Delft 2020. Exploration chemical recycling - Extended summary: What is the potential contribution of chemical recycling to Dutch climate policy.

Cefic 2019. A journey into the Future of Europe with the European Chemical Industry.

CEMBUREAU 2018. Building carbon neutrality in Europe: Engaging for concrete solutions.

CEMBUREAU 2019. Technological pathways and innovation projects for the EU Cement Sector.

CEMBUREAU undated. CEMBUREAU - The Role of Cement in the Low Carbon Economy Roadmap.

CEPI 2013. The two Team Project.

CEPI 2017. Investing in Europe for Industry Transformation. 2050 Roadmap to a low-carbon bioeconomy.

CEPI 2018. The challenge: decarbonising whilst being recycling pioneer.

CEPI undated. The pulp and paper industry from an energy and climate perspective.

Chalmers University of Technology undated. Plastics the material for a sustainable circular future.

Climate Action Tracker 2017. Manufacturing a low-carbon society: how can we reduce emissions from cement and steel.

Concawe 2018. Concawe's Input to the EU Long-term strategy - EII Initiative: Preliminary figures based on on-going Concawe work.

Concawe 2019. Refinery 2050: Conceptual Assessment. Exploring opportunities and challenges for the EU refining industry to transition towards a low-CO2 intensive economy.

Concawe 2019. Refinery 2050: Conceptual Assessment. Exploring opportunities and challenges for the EU refining industry to transition towards a low-CO2 intensive economy. Appendixes.

Concawe 2019. Review: Special Symposium Edition.

Concawe undated. Low Carbon Pathways.

Corpower Ocean 2019. High efficiency wave energy - Corpower Ocean.

CSI/ECRA 2017. Development of State of the Art Techniques in Cement Manufacturing: Trying to Look Ahead.

DECHEMA 2017. Technology Study: Low carbon energy and feedstock for the European chemical industry.

DRIP 2020. Water efficient industrial food production is associated with large energy savings.

EBB 2019. Ceramics 6. EEB input GHG emissions CER BREF review Initial position EEB.

ECCA 2019. Comparative life cycle assessment of pre-painted (coil coated) and post-painted sheet aluminium for the construction market.

ECCA 2019. Comparative life cycle assessment of pre-painted (coil coated) and post-painted sheet steel for domestic appliance manufacture: Summary Report.

ECF - Net Zero 2050 2019. Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry.

ECF - Net Zero 2050 2019. Industrial Transformation 2050 - Towards an Industrial strategy for a Climate Neutral Europe.

ECOFYS 2017. Status and prospects of co-processing of waste in EU cement plants - Executive Summary.

Ecologic Institute Berlin undated. The Innovation Fund: How can it support low-carbon industry in Europe?

ECRA 2017. Evaluation of the energy performance of cement kilns in the context of co-processing.

EEB 2020. EEB alternative proposal for the item: 'GHG emissions / Decarbonization co-benefit from Waste Gas Management and Treatment Systems in the Chemical Sector' under the WGC BREF Review.

EECA 2020. Study on the wider environmental impacts of industry decarbonisation.

EiiF 2020. European Industrial insulation Foundation. EiiF supports EU initiative to become climate-neutral by 2050.

Ekopolitan 2010. Amines: A closer look at the toxic compounds released to the atmosphere by carbon capture processes.

Enel Green power 2019. The 3SUN 2.0 Initiative: Innovative HJT PV Technology Lower Energy Costs.

Energy Transitions Commission (ETC) 2018. Mission Possible: Reaching Net-Zero Carbon Emissions from harder-to-abate Sectors by Mid-Century.

EPE 2019. ZEN 2050 - Imagining and building a carbon-neutral France.

Equinor 2019. Northern Lights Project.

ETH Zurich 2018. A sustainable future for the European Cement and Concrete Industry: Technology assessment for full decarbonisation of the industry by 2050.

ETIP SNET 2020. Flexible Power Generation In A Decarbonised Europe.

Eurelectric 2018. Decarbonisation Pathways.

EUROFER 2019. Low Carbon Roadmap: Pathways to a CO2-Neutral European Steel Industry.

Eurofer 2020. Towards a green deal on steel: Priorities for Transitioning the EU to Carbon Neutrality and Circularity.

Euroheat & Power 2020. Industrial Emissions Directive Review: Study on the wider environmental impacts of decarbonisation.

EUROMOT 2012. Methane Slip from Internal Combustion Gas Engines.

European Climate Foundation 2019. Industrial Transformation 2050 - towards an industrial strategy for climate neutral Europe.

European Commission 2017. CCUS Projects Network.

