Cleaner Coke-Making with non-recyclable Waste Plastics: A Techno-Economic Assessment from a European Perspective

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Abstract:

Given the growing economic and environmental concerns about steelmaking processes, there are clear drivers to move towards a cleaner production. One step in this direction is to substitute part of the coking coal used in coke production with waste-derived materials that are typically landfilled or incinerated. In this paper, a techno-economic assessment from the point of view of a typical European coke-making plant was conducted. Two scenarios were evaluated: the Benchmark scenario (BS), involving coke production from fossil coal, and the AlterCoal scenario (AS), where 2 wt% of coal is replaced by AlterCoal® pellets made from non-recyclable waste plastics. Gross profit (GP) for 2019 and 2022 was the main indicator for comparing the economic performance of both scenarios. In both years, the AS had higher GP than the BS, mainly due to the reduced need of coal, and to the increased production of coke oven gas. An uncertainty analysis based on the Monte Carlo method showed that the economic volatility of the AS is lower than that of the BS, while a sensitivity analysis identified that coke, coking coal, electricity, and natural gas prices were the most influential variables on GP. Finally, direct CO_2 emissions were 11.2% lower in the AS compared to the BS, primarily due to biogenic carbon in AlterCoal® pellets leading to a more sustainable production process. This combination of unfavourable GP, high uncertainty, and high dependency on critical raw material prices in the BS elucidates the trend of various European steel plants reducing or suspending steel production.

Keywords: Steelmaking – Coke-making – Biogenic emissions – Solid recovered fuel – techno-economic assessment– Low carbon manufacturing

Nomenclature

AMG	*ArcerlorMittal Gent*
AS	*AlterCoal Scenario*
ASK	*Ammoniumsulphide Circuit Scrubber*
BS	*Benchmark Scenario*
BTX	*Benzene, Toluene, Xylene*
COGS	*Costs of Goods Sold*
ESP	*Electrostatic Precipitators*
ETS	*Emissions Trading System*
FTE	*Full Time Equivalents*
GR	*Gross Revenues*
GP	*Gross Profit*
NCV	*Net Calorific Value*
VEG	*Vanheede Environment Group*

1. Introduction

The European steel industry encountered several major economic disturbances over the past years. Following the production peak in 2017, steel manufacturers started to face tightened emissions regulations, lower availability of raw materials, and high import levels from third countries (Diana Kinch and Laura Varriale, 2021). During the first half of 2020, steel consumption in the European Union (EU) decreased by 25.5% due to lockdown measures implemented during the Covid-19 pandemic, which substantially affected the automotive and construction sectors (European Steel Association, 2020). The production started to recover in the second half of that year, reaching notable price spikes due to stock shortage (MEPS International, 2021). Consequently, the EU production of steel only decreased about 11.8% in 2020 (Diana Kinch and Laura Varriale, 2021).

In 2021, steel prices steadily increased, reaching global record prices (Matthieu Depreter, 2021). This price surge was primarily driven by high energy costs, increased demand, insufficient supply, and rising raw material prices (CRU Group, 2021). Normal production levels were achieved through Europe during that year (EUROFER AISBL, 2023). However, at the beginning of 2022, the start of the Russo-Ukrainian War raised concerns about a potential shortage of steel supply in the European market, forcing companies to stockpile this commodity (Michael Cowden, 2022). Ultimately, the expected shortage failed to materialize, resulting in a regional surplus that pushed down the steel selling price (Maria Tanatar and Hector Forster, 2023). This surplus, combined with the unprecedented energy prices, created a dire situation for steelmaking companies, leading to production cutbacks in mid-2022 (Ben Aris, 2022). Additionally, exceptionally high coking coal prices strongly impacted blast furnace (BF) – basic oxygen furnace (BOF) route based steel plants, which heavily rely on this critical raw material (Clyde Russell, 2023).

A summary of the status of all BF Steelmaking plants across the European Union during 2022, together with pig iron production rate per country in 2022 compared to levels achieved in 2017 is presented in Figure S1 in the Supplementary Materials, showing that 14 out of 24 plants either partially or completely ceased their production. As a consequence, regional production levels dipped to a point as low as they were in 2020, which had already been a bad production year for the steel industry (EUROFER AISBL, 2023). A summary of the duration and reasons behind the disruption in steel operations is provided in Table S1 from the Supplementary Materials, where it can be seen that nearly all affected plants attribute their shutdowns to the combination of high energy prices and diminished steel demand. In Poland, one BF that was paused since 2019 for different reasons, was permanently shut down because of the poor market conditions. In September 2023, Liberty Steel in Ostrava made the decision to close one of their coke oven batteries, citing its lack of profitability as the reason (Colin Richardson, 2023). Just one month later, they announced the shutdown of their last operational BF due to low demand (Halina Yermolenko, 2023). The steel sector is hitting its fourth annual recession in five years, and the outlook for 2024 does not appear to be promising (Hellenic Shipping News Worldwide, 2023).

Since shutting down and starting up a BF is an overly complex and time-consuming process, BF plants are more susceptible to fluctuations in energy and raw materials prices when compared to their technological counterpart, the electric arc furnace (EAF). BF economics is based on large-scale production, requiring a consistent and reliable supply of inputs to maintain profitability. Therefore, it is crucial to explore alternative ways to produce pig iron that are more efficient and cost-effective, ultimately reducing the dependence of the operation on the volatile energy market, especially the price of coking coal.

The relevance of waste plastics as a source of carbon and energy has increased in recent years, leading to various methods for their reutilization (Devasahayam et al., 2019; Jeswani et al., 2021; Ragaert et al., 2017). This is because certain types of plastics lack a viable recycling route and often end up being landfilled or incinerated (Dieter Mutz et al., 2017). Since plastics are primarily composed of hydrocarbons, they exhibit similar behaviour to coal when subjected to slow pyrolysis (Khopersky et al., 2020). Consequently, when chosen appropriately, they can serve as a viable substitute for coal in the coke oven, provided that the final product meets the necessary chemical and mechanical specifications for a BF application. This approach can contribute in several ways to a more sustainable production process in comparison to conventional coke-making processes. First, it leads to a reduction in carbon emissions as it diminishes the need for fossil coal, avoiding indirect emissions related to mining, transport, and grinding of coal, and direct emissions thanks to the biogenic carbon content of wastes. Second, it reduces the reliance on costly coking coal, which has been considered by the European union as a critical raw material since 2014 (European Comission, 2023; European Commission, 2024).. Additionally, from the end-of-life non-recyclable waste plastics point of view, when these are introduced into the coke oven, both the energy and reductive capacity are recovered, as opposed to the alternative of incineration for electricity production, which has notably low efficiency rates (Johnny Stuen and Christophe Cord´homme, 2023).

