



Smart

Closing the carbon loop via steel and chemical industry

Inge Bellemans, Nico Kimpe, Dieter Grimmelprez, Ludwin Daal, Bert Riems, Kim Verbeken



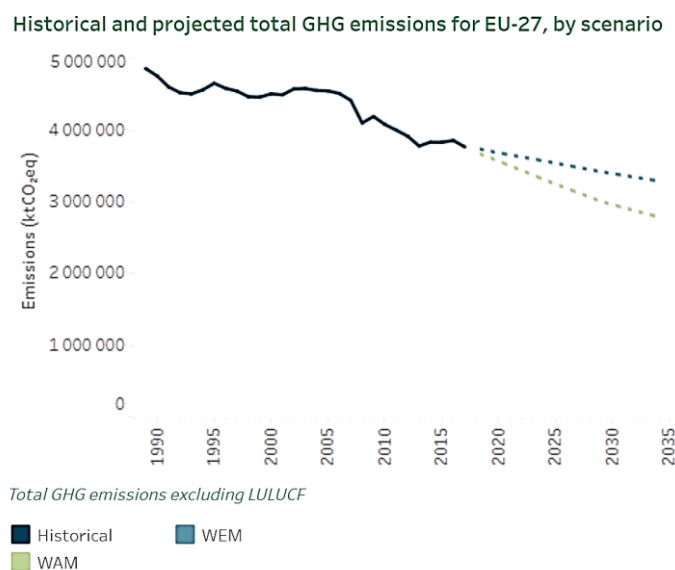
Contents of this publication are the sole responsibility of ArcelorMittal Belgium, Vanheede environment group, CRM group and Ghent University and do not necessarily reflect the opinion of the European Union.

The Green Deal

Climate change is one of the greatest long-term challenges our society is facing. With global emissions continuing to rise and extreme weather occurrences intensifying, this is a border-crossing phenomenon. Europe has stepped up to the challenge by making a clear commitment to be the first continent to be **carbon neutral by 2050** with the motto “We have to act now”.

For this, the European Green Deal has been introduced as Europe’s new growth strategy to make from the EU a modern resource efficient and competitive economy. The goals of the Green Deal are to reduce the net emissions of greenhouse gasses to zero by 2050, while providing economic growth without resource depletion and doing this for all people and regions. This requires, amongst others, the more efficient use of resources and the switch to a clean circular economy. ¹

Compared to the 1990 greenhouse gas emissions (totalling 4 392 million tons (Mt) of carbon dioxide equivalent), a 20 % reduction in GHG emissions by 2020 was targeted and is being met.² Looking forward towards the climate mitigation targets for 2030, the EU's GHG emission reductions will be the joint efforts of the EU-27 Member States. Based on Member States' current policies and measures, emissions are projected to decline by an average 36 MtCO₂eq per year until 2030. Additional planned or prepared policies and measures that Member States have included in their Monitoring Mechanism Regulation (MMR) projections would enhance the annual average reduction to a total of 70 MtCO₂eq by 2030, which results in a 36 % emissions reduction compared to 1990. To achieve the current 2030 target of a 40 % reduction across the EU-27, Member States would have to reduce their emissions by an annual average of 86 MtCO₂eq per year. ³



Industry in Flanders produced 31.9 Mton CO₂eq in 2019, but by 2030, this should be reduced to 24.7 Mton CO₂eq.⁴ In the future, it is expected that the price of the CO₂-emission rights will increase significantly, hence if no actions are taken now, this will have **a clear effect on the industry and employment opportunities in Flanders**. However, several problems concerning greenhouse gas emissions or fossil fuel-based inputs remain to be solved in various industries. Three such industries will be discussed in the following sections.