European Commission 2017. Investing in a smart, innovative and sustainable Industry. A renewed EU Industrial Policy Strategy. Brussels, 13.9.2017 COM(2017) 479 final.

European Commission 2019. CEF: Support to CCS projects and synergies with the Innovation Fund.

European Investment Bank 2019. Innovation Fund - Lessons learned from ner 300 and the future role of EIB in supporting CCS projects.

European Lime Association 2020. IED consultation: Study on the wider environmental impacts of industry decarbonization European Lime Industry contribution.

European Turbine Network (ETN Global) 2020. ETN Hydrogen Gas Turbines – the path towards a zero-carbon gas turbine.

EUTurbines 2019. The gas turbine industry's commitments to drive the transition to renewable-gas power generation. Gas turbines: powering a carbon neutral energy system.

Fulcrum undated. Low Carbon Fuels project.

Griffin, P. and Hammond, G. 2018.Analysis of the potential for energy demand and carbon emissions reduction in the iron and steel sector.

Heidelberg Cement 2019. Workshop European Commission – CEMBUREAU Financing Research & Innovation in the cement sector.

Hybrid joint venture 2019. Steel 3 - HYBRIT CO2 free steel industry.

Hydrogen Europe 2019. GetH2.

Hydrogen Europe 2019. Green Steel.

Hydrogen Europe 2019. H2Magnum.

Hydrogen Europe 2019. H2V NORMANDY & H2V59 - Hydrogen Europe.

Hydrogen Europe 2019. H-Vision.

Hydrogen Europe 2019. Hybrid Steelmaking.

Hydrogen Europe 2019. HySynGas.

Hydrogen Europe 2019. LOHCIT.

Ibn-Mohammed, T., Randall, C.A., Mustapha, K.B., Guo, J., Walker, J, Berbano, S., Koh, D., Wang, D.C. and Sinclair, I.M. 2019. Decarbonising ceramic manufacturing: A techno-economic analysis of energy efficient sintering technologies in the functional materials sector.

ICF & Fraunhofer 2019. Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 2: Scenario analysis and pathways to deep decarbonisation.

ICF & Fraunhofer undated. Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 1: Technology Analysis.

ICF and Fraunhofer 2019. Industrial innovation: Pathways to deep decarbonisation of Industry ; and Part 1: Technology Analysis.

IEA 2013. Technology Roadmap: Energy and GHG Reductions in the Chemical Industry via Catalytic Processes.

IEA 2019 Technology report: Transforming Industry through CCUS.

IEA 2019. Technology report – The Future of Hydrogen.

IEA Bioenergy 2020. Developing business models for efficient use of biomass: Summary and conclusions from the IEA Bioenergy workshop, Tallinn (Estonia).

IES and VUB 2018. Industrial Value Chain: A Bridge Towards a Carbon Neutral Europe.

IES and VUB 2018. Industrial Value Chain: A Bridge Towards a Carbon Neutral Europe – Addenda.

IES and VUB 2016 Decarbonising energy intensive industries: The Final Frontier

INA 2019. BIO - CCUS/CCUS potential in Croatia: Short Overview.

Institute of European Studies (IES) 2016. Decarbonising energy intensive industries: The Final Frontier.

Institute of European Studies (IES) 2018. A Bridge Towards a Carbon Neutral Europe.

Institute of European Studies (IES) 2018.Decarbonization of industrial sectors: the next frontier.

International Energy Agency (IEA) 2018. Technology Roadmap: Low-Carbon Transition in the Cement Industry.

IOGP 2019. The Potential for CCS and CCU in Europe – Report to the thirty second meeting of the European Gas Regulatory Forum 5-6 June 2019.

Jernkontoret 2019. Steel 6 - The proactive and competitive Swedish steel industry of the future.

Jernkontoret 2020. HYBRIT - towards fossil-free steel production.

Jesper Sand Damtoft 2018. Climate Change Solutions utilising local symbiosis.

JRC 2017. Best Available Techniques (BAT) Reference Documents for Combustion Plants.

JRC 2017. EE and GHG mitigation from petrochemicals.

JRC undated. Energy efficiency and GHG emissions: prospective scenarios for the chemicals and Petrochemicals industry.

Karlsruhe Institute of Technology/ECCA 2019. Energy Efficient Coil Coating Process.

Karlsson, M., Alfredsson, E. and Westling N. 2019. Climate policy co-benefits: a review.

Klimadan 2020. Manure cooling in pig farms – Intensive rearing of pigs.

KTH Royal Institute of Technology/ECCA 2019. Bio-based building blocks for organic coatings: from reactive diluents in coil coatings to UV-curable coatings utilizing epoxy chemistry.