The replacement of about 1-2% of the coal used in a coke oven with waste plastics has been investigated and successfully implemented in some few coke plants worldwide (Krishnan et al., 2006; Nomura, 2015; Palone et al., 2022). Higher replacements may hinder the mechanical properties of the main product, metallurgical coke, to the extent that it cannot be longer used in a blast furnace (Lange and Ferreira, 2017; Nomura and Kato, 2006). To our knowledge, there are no techno-economic analyses available in literature regarding the use of waste plastics to produce metallurgical coke. Furthermore, having the perspective of a modern European coke-making process in conjunction with current market prices would be immensely valuable for coke plants looking to reduce their carbon footprint and create more sustainable products, while simultaneously cutting costs and minimizing uncertainties.

The approach presented here is currently being tested and implemented at the ArcelorMittal Gent plant (AMG), in Belgium, as part of the Life SMART project (LIFE SMART, 2019). This innovative and cleaner method for coke production could be replicated in other steel plants, contributing to the broader effort to reduce emissions, which aligns with the goal posed in European Green Deal of reducing greenhouse gas emissions by 55% by 2030 compared to 1990 levels (European Commission, 2020). An overview of the scope of the LIFE SMART project is presented in Figure S2 from the Supplementary Materials. Note that the current paper links to the initial phase of the project, where the focus is solely on the coke-making process However, future phases of the project will extend the scope to include the BF, where a big part of the coal utilized in pulverised coal injection (Carpenter, 2006) will be replaced by bio-coal produced at the Torero plant through pyrolysis of mixtures of non-recyclable waste plastics and waste wood (Biermann et al., 2020).The plastic cycle will be closed by transforming the blast furnace gas (BFG) into ethanol by the Steelanol process (Perathoner et al., 2021), from which new plastics can be manufactured. The plastics would then be transformed at their end-of-life into AlterCoal® pellets by Vanheede Environment Group (VEG) (Vanheede Environment Group, 2023), which are then carbonised and fed into the BF to ultimately produce BFG, closing the cycle. In this way, all the materials coming out of the BF can be recycled, making it a cleaner process (Singh, 2023).

This study aims to assess the technical, economic, and environmental implications of substituting 2wt% of the coking coal used in coke production with AlterCoal® pellets, from the point of view of an average European coke-making plant. The analysis compares this approach to the conventional coke-making process, which relies entirely on coking coal, for the years 2019 and 2022. Additionally, the study seeks to assess the economic volatility of the process based on historical price trends and identify the key factors influencing its economic performance. However, due to the confidential nature of data from individual plants, this study relies on industrial average values. Consequently, the results and conclusions provided here serve as general guidelines for the industry, but they may differ for each specific plant.

2. Methodology

In this study, the addition of end-of-life non-recyclable waste plastics to a benchmark European by-products coke-making process was analysed. A thorough quantitative assessment from technical, environmental, and economic perspectives was conducted. Any type of gas emissions and/or air pollutants other than direct CO_2 emissions are beyond the scope of this work.

The economic model discussed in this work, called “TEA-CARE” (TEA of Coke-making with an Alternative Reductants Emphasis), was developed as a versatile application that can be customized to various plant configurations and market conditions. Readers interested in performing a techno-economic assessment of particular plant designs can reach out to the corresponding authors of this work.

2.1. Scenarios and scope

To perform the Techno-Economic Assessment (TEA), we examined two scenarios: the benchmark scenario (BS), which employs 100% coking coal as the input, and the AlterCoal scenario (AS), where 2 wt% of the coking coal is substituted with non-recyclable waste plastics pellets known as AlterCoal®. These AlterCoal® pellets are produced and supplied by VEG, a Belgian waste management company (Vanheede Environment Group, 2023). The products and by-products obtained in each scenario do not change, but they are produced in different amounts. These outputs are: coke, coke breeze, tar, BTX (benzene, toluene, xylene), sulphur, coke oven gas (COG), and waste water.

Figure 1 illustrates the gate-to-gate boundaries of the process for both scenarios, which corresponds to the scope considered in this work. It spans from the reception of the raw materials at the gate of the company to the completion of the production process (Zimmermann et al., 2020). The solid waste in the BS is either landfilled or incinerated (red path), while in the AS it is used to produce AlterCoal® pellets (green path), which are then used during the coal distillation process. The rest of the process is common for both scenarios (black path), namely: coal crushing/blending, coal distillation, COG cleaning, and wastewater treatment. Since collection, transport, and landfill/incineration of the waste, together with mining and transport of coal, and production of AlterCoal® pellets, are outside of the scope, they were not considered in this study.