¹ https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_nl

² <https://www.eea.europa.eu/data-and-maps/data/data-viewers/eea-greenhouse-gas-projections-data-viewer>

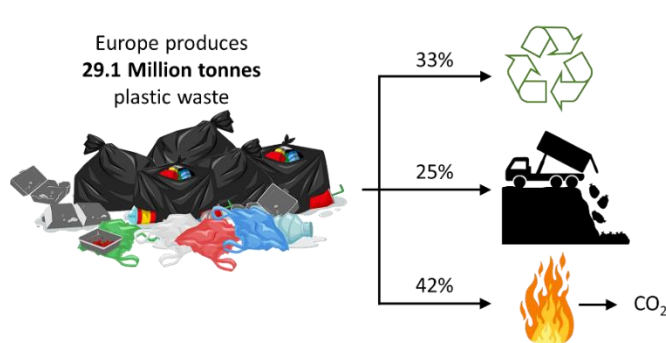
³ <https://www.eea.europa.eu/publications/trends-and-projections-in-europe-2020>

⁴ www.milieurapport.be/milieuthemas/klimaatverandering/broeikasgassen/emissie-broeikasgassen-per-activiteit

1. Recycling industry

Problem 1: Limited recyclability options for mixed end-of-life materials

Recycling of end-of-life (EOL) carbon-based materials is a problem which is firmly linked with the plastics industry. When it comes to recycling EOL plastics, there are two options: mechanical recycling and chemical recycling. For other streams such as EOL textiles, there are in general no viable recycling routes.



At the moment, **only a small fraction of collected EOL plastics can be mechanically recycled**, i.e. streams consisting of specific single plastic types (PET, PVC, HDPE and LDPE). Virtually all recyclable streams belong to the ‘thermoplastics’, which soften when heated and become more fluid as additional heat is applied. On the other hand ‘**thermosets**’ are set in their physical and chemical properties after an initial heat treatment.

Unfortunately, these thermosets are afterwards no longer affected by additional heat exposure until they degrade. Therefore, they are **not yet mechanically recyclable at industrial scale**.

The other, more versatile option for EOL plastics, is chemical recovery. In chemical recovery, the chemical structure of the EOL material is destroyed, yielding small molecules which can then be used anew in the production process. For thermoset materials and EOL materials which consists of several layers of different materials, e.g. laminated food packaging, this is the most viable route. However, chemical recovery of EOL materials is, at the moment not yet viable at large scale.

Hence, from the total of 29.1 million tonnes of collected plastic waste, **only 33% was sent to recycling** in 2018. The rest of **these streams is landfilled (25%) or incinerated for energy recovery (42%)**⁵. Other streams (such as textiles, PUR, automotive shredder residues, etc.) are also incinerated at the moment, resulting in direct CO₂ emissions. Note that there are different types of incineration: without energy recovery and with energy recovery. Of course the latter is preferred over the former. In energy recovery, only the energetic value and not the inherent chemical potential of the EOL materials is valorised.

This combination of energy recovery with material recovery is called ‘co-processing’ and can in theory range from 100% energy recovery to 100% material recovery. Chemical recovery falls in this category. Co-processing is currently already used in the cement-industry, where 50% of the fossil fuels are substituted by co-processing. Co-processing clearly has a lot of potential, but is not fully exploited.

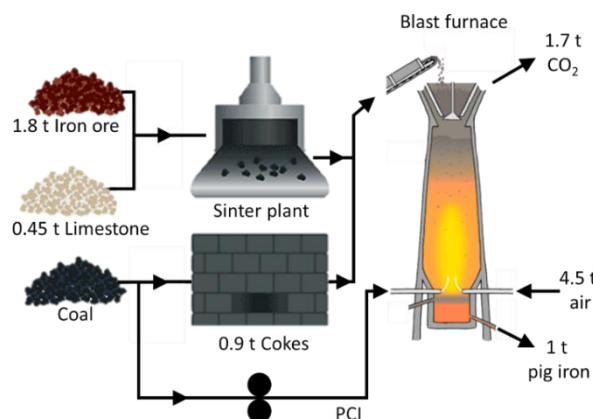
⁵Data from plasticseurope.org.

From the 29.1 million tonnes of total collected post-consumer plastic waste, 48% was collected via separate waste collection. This separated waste was recycled for only 62%, for the other part, 11% was landfilled and 27% was incinerated for energy recovery. For the non-separated waste (typically household residual waste and municipal waste), only 6% was recycled. The rest was landfilled for 37% and incinerated for energy recovery (57%).