LafargeHolcim 2019. LafargeHolcim CO2 Reduction Projects 2020-2030.

LOVOCHEMIE 2019. CO2 Capturing via Gypsum Conversion.

Many 2019. Innovation Fund Workshop.

Martin, M., Wetterlund, E., Hackl, R., Holmgren K. and Peck, P. 2017. Assessing the aggregated environmental benefits from by-product and utility synergies in the Swedish biofuel industry.

Material Economics 2018. Material Economics, The Circular Economy: a Powerful Force for Climate Mitigation, Transformative innovation for prosperous and low-carbon industry.

Minesto 2019.Power to change the future.

Minijos Nafta 2019. Minijos Nafta Innovation Fund Workshop 5 Sept 2019 Oslo.

Mitsubishi Hitachi Powers Systems (MHPS) Europe GmbH 2019. Use of biomass and hydrogen in thermal power plants towards EU carbon neutrality.

Mitsubishi Hitachi Powers Systems (MHPS) Europe GmbH 2019. Use of biomass and hydrogen in thermal power plants towards EU carbon neutrality PPT.

Neo Carbon Energy 2015. Emission-Free Future Now Available: Impact and Results.

Ocean energy 201.9 Ocean energy - A world of power.

OECD 2019. Low and zero emissions in the steel and cement industries.

OMV 2019. OMV Refining & Petrochemicals: Innovation Portfolio.

Policy Forum 2017. Rockström et al, A roadmap for rapid decarbonisation.

Port of Antwerp 2019. Development of CO2 capture and transport infrastructure in Port of Antwerp.

Publications Office of the European Union 2019. Masterplan for a Competitive Transformation of EU Energy-intensive Industries Enabling a Climate-neutral, Circular Economy by 2050.

right. Based on science 201.9 What if the 30 German stock market's largest and most liquid companies would reach their current climate targets?

Rocky Mountain Institute 2020. Hydrogen's Decarbonization Impact for Industry.

Rokkedahl Energy 2020. Heat exchanger for Poultry houses – Intensive rearing of poultry.

SABELLA 2019. The PHARES Project.

Salzgitter AG 2019. Steel 4 - SALCOS-Summary.

SARTEC 2019. Development of an NMR Analyzer for Refinery Applications: Increasing data availability for improved process operations.

Scottish Environment Protection Agency and Natural Scotland 2015. Review of amine emissions from carbon capture systems.

SIMEC Atlantis Energy 2019. 10 MW Raz Blanchard tidal power.

Steelanol 2020. Steelanol recycles carbon into sustainable, advanced bio-ethanol.

SUSCHEM 2019. Strategic Innovation and Research Agenda: Innovation Priorities for EU and Global Challenges.

SveMin 2018. Roadmap for a competitive fossil-free mining and minerals industry in Sweden.

Swedish Environmental Protection Agency 2020. The wider environmental impact of decarbonisation - contribution from Sweden.

Thunman, H., Berdugo Vilches, T., Seemann, M., Maric, J., Cañete Vela, I., Pissot, S. and Nguyen H. 2019. Circular use of plastics-transformation of existing petrochemical clusters into thermochemical recycling plants with 100% plastics recovery.

Tocardo 2019. The Dutch and water, a royal combination.

Torero 2019. TOR refying wood with Ethanol as a Renewable Output: large-scale demonstration.

UBA (German Environment Agency) 2019. A resource efficient pathway towards a greenhouse gas neutral Germany.

UBA (German Environment Agency) 2019. Comparative analysis of options and potential for emission abatement in industry – summary of study comparisons and study factsheets.

UK Government, Department for Business, Energy & Industrial Strategy and Department of Energy & Climate Change, 2015a. UK Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050 - Iron and Steel.

UK Government, Department for Business, Energy & Industrial Strategy and Department of Energy & Climate Change, 2015b. UK Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050 – Chemicals.

UK Government, Department for Business, Energy & Industrial Strategy and Department of Energy & Climate Change, 2015c. UK Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050 -Oil Refining.

UK Government, Department for Business, Energy & Industrial Strategy and Department of Energy & Climate Change, 2015d. UK Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050 - Pulp and Paper.

UK Government, Department for Business, Energy & Industrial Strategy and Department of Energy & Climate Change, 2015e. UK Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050 – Cement.

UK Government, Department for Business, Energy & Industrial Strategy and Department of Energy & Climate Change, 2015f. UK Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050 – Glass.

UK Government, Department for Business, Energy & Industrial Strategy and Department of Energy & Climate Change, 2015g. UK Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050 – Ceramics.

UK Government, Department for Business, Energy & Industrial Strategy, 2017a. UK Industrial decarbonisation and energy efficiency action plans -cement.