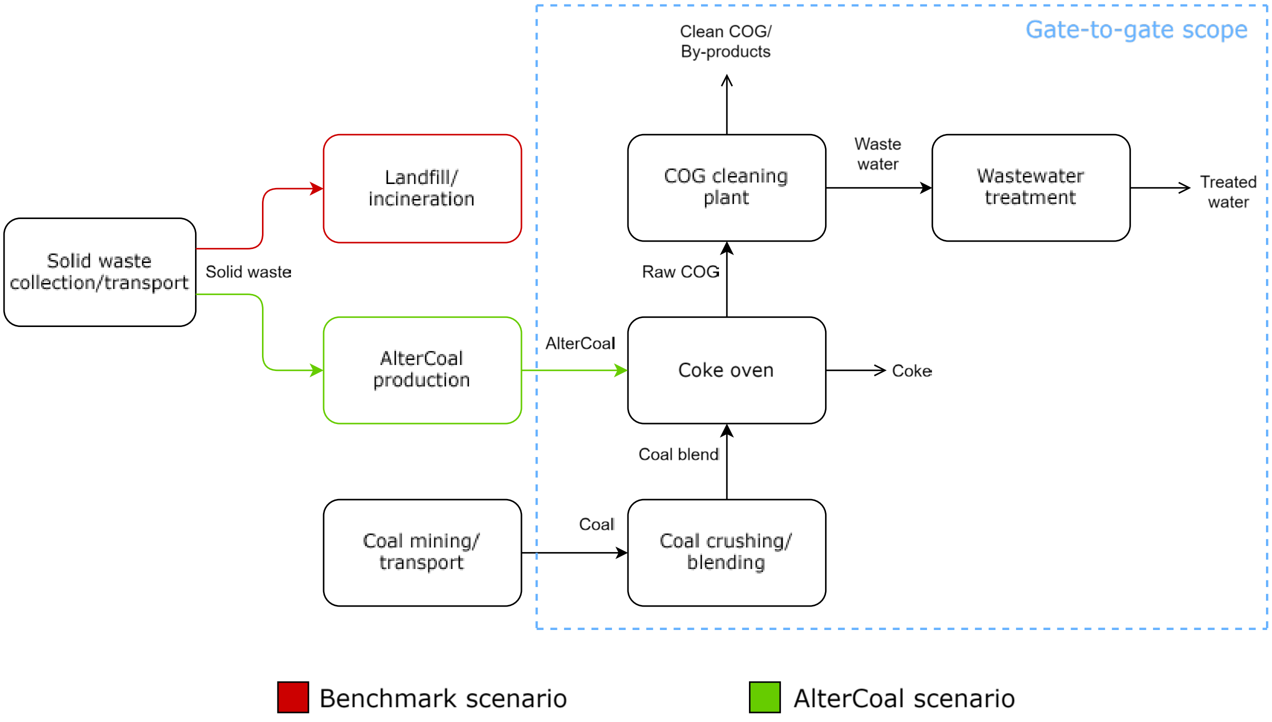

Figure 1. Gate-to-gate scope of this research. Red path shows the disposal method of solid waste in the benchmark scenario, while the green path shows the disposal method of solid waste in the AlterCoal scenario. Both scenarios share the black path.

2.2. Environmental analysis

Emissions from an industrial process can be divided into two categories: direct and indirect. On one hand, direct emissions correspond to the emissions produced on-site, as part of the operation of the process, which are released as off-gas to the atmosphere. On the other hand, indirect emissions correspond to the carbon dioxide produced as a consequence of the plant operation, but is generated outside of the plant installations (e.g., electricity consumption, production and supply of input materials, processing of materials outside of the plant installations, etc).

Direct CO_2 emissions produced during coke-making arise solely from burning COG. To account for emissions, it was assumed that all carbon in the COG would ultimately be converted to CO_2. To determine biogenic emissions from AlterCoal® pellets, it was considered that all biogenic carbon would be transformed into CO_2, as this is a common practice regarding reporting of emissions in industrial environments in the EU.

2.3. Economic analysis

In order to conduct a meaningful comparison of economic performance across different scenarios, and for an information-based decision making, the decision-making principles outlined in (Eschenbach, 2003) were taken into consideration, which are outlined in this section.

After defining the scenarios, the focus was placed on identifying and prioritizing the differences between them. The perspective of a European coke-making plant was chosen, and all prices were converted to euros. The analysis considered two base price years: 2019 and 2022. For older prices, adjustments were made to account for inflation rates when necessary. All pertinent aspects of the process were thoroughly examined, and an inventory of each process stream was created, including corresponding purchasing costs for inputs, and selling prices for outputs.

Since the site installations remain virtually the same in both scenarios, this work solely considered the operational costs of the process. Potential minor changes might be needed for feeding the AlterCoal® pellets to the system. However, the authors estimated that the required investment would be less than 1% of the yearly operational cost, making it negligible.

Based on the gathered information, three specific indicators were calculated:

- Cost of goods sold (COGS): this represents the direct costs associated with manufacturing the products that a company sells. It encompasses expenses related to materials and labour that directly contribute to the production. COGS excludes indirect expenses such as distribution and sales team costs (Jason Fernando, 2023).
- Gross revenue (GR): this includes the total monetary value of all sales conducted by a company within a specific period before any cost deductions are applied (The Investopedia Team, 2023).
- Gross profit (GP): defined as the income that a company generates after deducting the costs associated with making and selling its products, without considering fixed costs such as rent, advertising, insurance, non-production staff salaries, and office supplies. It is calculated by subtracting COGS to the gross revenue (Adam Hayes, 2023).

2.4. Uncertainty analysis

A Monte Carlo analysis was employed to determine the uncertainty within the economic model. In this type of analysis, random input values of different parameters within the model, in this case prices, are varied to represent different market conditions with the aim of evaluating the uncertainty and economic risk of the scenarios (Glasserman, 2004).

The analysis conducted in this work consisted of 500,000 random combinations of values for key prices affecting the economic model, namely: coke, coking coal, natural gas, electricity, tar, benzene, and CO_2 emissions allowances. The price values used in the uncertainty analysis were derived from their yearly average values and standard deviations, assuming normal distributions. These values are detailed in Table S2 from the Supplementary Materials.

. A Pearson test was used to detect linear correlation between two parameters (Cohen et al., 2009). It was defined that pairs of streams with a correlation coefficient bigger than 0.7 have a strong correlation. In each simulation, a gross profit value is generated for both scenarios. By aggregating the results from all simulations, an average gross profit and its standard deviation can be computed. The scenario with the lowest standard deviation is thereby identified as the least risky.

2.5.Sensitivity analysis

In this study, a sensitivity analysis, which consisted on adjusting within a range of -50% to +50% the average yearly prices of the main variables of the process, namely coke, coking coal, electricity, tar, benzene, natural gas, and CO_2 emission allowances, was performed to evaluate and rank their influence on gross profit in 2019 and 2022.

2.6.Assumptions

During the development of the TEA, the following assumptions were considered:

- The quality of the coke and by-products produced are consistent in both scenarios and meet the necessary standards to be sold at regional market prices.
- No mass-energy-losses occur in any of the process streams discussed here.
- The plant is equipped with all the necessary facilities to produce steam, oxygen, nitrogen, and compressed air at competitive prices.
- The treated water meets the process requirements, and it is completely reused.
- When burned, all carbon present in the COG is converted to carbon dioxide CO_2.
- The gas emissions and air pollutants comply with the regional environmental limits.

3. Description of the economic model

Developing an economic model for an industrial plant requires consideration of all technical, economic, and administrative aspects of the process. This section provides a detailed overview of these aspects.

In order to simulate a representative European coke plant, it was necessary to define the dimensions of the coke oven batteries. To achieve this, large ovens with a semi-modern configuration was chosen, guided by the characteristics described in (Neuwirth, 2014; Rainer Remus et al., 2013). The specific details of the selected plant configuration can be found in Table S3 from the Supplementary Materials. The coal blend bulk density was set to 793 kg/m^3 with a humidity of 9.1 wt% (The Engineering ToolBox, 2003). The industrial average conversion rate of coal blend in European coke-making plants was sourced from (Rainer Remus et al., 2013), and the conversion rate of the AlterCoal® pellets was provided by VEG (Vanheede Environment Group, 2023). The coke breeze generated from coal was calculated from (Adahama et al., 2008) These values are presented in Table 1.