2. Integrated metal industry

Problem 2: Metal production industry has limited options to reduce its CO₂ footprint

Steel is produced from a combination of processes to obtain very specific end products with a wide variety of compositions. This allows for a large variability in properties, which yields steel's broad usability. Steel is produced from a combination of ores and scrap because scrap alone is not able to fulfil current nor future demands. Therefore, ores will remain an important source of raw materials in the foreseeable future.

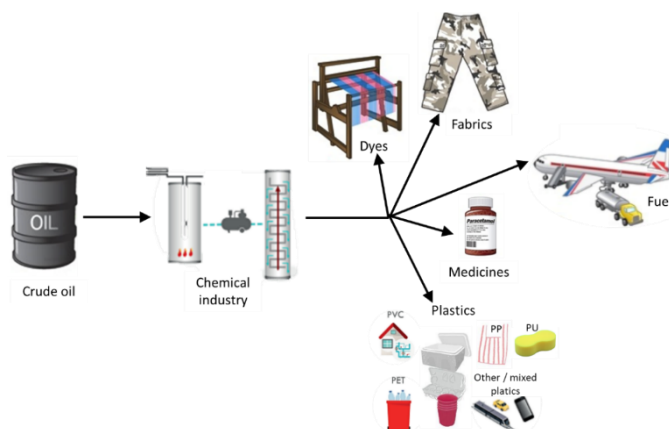


The first step in the production process typically takes place in the blast furnace, where the ores (metal-oxygen compounds) are 'reduced' by reacting with a reducing compound (called a reductant, e.g. cokes, coal or natural gas). In the ensuing reaction, the reductant takes away the oxygen from the ores, so that metallic Fe is produced. Today, **fossil carbon-based sources are used as reductants**. This in turn inevitably produces fossil CO₂, one of the most important greenhouse gasses. The need for these reductants in the blast furnace process is why the use of coal and cokes is by far the largest component of steel's greenhouse gas emissions.

3. Chemical industry

Problem 3: Difficult to adopt circularity approaches that replace oil feedstock in chemical industry

Crude oil is the starting point for versatile and valued materials for modern life: construction materials, paints, multifunctional polymers, medicines, ... In the chemical industry, the hydrocarbons present in crude oil are transformed into simpler compounds and then reassembled in building blocks, which are widely applicable in the chemical industry. One of the most important production chains in chemical industry is the **production of polymers, using a vast amount of oil as a raw material**. Furthermore, the **use of petroleum by the chemical industry accounts for 14% of all greenhouse gas emissions⁶**.



All of this shows that there is a limited 'circularity' in the chemical industry: it starts from fossil fuels and produces a large amount of non-recyclable materials. In that context, the European Union started to tax non-recycled plastic packaging waste from 1 January 2021 through national contributions in the 'plastic tax'. This means that circularity has become a more important issue in chemical industry.

⁶ doi:10.1126/science.aaz5517

How to find a solution for these three problems at once?

Energy-intensive industries such as steel production and chemical industry, are indispensable for the European economy. Hence, the decarbonisation of these sectors is of the utmost importance. Up till now, the three industries have been working on these problems separately. It is clear that the development of clean technologies and low- or zero-carbon energy is key in **all three industries** (recycling, metal and chemical industry) in the low-carbon economy roadmap of the European commission.

The LIFE SMART projects aims to tackle these three problems by **implementing a two-step solution to close the carbon loop, avoid fossil resources and emissions and reach full circularity**. These two steps rely on the **steelmaking industry acting as a 'recovery hub' for EOL carbon-based material**. The first step is co-processing in the cokes and powder coal production installations. In practice, this comes down to the **substitution of raw materials with difficult to recycle EOL carbon-based materials**, thereby **chemically recovering** these EOL materials while simultaneously reducing steelmaking emissions. The second step is the **production of basic molecules for the chemical industry** from steelmaking gasses, thereby creating the opportunity **to close the carbon loop**.

In the next paragraphs, several routes leading to emission reduction in steelmaking will be discussed and the co-processing steps, which are the first step of the solution, are highlighted. The subsequent section goes into more detail on how the second step can help **close the carbon loop**.