UK Government, Department for Business, Energy & Industrial Strategy, 2017b. UK Industrial decarbonisation and energy efficiency action plans -ceramic.

UK Government, Department for Business, Energy & Industrial Strategy, 2017c. UK Industrial decarbonisation and energy efficiency action plans – chemical.

UK Government, Department for Business, Energy & Industrial Strategy, 2017d. UK Industrial decarbonisation and energy efficiency action plans -food and drink sector.

UK Government, Department for Business, Energy & Industrial Strategy, 2017e. UK Industrial decarbonisation and energy efficiency action plans -Oil Refining Sector.

UK Government, Department for Business, Energy & Industrial Strategy, 2017f. UK Industrial decarbonisation and energy efficiency action plans -Pulp and Paper Sector.

Umweltbundesamt 2019. Resource-Efficient Pathways towards Greenhouse-Gas- Neutrality.

Universidad Pontificia Comillas 2018. A Review of Cross-sector Decarbonisation Potentials in the European Energy Intensive Industry.

VTT 2019. Outlook on bioenergy combined with carbon capture, utilization and storage.

Wuppertal Institute 2018. A review of technology and policy deep decarbonization pathway options.

Zero Emissions Platform 2017. Climate solutions for EU industry: interaction between electrification, CO2 use and CO2 storage.

Zero Emissions Platform 2017. Commercial Scale Feasibility of Clean Hydrogen.

Zero Waste Scotland 2015. Zero Waste Scotland, 2015. Industrial Decarbonisation and Energy Efficiency Roadmaps: Scottish Assessment. See Appendix A for the list of references under Task 1.

Task 2 references

Abbasi, T. and Abbasi, S. A. 2010. Biomass energy and the environmental impacts associated with its production and utilization.

Acar, C. and Dincer, I. 2014. Comparative assessment of hydrogen production methods from renewable and non-renewable sources.

Akella, A. K., Saini, R. P. and Sharma, M. P. 2009. Social, economical and environmental impacts of renewable energy systems.

An, J., Middleton, R. S. and Li, Y. 2019. Environmental Performance Analysis of Cement Production with CO2 Capture and Storage Technology in a Life-Cycle Perspective.

Archer S. A. and Steinberger-Wilckens R. 2018. Systematic analysis of biomass derived fuels for fuel cells.

Balomenos, E., Panias, D., Paspaliaris, I., Friedrich, B., Jaroni, B., Steinfeld, A., Guglielmini, E., Halmann, M. and Vishnevsky, I. 2011. Carbothermic reduction of alumina: a review of developed processes and novel concepts.

Brough, D. and Jouhara, H. 2020. The aluminium industry: A review on state-of-the-art technologies, environmental impacts and possibilities for waste heat recovery.

CEMBUREAU 2020. Reaching climate neutrality along the cement and concrete value chain by 2050.

CEPI 2013. CEPI - Two Teams Project Report.

CEPI 2018. The challenge: decarbonising whilst being recycling pioneer.

Chan, Y., Petithuguenin, L., Fleiter, T., Herbst, A., Arens, M. and Stevenson, P. 2019. Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 1: Technology Analysis.

Demirbas, A. 2009. Political, economic and environmental impacts of biofuels: A review.

Gasparatos, A., Doll, C. N., Esteban, M., Ahmed, A. and Olang, T. A. 2017. Renewable energy and biodiversity: Implications for transitioning to a Green Economy.

Hills, T. P., Sceats, M., Rennie, D. and Fennell, P. 2017. LEILAC: Low cost CO2 capture for the cement and lime industries.

Jouhara, H., Khordehgah, N., Almahmoud, S., Delpech, B., Chauhan, A. and Tassou, S. A. 2018. Waste heat recovery technologies and applications.

Luderer, G., Pehl, M., Arversen, A., Gibon, T., Bodirsky, B. L., Sytze de Boer, H., Fricko, O., Hejazi, M., Humpenöder, F., Iyer, G., Mima, S., Mouratiadou, I., Pietzcker, R., Popp, A., Van den berg, M., Van Vuuren, D. and Hertwich, E.G. 2019. Environmental co benefits and adverse side-effects of alternative power sector decarbonization strategies.

Material Economics 2019. Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry.

Nie, Z., Korre, A. and Durucan, S. 2011. Life cycle modelling and comparative assessment of the environmental impacts of oxy-fuel and post-combustion CO2 capture, transport and injection processes.

Petrakopoulou F. and Tsatsaronis G. 2014. Can Carbon Dioxide Capture and Storage from Power Plants Reduce the Environmental Impact of Electricity Generation.