Table 1. Conversion rate of the coal blend and the AlterCoal® pellets considered in this work. (Rainer Remus et al., 2013; U.S. Energy Information Administration (EIA), 2024; Vanheede Environment Group, 2023).

Product	Coal blend conversion rate	Pellets conversion rate
Coke	77.8%	28.9%
Coke breeze	3.2%	0.5%
Tar	2.9%	21.4%
BTX	0.9%	3.7%
Sulphur	0.1%	0.0%
COG	14.1%	45.3%

The waste plastics pellets considered in this work have a carbon content of 62.6 wt%, from which 30% is biogenic, a density of 450 kg/m^3, and a humidity of 4 wt% (Vanheede Environment Group, 2023). The replacement ratio considered in the AS is 2 wt%, which has been successfully applied at pilot scale, and it is currently being tested at industrial scale at AMG coke plant.

The composition of the clean COG produced was sourced from (Yang et al., 2014), which corresponds to 60% H_2, 6% N_2, 6% CO, 2% CO_2, and 24% CH_4. The net calorific value (NCV) of the COG was set to 17.5 MJ/Nm^3 based on information from (Rainer Remus et al., 2013), and its density was calculated from its composition to be 414 g/Nm^3.

To calculate labour costs, the full-time equivalents (FTE) necessary for plant operation were sourced from the specifications provided by (Neuwirth, 2014), based on number of pushes per day and number of full-time employees This calculation resulted in the determination that 2.3 FTE are required per each daily push of the coke plant. Consequently, the proposed plant would require 286.2 FTE/year.

The yearly FTE costs of coke manufacturing in 2020 in the EU were sourced from (Eurostat, 2023), and the yearly variation indexes were obtained from (Statistisches Bundesamt (Destatis), 2023). As a result, we estimated that the yearly FTE was €76,660 in 2019 and €83,069 in 2022.

3.1.Coal distillation process

There exist various methods and paths for coke production, each with their own set of advantages and disadvantages. The specific coke-making path considered in this study closely resembles a typical European plant (Rainer Remus et al., 2013) and is depicted in Figure 2. The coke manufacturing process is subdivided into two primary stages: coal distillation (indicated by the green square), and coke oven gas cleaning (indicated by the purple rectangle). Each step of this process is described in the following sub-sections.

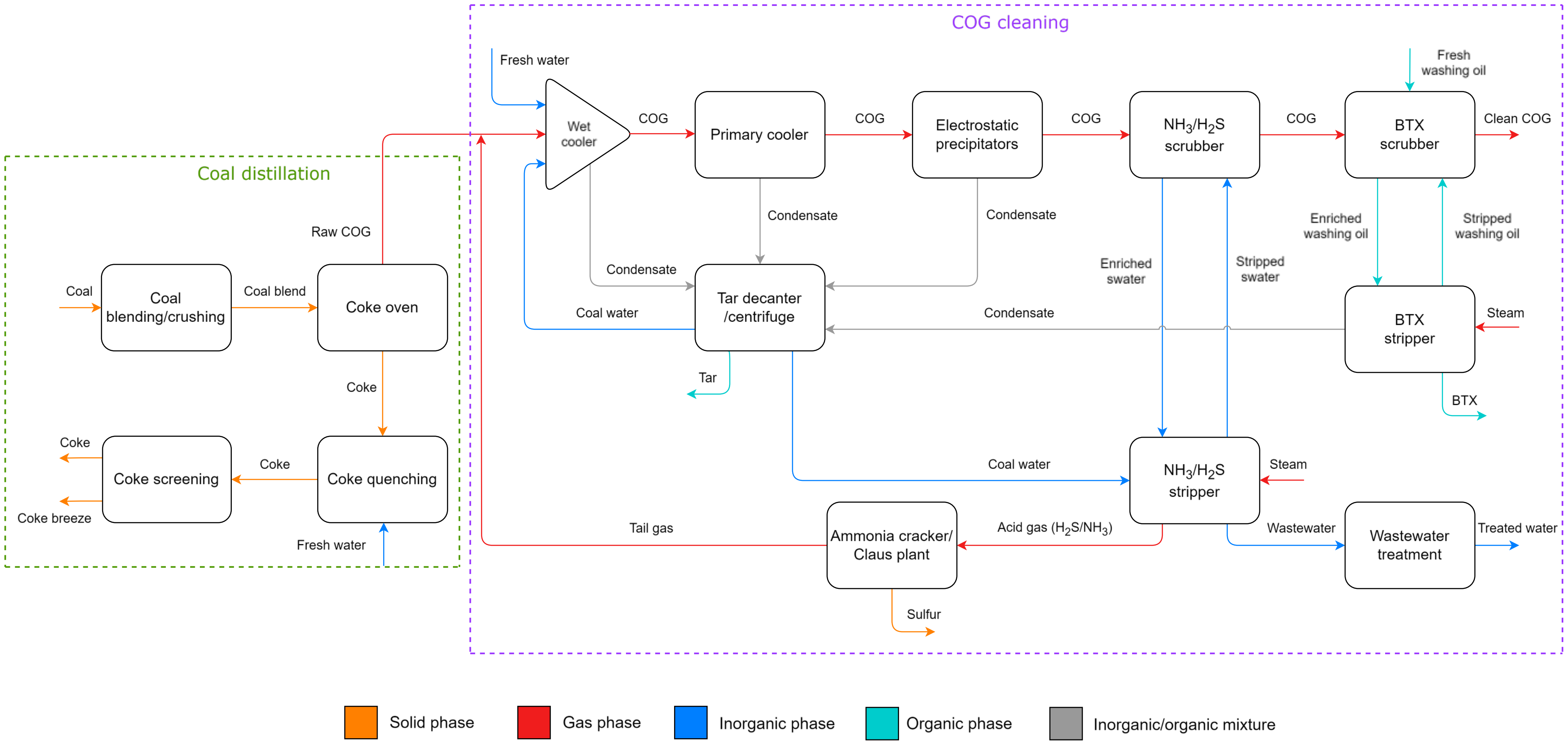

Figure 2. Process flow diagram of by-products coke-making considered in this research. Green square corresponds to the coal distillation part of the process, while the purple rectangle encloses the coke oven gas (COG) cleaning process. Adapted from (Fang et al., 2022; Rainer Remus et al., 2013).