Possible routes to reduce CO₂ emissions in steelmaking

In steelmaking, there are different technological pathways offering the potential for significant carbon emissions reduction. These range from circular carbon in the form of renewable biomass and bio-waste; clean electricity; to carbon capture and storage. To evaluate these, it is important to make a distinction regarding long and short term.

For the extraction from iron out of its ores, **the use of hydrogen as reductant would not produce greenhouse gas emissions**. However, green hydrogen production is not yet economically feasible in the high amounts required by the industry. In the longer term, green hydrogen could be used. Green hydrogen can be produced from water through electrolysis using green electricity. Green electricity is carbon-neutral energy that comes from renewable sources such as solar and wind energy, that do not emit CO₂ to generate the electricity. While innovations should drive costs down, the timetable remains unclear and it is likely to be **decades before clean electricity and hydrogen are available at a scale and cost that would benefit the steel industry**. If the European steel industry fully switched to clean electricity today, this would imply a 15% increase in power consumption. It was estimated that green hydrogen costs would have to decrease by at least 50% to become competitive with other clean energy sources, and more than 75% compared with current fossil sources. Hence, it is clear that **intermediate solutions are required to get enough reductions of greenhouse gas emissions by 2030**.

Such a faster route could be achieved by relying on the earth's natural carbon cycle and making use of **biowaste materials and waste streams for steelmaking**.

Using alternative reductants in steelmaking

By using EOL carbon-based materials as an alternative for the cokes and coal used in the steel production, **both the energetic and the chemical intrinsic value can be recovered**. In this way, the EOL material is used as energy carrier and a reductant for the blast furnace process. It should be clearly stated that EOL material does not only contain carbon, but also hydrogen. In this way, not only carbon is used as a reductive agent (taking away bound O from the ores to produce metallic Fe), but hydrogen's reductive potential is also utilized, hereby **replacing some of the normally produced CO₂ by H₂O**. This significantly **decreases the amount of CO₂ produced in the metal production process**.⁷

Furthermore, the substitution of fossil carbon resources by EOL carbon-based materials is clearly a better alternative than burning the EOL material as it partially substitutes for cokes and the corresponding CO₂ emissions. This would position this route in the **co-processing category** of the waste hierarchy, towards the material recovery end, as shown below. This means that EOL materials from the waste to energy category can be shifted upwards towards the better ranked co-processing category, thereby increasing the usefulness of the material.



Blast furnace processes can utilise EOL carbon-based materials by:⁸

- Injection as a solid through the tuyeres in a similar way to pulverised coal.
- Carbonisation with coal to produce metallurgical cokes
- Gasification of the EOL materials outside the furnace. The resultant synthesis gas can then be injected through the tuyeres. This method will be discussed in combination with the previous option.
- Top charging into the BF. Note that this generates unwanted tar from the decomposition of the EOL materials in the shaft. This option is not discussed further in the text.

Various R&D attempts have been made worldwide (Japan, Germany, Austria, ...) to replace metallurgical coke as a reducing agent and fuel. However, the work done so far, mostly focused on waste streams, typically thermoplastics, for which recycling already is or will be the most valuable option, as sorting systems are becoming more advanced. **Other streams, e.g.: thermosets, unfortunately, do not currently, nor in the foreseeable future, have such a high-value solution.** Our LIFE SMART (SteelMaking with Alternative ReductanTs) project will investigate the **use of these non-recyclable waste streams** and the unrecyclable

⁷ doi:10.3390/ma12040655

⁸ Injection of coal and waste plastics in blast furnaces, Anne M Carpenter, 2010, IEA Clean Coal Centre, ISBN 978-92-9029-486-3

fractions from other plastic streams. It is emphasized that we use **mixed EOL materials that are not of sufficient quality or are too expensive to be sorted into separate types for mechanical recycling.**

Injection in the blast furnace

Over the last few decades, injection of carbon via the tuyeres, called pulverized coal injection (PCI), has become a well-established technology. Pulverized coal injection is a process which involves injecting large volumes of fine coal particles into the raceway of the blast furnace. The use of PCI decreases the need for coke production and hence energy consumption and CO₂ emissions from the coking plant. Financially this is a beneficial operation as coke forms a major portion of the cost of hot metal. Furthermore, with high PCI rates, coke oven life is extended since less coke is required to be produced.