Petrescu, L., Chisalita, D. A., Cormos, C. C., Manzolini, G., Cobden, P. and van Dijk, H. A. J. 2019. Life Cycle Assessment of SEWGS technology applied to integrated steel plants.

Ruuskanen, V., Givirovskiy, G., Elfving, J., Kokkonen, P., Karvinen, A., Järvinen, L., Sillman, J., Vainikka, M. and Ahola, J. 2020. Neo-Carbon Food concept: A pilot-scale hybrid biological–inorganic system with direct air capture of carbon dioxide.

Schmidt, P., Weindorf, W., Roth, A., Batteiger, V. and Riegel F. 2016. Power-to-Liquids Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel.

Stropnik, R., Sekavčnik, M., Lotrič, A. and Mori, M. 2019. Life Cycle Assessment of 1kW PEMFC system with the focus on critical materials.

Swedish, I. C. T. and Kimab, S. 2014. Compact industrial LIBS systems can assist aluminum recycling.

Thyssenkrupp 2020. Chlor-Alkali Electrolysis: Three Best-in-Class Technologies.

Vogl, V., Åhman, M. and Nilsson, L. J. 2018. Assessment of hydrogen direct reduction for fossil-free steelmaking.

Wyns, T. and Khanderkar, G. 2020. Metals for a climate neutral Europe.

Task 4 references

Accenture 2017. Taking the European Chemical Industry into the Circular Economy. https://www.accenture.com/_acnmedia/pdf-45/accenture-cefic-report-exec-summary.pdf

Accenture 2020. Winning in a Circular Economy. Practical Steps for the European Chemical Industry. https://cefic.org/app/uploads/2020/04/Accenture-Winning-In-A-Circular-Economy-Executive-Summary.pdf

CEFIC 2020. 2020 FACTS & FIGURES of the European chemical industry. https://cefic.org/app/uploads/2019/01/The-European-Chemical-Industry-Facts-And-Figures-2020.pdf

CEMBUREAU 2020. Feedback to New Circular Economy Action Plan Roadmap. https://cembureau.eu/media/o5cpztwl/17523-cembureau-feedback-circular-economy-roadmap-final-2020-01-21.pdf

CEN 2018. Final Report Identification of Potential Needs of Standardisation for 'Sustainable Chemicals' from Primary and Secondary Raw Materials Related to the Circular Economy Action Plan. Reference: SA/CEN/GROW/EFTA/000/2017-05 Rev2 Prepared by: CEN-CLC/BTWG 11 'Sustainable Chemicals'. https://www.cen.eu/work/Sectors/Chemicals/Pages/ChemicalsGeneral.aspx

CEPI 2019. Key Statistics 2019. European pulp & paper industry. https://www.cepi.org/wp-content/uploads/2020/07/Final-Key-Statistics-2019.pdf

Cerame-Unie 2020a. Circular Economy and Sustainability. Best Practices from the Ceramic Industry. http://cerameunie.eu/media/2884/circular-economy-brochure.pdf

Cerame-Unie 2020b. Circular economy in the ceramic industry. Position paper. http://cerameunie.eu/topics/construction-sustainability/circular-economy/circular-economy-in-the-ceramic-industry-position-paper/

Cerame-Unie 2020c. Waste Shipment Regulation revision. Cerame-Unie's feedback to the inception impact assessment http://cerameunie.eu/topics/construction-sustainability/circular-economy/waste-shipment-regulation-revision-cerame-unie-s-feedback-to-the-inception-impact-assessment/

Circular Plastics Alliance 2020. Commitments for Action and Deliverables as Included in the Declaration of the Circular Plastics Alliance. https://ec.europa.eu/docsroom/documents/43445
Circular Plastics Alliance 2020. State of Play for Collected and Sorted Plastic Waste in Europe. https://ec.europa.eu/docsroom/documents/43694

CONCAWE 2017. 2013 survey of waste production and management at European refineries. https://www.concawe.eu/publication/2013-survey-waste-production-management-european-refiners/
Cullen, J.M. 2017. Circular Economy Theoretical Benchmark or Perpetual Motion Machine? Journal of Industrial Ecology. DOI: 10.1111/jiec.12599

Cullen, J. M. and Allwood, J. M. 2013. Mapping the Global Flow of Aluminium: from Liquid Aluminium to Fabricated Goods: Supplemental Information. Environ. Sci. Technol., 47: 1−17

Cullen, J. M., Allwood, J. M. and Bambach, M. D. 2012. Mapping the Global Flow of Steel: From Steelmaking to End-Use Goods. Environ. Sci. Technol., 46: 13048−13055.