During coal distillation, a coal blend is prepared mixing diverse types of coal, over a wide range of qualities. The composition of the blend is determined as “the most cost-effective one that complies with the requirements to produce a suitable coke for a blast furnace application” (Ghosh et al., 2022). Subsequently, the coal blend is crushed to a size suitable to be charged in the oven, typically until 80-90% of the coal passes through a 3.2 mm screen (Rainer Remus et al., 2013). The blend is then subjected to heating for about 18-27 hours, reaching temperatures of about 900-1100 °C, all in the absence of oxygen. The process involves heating the oven walls to release the volatile components present in the coal (RTI International, 2008). For the heating of the coke oven walls, cleaned COG is often employed as fuel. This process results in a product now referred to as coke, characterized by an elevated carbon content, improved mechanical properties, and a good porosity, making it suitable for a BF application.

Following this, the coke is discharged and rapidly quenched with water to reduce its temperature to 80 °C and prevent spontaneous combustion (RTI International, 2008). Typically, there is minimal wastewater generated, as the water fraction that does not evaporate can be reused in the subsequent batch (Rainer Remus et al., 2013). The coke is then crushed and screened. The preferred size fraction of coke typically falls within 40-80 mm (Carpenter, 2006).

When manufacturing coke using a blend of waste plastic pellets and fossil coal, both materials are combined and fed onto the conveyor belt at the defined weight ratio, which will introduce them into the coke ovens. The following steps remain the same as mentioned earlier in this section.

Table 2 presents the inventory of the coal distillation step for both scenarios, along with their respective prices and references. The consumption of materials and energy, excluding water and coking coal, was assumed to be equal in both scenarios. This is due to their dependence mainly on the dimensions of the oven rather than on the specific charges used. The water consumption is lower in the AS since less coke needs to be quenched. Additionally, because the pellets have a lower fixed carbon ratio, less coke is produced in the AS, resulting in a higher production of COG due to the increased volatile matter content. The CO_2 production in the AS is lower because the biogenic carbon content of the pellets is subtracted from the total emissions. Further details on emissions are discussed in Section 4.1.

The freshwater price considered in this work corresponds to the average price of mainland EU countries provided in (EurEau, 2021) for 2018, which was adjusted to 2019 and 2022 prices using the corresponding inflation rate (Ian Webster, 2023).

The cost of oxygen production in 2019 is based on on-site costs, assuming a purity of 95% (Advance Gas Technologies, 2019) . The price in 2022 was calculated by accounting for inflation. The cost of nitrogen production in 2022 is determined by on-site costs, considering production for a mid-volume user, which is in the range of an average European coke-making plant (Chris Styles, 2022). The price in 2019 was calculated by accounting for inflation. The cost of compressed air was calculated following the guide proposed by (Sivent AB, 2019), by assuming that electricity costs represent 70% of the total production costs, and that, on average, an industrial air compressor consumes 0.106 kWh per cubic meter of air compressed.

The cost of electricity in this work corresponds to the average EU price for non-household consumers in the range of 150 GWh or over (Eurostat, 2024a). The COG price corresponds to the average EU price of natural gas for non-household consumers in the range of 4,000 TJ or over (Eurostat, 2024b), as COG can be directly substituted for natural gas. The coke price corresponds to the Polish export price, as Poland is the primary exporter of coke in the EU, making it a representative benchmark (Asian Metal, 2023a). Details on emission calculations are presented in Section 4.1.

The energy needed to heat the ovens during coal distillation and to preheat the stripped washing oil in the BTX absorption step of the COG cleaning process is obtained from the combustion of clean COG. Likewise, the energy needed for generating the required steam is acquired through clean COG combustion. It was assumed that the steam would be produced on-site via a steam boiler, by heating water from room temperature to 150 °C with an efficiency rate of 94% (Vakkilainen, 2017).

3.2.COG cleaning process

The gas phase generated during coal distillation contains valuable components that are suitable for recovery. It also holds a high energy content, which can be only used after the gas has undergone purification to remove the primary impurities, namely ammonia and hydrogen sulphide. The cleaning process of COG is outlined in Figure 2 (purple rectangle), and can be divided into six distinct sub-processes:

- Wet gas cooler: the initial raw COG obtained from the coke oven is pre-cooled from 650-750°C to 80-90°C via direct contact with a spray of ammonia liquor (Wright, 2005). As a result of this temperature drop, the nitrogen present in the gas condenses as ammonia (NH_3). This process also causes water vapor, originating from the coal's moisture content, and heavy hydrocarbon chains (tars) within the gas to condense, forming an organic/inorganic liquid mixture. This liquid mixture is then transferred to a decanter, which separates the tar from the water, while the gas phase proceeds to the primary coolers (Li et al., 2020). Approximately 70% of the tar is removed in this stage (Nazarov, 2016).
- Primary coolers: in this step the gas is further cooled to about 20-25 °C through indirect contact with water (which is subsequently cooled by air), followed by direct contact with a water spray. Here, a second organic fraction, primarily naphthalene, will condense within the gas (Wright, 2005). The condensate is then transferred to the tar decanter for separation.
- Electrostatic precipitators (ESP): the gas is cleaned of the coal dust and tar droplets suspended in it by using electrostatic precipitators (Van Paasen et al., 2004).
- Tar decanter/centrifuge: most of the water and long-chain hydrocarbons present in the COG are recovered during the previous stages as condensate and are subsequently transferred to the tar decanter. The separated tar is then processed through a centrifuge for further separation, resulting in a high purity product (Kazak et al., 2009). The bulk of the water is reused in the wet cooler as an “ammonia flush” while any excess water is transferred to the sulphur-ammonia removal step (Sowa et al., 2009).
- Sulphur-Ammonia removal: in this study, the ASK process (Ammoniumsulphide Circuit Scrubber, or Ammoniumsulphid-Kreislaufwäscher in German) was chosen as the desulphurisation step, as it is the most employed method in Europe (Rainer Remus et al., 2013). A comprehensive description of it can be found in the work by Sowa et al. (Sowa et al., 2009). In summary, the ASK process comprises three main stages: combined scrubbing of ammonia and H_2S, by contacting the COG with stripped water, which produces enriched water and desulphurised COG; stripping of H_2S and NH_3, by contacting the

enriched water with steam, which produces stripped water and acid gas; and processing of the acid gas to produce elemental sulphur in a Claus reactor, combined with cracking of NH_3 to produce nitrogen and hydrogen. A big amount of wastewater is generated in this step and is later cleaned in the wastewater treatment system (Wright, 2005).

- BTX plant: in this final gas cleaning step, the COG is contacted with a cold organic washing oil which dissolves the benzol present in the gas, resulting in a purified and clean COG. The enriched washing oil is then heated and subjected to contact with steam in a second column, allowing it to release the captured benzol. Subsequently, the washing oil is cooled through heat exchangers and recycled back to the first column. The vapor mixture of benzol and water is condensed and transferred to a decanter, where benzol is extracted as the final product. The inorganic liquid fraction, which may contain minor organic impurities, is directed to the tar decanter. Due to constant heating and cooling of the washing oil, fresh oil needs to be added to compensate for losses (Fang et al., 2022).