As plastics and synthetic textile materials are made from petroleum and natural gas, the main constituents are carbon and hydrogen. Therefore, it is possible to use EOL materials containing waste plastics and textiles as a replacement for the coke reductant in the blast furnace process. The pre-processed EOL material can be fed into the blast furnace through blast furnace tuyeres and is gasified in the raceway. Some of the gases are used as a reducing agent to remove the oxygen from iron oxide. The remaining gases are used as an energy source in the blast furnace to generate heat to drive this reaction.⁹ The composition and properties of the injectants influence the operation, stability and productivity of a BF, the quality of the hot metal product, and the off gas composition. The lower consumption of both coke and pulverised coal, thus saves coal resources. Neither EOL material injectants nor coal injectants can completely replace coke and so cokemaking facilities will always be needed in BF-based ironmaking. Furthermore, cokes have been recognised by the EU as a **Critical Raw Material**, highlighting the importance of **continued production of metallurgical cokes** in Europe. The amount of coke replaced in the BF will be partly dependent on the quality of the waste plastics and coal.

There are several advantages to the injection of plastic waste in blast furnaces:

- **Decrease in carbon dioxide emissions due to:**
 - The replacement of fossil resources in steelmaking by renewable EOL resources. **The actual emissions from the use of EOL material will replace fossil emissions.**
 - Due to the production of syngas for the chemical industry, which can replace the fossil resources used in this industry.
 - The presence of hydrogen as a result of the use of EOL carbon-based materials. For a similar combustion energy as pulverised coal, hydrogen is also present, resulting in less CO₂ and more H₂O produced)
 - Hydrogen is a more favourable reducing agent than carbon, requiring less energy so that less PCI is required and hence less CO₂ emitted.
- **High energy efficiency:** So that EOL carbon-based materials can be employed more efficiently in BFs than in plants which directly combust these materials to generate heat or electricity or just incinerate them.
- Lower sulphur and alkalis contents than coal, which could positively affect the hot metal and coke, sinter and refractory.
- **Low emissions of dioxins and furans:** Due to high temperatures in the blast furnace, which are often associated with conventional waste incinerators.

⁹ <https://doi.org/10.1007/s11367-008-0055-3>

Initial research shows that injecting EOL plastics, which have higher calorific values (CV) than coal, decreases blast furnace coke and energy consumption and **lowers CO₂ emissions by about 30%** in comparison to coke and coal depending on the type of polymers used. There are very few reports that describe in detail the behaviour of waste plastics injected into a blast furnace. The injection of plastics influences combustion and gasification behaviour, CO₂ concentration peak, temperature peak in the raceway and hardness. The optimum condition on the plastics injection thus depends on the particle size and preparation method (agglomeration, crushing, etc.). For mixed waste plastics, low chlorine, moisture, ash and sulphur contents are preferred. Most types of coal and EOL plastics can be utilised at low injection rates. However, as injection rates increase more complex characteristics, such as combustibility, char reactivity and flow properties, influence their selection.

The injection of waste plastics, either as a separate injectant or co-injected with coal, is practised only in a few BFs in Japan and Europe. A factor restricting the utilisation of waste plastics is the cost of their collection and treatment. BF operators need a reliable supply of consistent quantity and quality, and at a suitable cost. Chlorine content in EOL materials is a potential concern due to the formation of corrosive compounds (e.g. HCl) and consequently the removal of chlorine from the waste plastics needs to be investigated. Furthermore, other pre-processing consists of crushing. This should happen in cool atmosphere, because heat generated by pulverization causes the plastic to soften and melt.