Ecofys 2017. Status and prospects of coprocessing of waste in EU cement plants. CEMBUREAU. https://cembureau.eu/media/itbhzglc/xfull-report- -2017-05-11_ecofys_publication_alternativefuels_report.pdf

ECOBA 2016. Production and Utilisation of CCPs in Europe (EU 15) in 2016. European Coal Combustion Products Association.

EDPR 2019. Monitoring Report 2019. European Declaration on Paper Recycling 2016-2020. https://www.paperforrecycling.eu/publications/

EFPRA 2016. The Facts about Rendering. https://efpra.eu/wp-content/uploads/2016/11/The-facts-about-rendering.pdf

EMF undated A: Short-loop recycling of plastics in vehicle manufacturing. https://www.ellenmacarthurfoundation.org/case-studies/short-loop-recycling-of-plastics-in-vehicle-manufacturing

EMF undated B Design and business model considerations for heavy machinery remanufacturing. https://www.ellenmacarthurfoundation.org/case-studies/design-and-business-model-considerations-for-heavy-machinery-remanufacturing

EMF 2015. Growth Within: A Circular Economy Vision for a Competitive Europe. Ellen MacArthur Foundation.

EMF 2019. Completing the Picture how the Circular Economy Tackles Climate Change. Ellen MacArthur Foundation.

EURELECTRIC 2017. Stakeholder Consultation – Chemical, Product, Waste Interface. EURELECTRIC Comments.

Eurometeaux 2016. EU Circular Economy Package – Overall Recommendations. https://eurometaux.eu/media/1459/circular-economy-package-overall-recommendations-from-the-eu-metals-industry.pdf

European Commission 2018a. Commission Implementing Decision (EU) 2018/1147 of 10 August 2018 establishing best available techniques (BAT) conclusions for waste treatment, under Directive 2010/75/EU. https://eur-lex.europa.eu/legal-content/EN/TXT/?toc=OJ:L:2018:208:TOC&uri=uriserv:OJ.L_.2018.208.01.0038.01.ENG

European Commission 2018b. A European Strategy for Plastics in a Circular Economy (COM(2018)28). https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1516265440535&uri=COM:2018:28:FIN

European Commission 2019a. Commission Implementing Decision (EU) 2019/2031 of 12 November 2019 establishing best available techniques (BAT) conclusions for the food, drink and milk industries. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2019.313.01.0060.01.ENG&toc=OJ%3AL%3A2019%3A313%3ATOC

European Commission 2019b. Factual Summary Report on the Public Consultation for the Evaluation of the Industrial Emissions Directive. Ref. Ares(2019)5994141 - 26/09/2019.

ESRG (undated). Together for Less. Europe's Green Agenda. The European Solvent Recyclers' Group Response to the Circular Economy. https://esrg.de/media/ESRG_Broschuere_EN_Solvent_Recycling_-A4-231120_DS-A4.pdf

Farmer, A.M. 2019. Developing the circular economy in the European Union. In: Circular Economy: Global Perspective, Ed. S.K. Gosh. pp. 389-412. Springer Nature. 10.1007/978-981-15-1052-6.

FuelsEurope 2020. Feedback from FuelsEurope to the Revision of the Industrial Emissions Directive - Inception Impact Assessment. 21 April 2020.

FuelsEurope undated. Vision 2050 A Pathway for the Evolution of the Refining Industry and Liquid Fuels.

Gyproc Saint-Gobain (undated). Providing Solutions for Sustainable Habitat.

Harris, D., Heidrich, H. and Feuerborn, J. 2019. Global aspects on Coal Combustion Products https://www.coaltrans.com/insights/article/global-aspects-on-coal-combustion-products

HAZBREF project 2020. Promoting non-toxic material cycles – challenges and opportunities in the BREF process. Work package 4, Activity 4.4. Final draft 19.2.2020.

Huybrechts, D. Derden, A., Van den Abeele, L., Vander Aa, S. & Smets, T. 2018. Best available techniques and the value chain perspective. Journal of Cleaner Production 174: 847-856.

IMA 2018. Recycling Industrial Minerals. https://www.ima-europe.eu/sites/ima-europe.eu/files/publications/IMA-Europe_Recycling%20Sheets_2018.pdf

Inter IKEA and Ingka Group 2020. Response to the European Commission's request for feedback for the roadmap on a New Circular Economy Action Plan.