The wastewater generated during COG cleaning must be treated before it can be discharged or reused. In this study, a denitrification-nitrification treatment system was considered, which is a standard approach used in European plants (Rainer Remus et al., 2013). A schematic diagram of the process is shown in Figure S4 from the Supplementary Materials. The treatment involves the following steps:

- Initially, the wastewater is directed to a sedimentation tank, where aluminium sulphate ($Al_2(SO_4)_3$) is added as a coagulant to remove suspended solids, dispersed tar, and dissolved metals. Additionally, during this step cyanide is converted to thiocyanate, which is easier to remove (Felföldi et al., 2020). Adjustments to the pH may be made using caustic soda (NaOH) and sulphuric acid (H_2SO_4) if necessary (Rainer Remus et al., 2013). The organic phase is separated and led to the sludge tank.
- The water is then pumped and heated, leading to a decanter where further recovery of organic matter occurs.
- The water is then pumped to a series of batch reactors. First, it enters an anaerobic reactor where denitrification takes place, converting nitrate (NO_3) to nitrogen gas (N_2) and water. Antifoam and flocculant are usually added to improve sedimentation conditions, while phosphoric acid (H_3PO_4) is introduced to control the conditions for bacterial proliferation and performance.
- Following the anaerobic reactor, the water flows through three aerobic reactors where nitrification occurs, converting ammonia (NH_3) to nitrate (NO_3). Dilution water and caustic soda (NaOH) are added to adjust and maintain pH conditions (Kwiecińska et al., 2017).
- The treated water flows to a final clarifier, where it is ready for discharge or reuse as dilution water. Meanwhile, the organic fraction is directed to the sludge tank for potential recycling to the coke-making process or recirculation to the batch reactors to support bacterial reactions. Further detailed information about this process is beyond the scope of this work and can be found in (Felföldi et al., 2020; Kwieciñska et al., 2017; Wright and Antill, 1991).

The mass-energy balance of the wet cooler, primary coolers, and BTX cleaning is based on the AMG plant, which has a typical European cleaning plant configuration. The electricity consumption of the ESP was sourced from (Van Paasen et al., 2004), while the materials and energy used in the sulphur/ammonia cleaning plant were derived from (Sowa et al., 2009). The projected plant consumption was escalated from the references on a gas processed-volume basis.

Table 3 provides a summary of the materials and energy consumed during COG cleaning for both scenarios, along with their corresponding prices and references. Due to the dependency of materials and energy consumption during COG cleaning on the processed volume of COG, the AS experiences 3.0% rise in input materials and input energy. This increase corresponds to the additional amount of COG processed in this specific scenario.

The output materials and energy were calculated based on the conversion rates outlined in Table 1. The selected fresh oil price corresponds to the European price of diesel since it could be a direct replacement. The tar price corresponds to the average export price of tar between Poland and France, the two main tar exporters in the EU (Asian Metal, 2023b), making it a representative benchmark.

The price of sulphur was derived from (Ahmed Abdalla, 2023), considering lump sulphur along with the transportation costs specified by the source. The wastewater treatment cost for the considered configuration in 1996 was obtained from (Rainer Remus et al., 2013). This cost was subsequently adjusted to 2019 and 2022 prices by accounting for inflation. Details on emissions calculations are presented in Section 4.1.

Table 2. Annual inventory of the coal distillation process.

Type	Stream	Units	Benchmark scenario	AlterCoal scenario	Net diff.	Relative diff.	Price 2019	Price 2022	Price units	Price diff.	Price reference
Input materials	Coking coal (wet)	ton/year	2,708,881	2,619,625	-89,256	-3.3%	164	386	€/ton	136%	(Business analytiq, 2023a)
	Fresh water*	m^3/year	1,437,973	1,401,132	-36,841	-2.6%	3.5	4.1	€/m^3	14%	(EurEau, 2021)
	AlterCoal® pellets (wet)	ton/year	0	50,649	-	-	15	30	€/ton	100%	(Vanheede Environment Group, 2023)
	Acetylene	ton/year	0.46	0.46	0	0.0%	1,329	1,981	€/ton	49%	(Businessanalytiq, 2023)
Input Energy	Oxygen	Nm^3/year	1,342	1,342	0	0.0%	0.06	0.07	€/ton	15%	(Advance Gas Technologies, 2019)
	Nitrogen	Nm^3/year	9,011	9,011	0	0.0%	0.4	0.4	€/Nm^3	15%	(Chris Styles, 2022)
	Compressed air	Nm^3/year	15,338,378	15,338,378	0	0.0%	0.01	0.03	€/Nm^3	165%	(Sivent AB, 2019)
	Electricity	MWh/year	66,573	66,573	0	0.0%	81	214	€/MWh	165%	(Eurostat, 2024a)
	COG (heating)	MWh/year	1,890,668	1,890,668	0	0.0%	32	134	€/MWh	331%	(Eurostat, 2024b)
	Steam	ton/year	309,503	309,503	0	0.0%	22	86	€/ton	286%	**
Output materials	Coke (dry)	ton/year	1,917,297	1,868,176	-51,445	-2.6%	278	493	€/ton	77%	(Asian Metal, 2023a)
	Coke breeze	ton/year	79,060	76,698	-2,362	-3.0%	85	150	€/ton	77%	(U.S. Energy Information Administration (EIA), 2024)***
	CO_2	ton/year	265,717	232,678	-33,039	-12.4%	25	82	€/ton	231%	(Sandbag, 2023)
Output energy	Steam	ton/year	99,329	96,784	-2,545	-2.6%	22	86	€/ton	286%	**

*Water required for coke quenching. **Price of steam was calculated considering the COG needed to heat water from room temperature to 150°C in a steam boiler with an efficiency of 94% (Vakkilainen, 2017) plus the cost of fresh water. ***Coke breeze price was estimated as 30% of coke price.

Table 3. Annual inventory of the COG cleaning process.