As direct injection of potential alternative reductants such as biomass and carbon-based EOL waste in the blast furnace is not possible, a new torrefaction process is proposed. A torrefaction process transforms waste and biomass into torrefied materials (biocoal) with a higher carbon content and better grindability. Once ground, the biocoal can be fed directly to the blast furnace or to the cokes ovens. Currently, ArcelorMittal Ghent is executing the Torero project, for which they are building a €50 million large-scale torrefaction plant, to convert waste wood into bio-coal, replacing a fraction of the coal currently injected as a reductant in iron and steelmaking. The plant is expected to be operational by the start of 2023. The LIFE SMART project will investigate the co-processing of EOL materials in the torrefaction plant for the production of pulverised coal. Together with co-processing of EOL materials in the coking plant this is step one of the two-step solution discussed above. Co-processing in Torero will only be possible by the end of-2023 as the installations will become available for this project.

Conversion to metallurgical cokes in the coke ovens

In a blast furnace, cokes are loaded from the top. Cokes are used instead of coal, because of the mechanical strength and porosity to allow for the charge of iron oxides and limestone to steadily move downwards, while the gas flow upwards and droplets of liquid iron and slag can move downwards. Coke is produced in a coke oven by carbonizing which is the heat treating of the coal in the absence of oxygen at a high temperature. The coke oven heating drives off volatiles from the coal, which are a valuable source of chemicals, and contain much of the undesirable sulphur (S), which would otherwise end up in the hot metal. Minerals like silica (ash) remain in the coke but they are easily collected in the blast furnace slag. Coke ovens produce coke, tar, BTX, elemental sulphur, and coke oven gas (COG). Ammonia liquor is used for flushing the ascension pipe exit at the top of the coke oven, and the high-temperature COG generated in the coke oven is cooled quickly to about 353 K or less.¹⁰

¹⁰ <https://doi.org/10.1007/s11367-008-0055-3>:

It is thought that the **coke-making process is also suitable for co-processing EOL materials** thanks to the following factors.

- Firstly, the EOL materials will partly decompose in a variety of chemical compounds as they can't be burned as there is no oxygen present in the coking process. These compounds may participate in condensation reactions, thereby forming coke or be extracted in the coke gas.
- Secondly, the coke-making process is equipped with the facilities to recover the decomposed compounds of EOL carbon-based materials, which facilitates their recovery.
- Thirdly, hydrogen chloride, HCl, which is considered to generate during the carbonization of EOL carbon-based materials containing PVC (polyvinylchloride) can potentially be trapped by ammonia enriched fluid which is normally used for cooling hot COG. This practice will be investigated in the project.

Hence, similarly as coal, EOL materials composed of carbon and hydrogen are converted to cokes, cokes gas and by-products in the cokes oven.¹¹ Previous R&D attempts have been made worldwide (Japan, Germany, Austria, ...) focused on specific waste streams such as packaging and container waste. Three fundamental and important questions need to be answered in developing the waste plastic recovery process using coke ovens:

1. Which products are obtained when EOL carbon-based materials are carbonized and decomposed with coal in a coking chamber.
2. Which critical parameters of co-carbonization of coal with EOL carbon-based materials adversely affect coke quality:
 - a. Type of materials
 - b. Pellet size of materials
 - c. EOL materials to coal ratio
3. The behaviour of chlorine during co-carbonization of coal and EOL carbon-based materials containing chloride compounds such as PVC.

As sorted plastic streams become more recyclable, the **LIFE SMART project focusses on the use of selective EOL carbon-based materials streams that can result in a highly controlled product to be used in a coke oven.** These waste streams are non-recyclable and would require too much effort to sort completely to become recyclable. However, they have been selected meticulously so that they are homogeneous and have a steady composition over time. By combining various selective waste streams, we believe we can obtain a high-quality product that can be used in the blast furnace.