JRC 2018a. Best Available Techniques (BAT) Reference Document for Waste Treatment. https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/JRC113018_WT_Bref.pdf

JRC 2018b. Kick-off meeting for the review of the Best Available Techniques (BAT) Reference Document for the textiles industry Seville, 12 – 15 June 2018 meeting report. https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/TXT_KoM_meeting_report_Sept18.pdf

JRC 2019a. Best Available Techniques (BAT) Reference Document for the Food, Drink and Milk Industries. https://eippcb.jrc.ec.europa.eu/sites/default/files/2020-01/JRC118627_FDM_Bref_2019_published.pdf

JRC 2019b. Best Available Techniques (BAT) Reference Document for the Ferrous Metals Processing Industry. Draft 1 (March 2019). https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/FMP_D1_web.pdf

JRC 2019c. Best Available Techniques (BAT) Reference Document for the Textiles Industry. Draft 1 (December 2019). https://eippcb.jrc.ec.europa.eu/sites/default/files/2020-01/TXT_bref_D1_1.pdf

JRC 2019d. Best Available Techniques (BAT) Reference Document on Surface Treatment Using Organic Solvents including Preservation of Wood and Wood Products with Chemicals. Final Draft (July 2019). https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/STS_FD_online.pdf

JRC 2019e. Kick-off meeting for the review of the Best Available Techniques (BAT) Reference Document for the slaughterhouses and animal by-product industry, Seville, 25 – 28 June 2019 meeting report. https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-12/KoM%20meeting%20report%20SA%20BREF.pdf

JRC 2019f. Kick-off meeting for the review of the Best Available Techniques (BAT) Reference Document for the smitheries and foundries (SF) industry Seville, 17 – 20 September 2019 meeting report. https://eippcb.jrc.ec.europa.eu/sites/default/files/2020-01/SF_BREF_KoM_report.pdf

High Level Group on Energy Intensive Industries 2019. Masterplan for a Competitive Transformation of EU Energy-intensive Industries Enabling a Climate-neutral, Circular Economy by 2050. https://ec.europa.eu/docsroom/documents/38403

Levi, P.G. and Cullen, J.M. 2018. Mapping Global Flows of Chemicals: From Fossil Fuel Feedstocks to Chemical Products. Environmental Science & Technology 2018 52 (4), 1725-1734. DOI: 10.1021/acs.est.7b04573

MiW and IMPEL. 2019. Making the Circular Economy Work. Guidance for regulators on enabling innovations for the circular economy (prevention and recycling of waste). Make it Work Project and IMPEL. http://minisites.ieep.eu/assets/2478/MiW_and_IMPEL_Guidance_-_Making_the_Circular_Economy_work_-_February_2019_v1.1.pdf

Monte, M.C., Fuente, E., Blanco, A. and Negro, C. 2009. Waste management from pulp and paper production in the European Union. Waste Management, 29: 293-308. https://doi.org/10.1016/j.wasman.2008.02.002

Morley, N., Tham, M., Larsson, E., Waker, H. Reuterswärd, F., Lind, M., Jönbrink, A-K. and Warkander, P. 2019. Sustainable fashion research agenda -future directions arising from the mistra future fashion research programme. Mistra Future Fashion report number: 2019:17. Mistra, Stockholm.

NEPA 2018a. From waste to secondary materials – Case descriptions. European Network of the Heads of Environment Protection Agencies. https://epanet.eea.europa.eu/reports-letters/reports-and-letters/ig-green-and-circle-economy_secondary-materials.pdf/view

NEPA 2018b. Turning waste into secondary materials on the way towards a circular economy. European Network of the Heads of Environment Protection Agencies. https://epanet.eea.europa.eu/reports-letters/reports-and-letters/ig-green-and-circle-economy_waste-as-resource.pdf/view

NEPA 2019. An EU Strategy is urgently needed for a Non-Toxic Environment. European Network of the Heads of Environment Protection Agencies. https://epanet.eea.europa.eu/reports-letters/reports-and-letters/non-toxic-environment-paper-epa-network.pdf/view

Plastics Europe 2019a. Plastics the facts 2018. p. 12. https://www.plasticseurope.org/en/resources/publications/619-plastics-facts-2018

Plastics Europe 2019b. The Circular Economy for Plastics. A European Overview. file:///C:/Users/a.farmer/Downloads/CircularEconomy_study_FINAL_061219_SINGLE.pdf

Riccardo and Vito 2019. IED Contribution to the Circular Economy https://circabc.europa.eu/sd/a/23fd890d-83f9-4372-8f26-669ff50e106a/IED%2520contribution%2520to%2520Circular%2520Economy%2520report.pdf

Royal Swedish Academy of Engineering Sciences 2020. Resource Effectiveness and the Circular Economy. Synthesis Report.

Skidmore, I. and Feuerborn, J. 2017. Developments in CCP Management in Europe. VGB PowerTech Journal 4/2017.