Type	Stream	Units	Benchmark scenario	AlterCoal scenario	Net diff.	Relative diff.	Price 2019	Price 2022	Price units	Price diff.	Price reference
Input materials	Fresh oil	ton/year	909	937	28	3.0%	1,330	1,780	€/m^3	34%	(Rhino Car Hire, 2023)
	Caustic soda	ton/year	6,611	6,811	200	3.0%	196	394	€/ton	101%	(Business analyt iQ, 2023)
	Fresh water	m^3/year	104,558	121,189	16,632	15.9%	3.5	4.1	€/m^3	14%	(EurEau, 2021)
Input Energy	COG	MWh/year	10,486	10,803	317	3.0%	24	105	€/MWh	331%	(Eurostat, 2024a)
	Electricity	MWh/year	499,280	514,385	15,105	3.0%	81	214	€/MWh	165%	(Eurostat, 2024b)
	Steam	ton/year	225,478	232,299	6,822	3.0%	22	86	€/ton	285%	*
Output materials	Tar	ton/year	70,940	79,008	8,068	11.4%	286	668	€/ton	134%	(Asian Metal, 2023b)
	Benzene	ton/year	18,502	19,399	898	4.8%	647	1,037	€/ton	60%	(Business analytiq, 2023b)
	Sulphur	ton/year	2,780	2,710	-70	-2.5%	184	374	€/ton	103%	(Ahmed Abdalla, 2023)
	CO$_2$	ton/year	24,292	24,842	550	2.3%	25	82	€/ton	231%	(Sandbag, 2023)
	Wastewater	m^3/year	575,189	592,591	17,402	3.0%	2.8	3.2	€/m^3	14%	(Rainer Remus et al., 2013)
Output Energy	Clean COG	MWh/year	4,091,566	4,215,350	123,785	3.0%	24	105	€/MWh	331%	(Eurostat, 2024a)

*Price of steam was calculated considering the COG needed to heat water from room temperature to 150°C in a steam boiler with an efficiency of 94% (Vakkilainen, 2017) plus the cost of fresh water.

4. Results and discussion

4.1. Environmental analysis

Given that CO_2 emissions from energy-intensive industrial installations fall under the scope of the EU emissions trading system (ETS) (McPhie and Rietdorf, 2021), assessing the tons of direct CO_2 emissions for both scenarios became an essential component of the economic model. Indirect emissions were not considered since they would add another layer of complexity to this work, and they are not required to accomplish the main goal of this study, which is to develop an economic model.

The summary of the direct emissions is presented in Table 4, where they are classified by process. Direct emissions only consider CO_2 produced on-site. Since all carbon of COG is converted into CO_2 and considering that COG is made of 6%CO, 2% CO_2, and 24% CH_4, on a volume basis, it was determined that for every ton of burned COG, 1.52 tons of CO_2 are emitted.

During the coal distillation step, the heat required to keep the ovens at the desired temperature is the same in both scenarios since it was assumed that the change in energy requirements by replacing 2wt% of the oven load by AlterCoal® pellets is negligible. The steam required in the AS increases about 1.2% due to the fact that less coke is produced, and therefore less steam is recovered from the coke wet quenching stage.

In the COG cleaning process, the AS requires about 3.0% more heat and steam, as this is directly related to the volume of COG that needs to be cleaned, which increases in this scenario by the exact same percentage, due to the higher volatile fraction of the AlterCoal® pellets compared to coking coal.

In the AS, the biogenic emissions were subtracted from the overall emissions, resulting in a 32.4 kton/year reduction in the AS. This leads to an overall 11.2% emissions decrease in AS. This outcome highlights one of the main advantages of the AS, namely its ability to offer a cleaner process. When we consider this outcome alongside the fact that incineration and/or landfill of the waste materials is being avoided, it provides compelling arguments to prefer this more sustainable approach of dealing with waste hydrocarbons.

Table 4. Summary of annual direct CO_2 emissions

Process	Category	Benchmark scenario	AlterCoal scenario	Units	Relative Difference
Coal distillation	Heat required*	6,806	6,806	TJ/year	0.0%
	Steam required**	210,174	212,719	ton/year	1.2%
	COG burned***	175,131	175,302	ton/year	0.1%
	CO_2 emitted****	265,717	265,975	ton/year	0.1%
COG cleaning plant	Heat required*	37.7	38.9	TJ/year	3.0%
	Steam required**	225,478	232,299	ton/year	3.0%
	COG burned***	16,011	16,495	ton/year	3.0%
	CO_2 emitted****	24,292	25,027	ton/year	3.0%
Biogenic CO_2		0	33,482	ton/year	-
Total CO_2 emissions		301,465	257,520	ton/year	-11.2%

*Corresponds to the energy required to heat the equipment (e.g., ovens) during coke-making; **corresponds to the steam required during coke-making; ***sum of COG burned to heat the equipment and to produce the required steam; ****emissions produced by the COG burned to provide the required energy.

Furthermore, we estimate that about 36.5 million tons of coking coal are required in Europe by coke-makers to produce enough coke to maintain pig iron production. If the AS was adopted in all coke-making plants, it would result in about 730.4 kton/year of waste plastics recycled, considerably reducing the amount of landfilled/incinerated materials.

4.2. Economic analysis

The economic analysis was conducted based on three indicators: cost of goods sold (COGS), gross revenue (GR), and gross profit (GP). Table 5 provides a summary of the results from the economic model. In 2019, the COGS for coal distillation in the AS is about 2.9% lower than in the BS. This reduction is primarily attributed to the lower amount of coal required for coke production, as a portion of the input materials is replaced with AlterCoal® pellets. Additionally, the price difference between coking coal and pellets contributes significantly, with pellets costing approximately 10% of the price of coal. However, the gross revenue in the AS experiences a decrease of about 2.6%, mainly attributed to the decrease in coke output, as the AlterCoal® pellets have a lower fixed carbon fraction than coal. This translates into a coal distillation step that is about €0.8 million more profitable in the AS compared to the BS. In 2022, the situation is similar in terms of percentage, but due to the huge increase in energy prices, the coal distillation step in the AS becomes about €11.0 million more profitable than in the BS.

In 2019, the COGS for COG gas cleaning experienced an increase of about 2.6% in the AS, primarily driven by the rise in raw gas input, which arises from the fact that AlterCoal® pellets produce more gas than coal during coal distillation. However, the gross revenue also experienced a positive shift, increasing by about 4.4%, with this rise attributed to the increase in by-products and COG produced. As more raw COG is produced from pellets, the mass of by-products recovered also increases. This results in a COG cleaning step about €4.3 million more profitable in the AS compared to the BS. In 2022, the situation is again similar in terms of percentage, but due to the huge increase in energy prices, the COG cleaning step in the AS is about €15.1 million more profitable than in the BS.

Maintenance costs are slightly higher in the AS due to the extra gas processed, which increases the wearing of the high alloy steel in the NH_3/H_2S stripper subprocess (Sowa et al., 2009). However, labour costs were equal in both scenarios, as the dimensions of the coke plant remain constant.