Closing the Carbon-loop

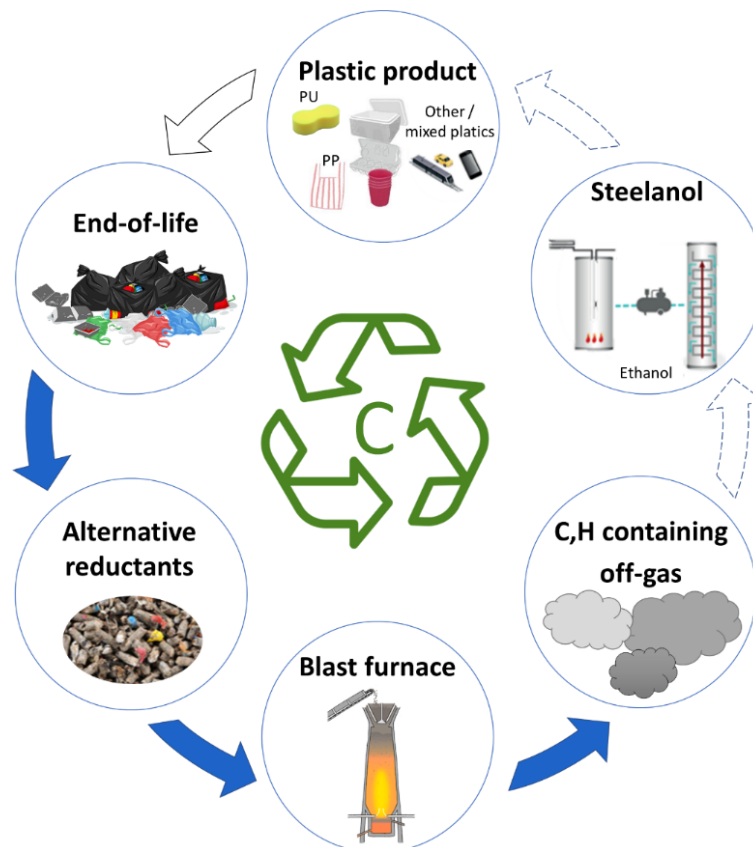
The LIFE SMART project fits in a bigger context to rely on the earth's natural carbon cycle.

The carbon-loop can be closed by converting the off-gas coming from the steel mill into products. This prevents the emission of CO₂ otherwise produced when burning the off-gas to produce electricity and heat. By transforming the carbon into hydrocarbon liquids (e.g. ethanol) and solids (e.g. polymers), we create a carbon neutral circular carbon cycle addressing society's waste challenge with EOL carbon-based materials.

The technologies required for this route are almost sufficiently mature and in the short term, they can make a significant contribution to the 2030 emissions reduction target. The LIFE SMART project two-step solution combines the **production of alternative reductants via chemical recovery, which falls under co-processing**

¹¹ 10.1007/s40831-014-0001-5

and their use in a **steel plant with the re-use of the carbon within the off-gas** towards the **chemical industry** and hence producing carbon-based products again, hereby **fully closing the carbon loop**, as illustrated in the figure below. The full arrows indicate processes that are part of the LIFE SMART project. The ambition of Life SMART is to ultimately realize “Carbon circularity”. The other arrows in the figure are part of the carbon circularity concept, but are the focus of other projects, such as ‘Steel2Chemicals’ and ‘Steelanol’. While this topic is not in the scope of this specific project, it is important to highlight that it is a part of the more global picture in which it would be possible to solve the three abovementioned problems at once and hence fully closing the loop for plastics and carbon.



With the urgent need to reduce CO₂ emissions significantly (with 30% by 2030 and completely by 2050), it is important to use the clean energy and reductant source that is the most cost effective and usable. For this, technologies are currently being developed, but an environment is also required where **carbon-neutral steel** is **more competitive** than steel which is not carbon neutral. ArcelorMittal is developing a certified CO₂-neutral product: **Green Steel**. First Indications show that the LIFE SMART project would be eligible for the production of Green Steel.

Besides import and export, also the distinction between primary and secondary sources should be made. A Carbon Border Adjustment (CBA) is a key **policy mechanism** needed to equalise the market and create a fair competitive landscape, by aligning the carbon costs of EU domestic steel producers with that of imports. Furthermore, extra financial support to innovate through funding schemes, such as Important Projects Common European Interest (IPCEI), and long-term investments is required.

Impact

The primary goal of the LIFE SMART project is to reduce fossil emissions by replacing fossil reductants by alternative reductants via co-processing. In 2019 ArcelorMittal Ghent emitted 3380 kton of CO₂ linked to the

The following figure illustrates the integration of the LIFE SMART project with the steel and plastic cycles.