Snop, R. 2019. How ECOBA will navigate in changing times. Presentation to ASHTRANS Europe, 21-22 October 2019, Lisbon, Portugal.

Swedish Enterprise 2019. Circular economy for a competitive and sustainable business community in Sweden.

Swedish Enterprise 2019b. Sector-specific appendices to the Confederation of Enterprise document entitled: Circular economy for a competitive and sustainable business community in Sweden.

Swedish Enterprise 2019c. Circular economy for a competitive and sustainable business community in Sweden.

Swedish Enterprise 2020. Reply to the Inception Impact Assessment of IED.

Swedish Enterprise 2020. Sector-specific appendices to the Confederation of Enterprise document: Circular economy for a competitive and sustainable business community in Sweden.

Szczygielski, T. (undated). Zero-waste Coal Power (ZWCP) as element of the practical implementation of the Circular Economy. http://cima.ibs.pw.edu.pl/wp-content/uploads/zerowastecoalenergy.pdf

Talens Peiro, L., Nuss, P., Mathieux, F. and Blengini, G., 2018. Towards Recycling Indicators based on EU flows and Raw Materials System Analysis data, EUR 29435 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-79-97247-8 (online), doi:10.2760/092885 (online), JRC112720

UBA 2016. Guide on Sustainable Chemicals A decision tool for substance manufacturers, formulators and end users of chemicals. UBA, Berlin.
https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/161221_uba_fb_chemikalien_engl_bf.pdf

von Bahr, J. Nyblom, A. Ekholm, H.M. Baue, B. and Watson, D. 2019. Policies supporting reuse, collective use and prolonged life-time of textiles. Mistra Future Fashion report number: 2019:04. Mistra, Stockholm.

Wyns, T. and Khandekar, G. 2019. Metals for a Climate Neutral Europe. A 2050 Blueprint. Institute for European Studies, Brussels. https://www.ies.be/files/Metals_for_a_Climate_Neutral_Europe.pdf

WRAP, 2020. Food surplus and waste in the UK – key facts. Updated January 2020.
https://wrap.org.uk/sites/files/wrap/Food_%20surplus_and_waste_in_the_UK_key_facts_Jan_2020.pdf

Appendix A Task 1 – Literature and technology database

Reference to Excel file "42312 Task 1 Literature and technology database.xls".

Appendix B Task 2 - List of interviewed organisations

Company	Sector	Project or study of interest
Heidelberg Cement	CCS/Cement	Carbon capture in 2 cement plants, pilot project integrated in Northern Lights
Equinor	CCS	Northern Lights: European CO_2 transport and storage network
Equinor	CCS	Northern Lights: European CO_2 transport and storage network
Fortum	CCS/Waste-to-energy	Carbon capture in a waste-to-energy plant, pilot project integrated in Northern Lights
CEMBUREAU	Minerals: Cement	Presentation "Financing research and innovation in the cement sector: technological pathways and innovation projects for the EU cement sector"
SACMI	Minerals: Ceramics	DREAM: improved architecture for ceramic industrial furnaces by optimised energy consumption, reduced emissions, and lower operating costs
Verbund	Hydrogen	H2FUTURE: World's largest "green" hydrogen pilot facility in operation aimed to be used in steel production
Salzgitter AG	Iron and steel	SALCOS: Direct Reduction of Iron, using hydrogen produced by electrolysers operated with renewable energy
Arcelor Mittal	Iron and steel	Multiple projects developed: TORERO (bio-coal product from waste wood), Siderwin (electrolysis), Steelanol (production of bio-ethanol from wate gases)…
SSAB	Iron and steel	HYBRIT: Direct Reduction of Iron
Tata Steel	Iron and steel	Hisarna process: low-carbon steelmaking integrating CCS
Concawe	Energy: Oil	"Refinery 2050: Conceptual Assessment. Exploring opportunities and challenges for the EU refining industry to transition towards a low-CO2 intensive economy", "The Low Carbon Pathways Project. A holistic framework to explore the role of liquid fuels in future EU low-emission mobility (2050)."
CEPI	Pulp and paper	"The pulp and paper industry from an energy and climate perspective", "The challenge: decarbonising whilst being recycling pioneer"
CEFIC	Chemicals	Follow-up from webinars
EuLA	Minerals : Lime	Follow-up from webinars

Company	Sector	Project or study of interest
Eurofer	Iron and steel	Follow-up from webinars
Eurometaux	Non-ferrous metals	Follow-up from webinars
CEMBUREAU	Minerals: Cement	Follow-up from webinars
IMA	Minerals	Follow-up from webinars

Appendix C Webinar summary report