Figure 3 presents a gross profit comparison between the two scenarios in 2019 and 2022. In 2019, the AS generates a GP about €5.2 million higher than in the BS, reflecting a 5.9% increase, which would be already sufficient argument to choose this scenario without even considering the environmental advantages linked to it. In 2022, the BS incurred a negative profit of about -€11.1 million, while the AS achieved a positive profit of about €15.0 million. This substantial difference (about €26.1 million) is primarily attributed to the significant increase in the cost of coking coal in 2022, a cost that is less pronounced in the AS due to the reduced consumption, while the price of the AlterCoal® pellets is one order of magnitude smaller than that of the coking coal, indicating its potential as a good substitute. Additionally, the higher price of natural gas, produced in larger quantities in the AS, contributed to the positive financial outcome in this scenario.

When a crucial component of an integrated steel facility, like the coke-making process, experiences a loss in profitability, coupled with decreasing steel prices due to weakened demand, it becomes logical to reduce or completely halt iron and steel production for extended periods. This strategic response was observed in multiple European steel plants in 2022, as illustrated in Figure S1 and detailed in Table S1 from the Supplementary Materials, with the aim to mitigate potential financial losses. In this context, producing coke via the AS configuration would imply a lower production cost and consequently, a lower dependence on steel price fluctuations, as such making the production process more robust.

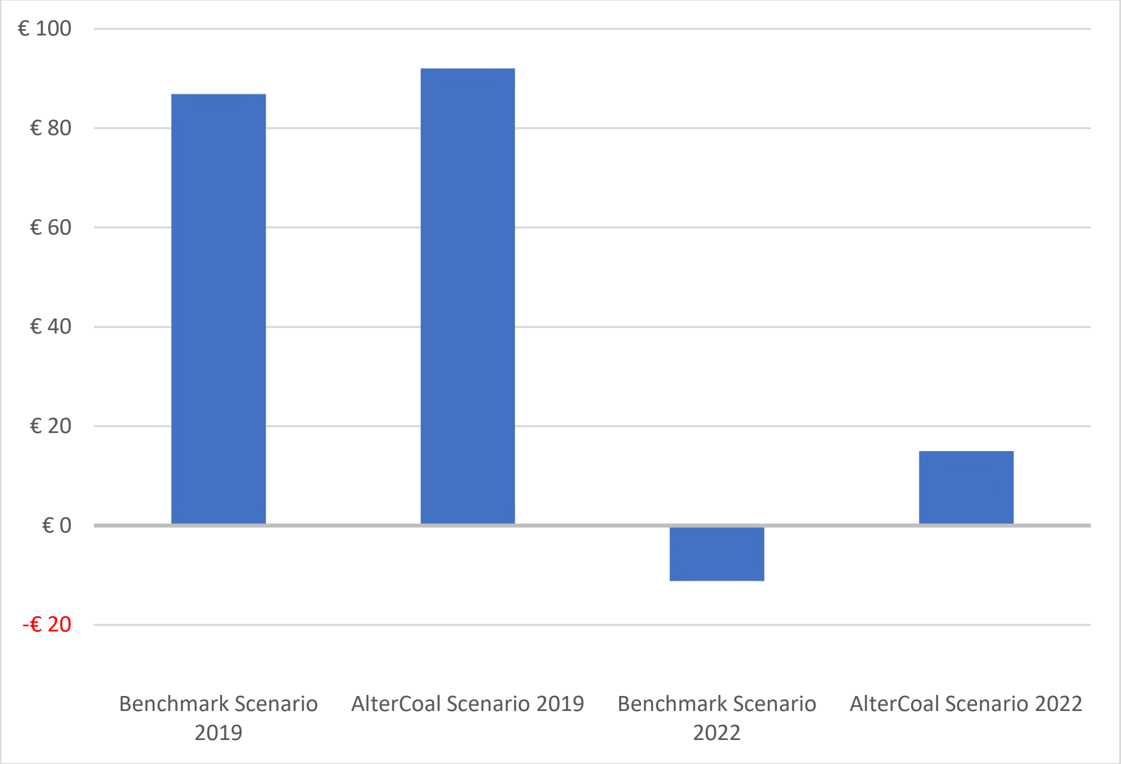

Figure 3. Comparison of gross profit for both scenarios in 2019 and 2022. It can be seen that the AlterCoal scenario outperforms the Benchmark scenario in both years.

4.3.Uncertainty Analysis

The uncertainty analysis based on the Monte Carlo method involved 500,000 random combinations of key price values influencing the economic model. Interdependencies among the prices of various streams were assessed through a Pearson correlation test. The results of the Pearson test revealed a strong correlation between prices of coke, coal, tar, natural gas, and electricity, in 2019. In contrast, for 2022, the correlation was identified between coke and benzene, and between natural gas, electricity, and tar prices. This means that when a specific cost goes up or down, the correlated costs will follow the same trend. These trends are depicted in Figure S1and Figure S2 from the Supplementary Materials.

The results of the 500,000 random combinations of prices for 2019 and 2022 are summarized in Table 6. The standard deviation of the gross profit (GP) for the BS in 2019 is around €22.3 million, accounting for 26% of the GP. On the other hand, the standard deviation of the GP for the AS in 2019 is also around €22.3 million, but given the larger GP, this only represents 24% of the GP. Positive profits were observed in 100% of the simulations both scenarios. When comparing the two scenarios, the AS outperformed the BS, generating a larger profit in 100% of the simulations, together with a lower standard deviation-gross profit ratio, making it economically less uncertain, which again highlights the benefits of using AlterCoal® pellets to replace expensive coking coal.

In 2022, the standard deviation experienced a substantial increase, primarily attributed to the volatility in the energy market that year, making the process economy highly uncertain. The standard deviation of the GP for the BS in 2022 is about €212 million, representing about 1,906% of the GP. On the other hand, the standard deviation of the GP for the AS in 2022 is about €206 million. Despite this being a larger absolute value, it accounts for 1,373% of the GP, making it less uncertain than the BS, as the price of AlterCoal® pellets is not linked to the energy market. Furthermore, in 2022, positive profits were observed in 48% of the simulations for the BS, while the AS exhibited positive profit on 53% of the simulations. When comparing the two scenarios, the AS thus again outperformed the BS, generating a larger profit in all simulations.

Figure 4 presents a comparison of the gross profits of both scenarios during 2019 and 2022, together with their corresponding 95% confidence intervals based on the average values and standard deviations obtained from the Monte Carlo Simulations. From this figure, it is clear that the AS is less uncertain than the BS in both years, as the vertical lines are shorter, and its confidence intervals are in a higher profit range. However, it also shows how catastrophic could be the economic performance of the process in 2022 if an unfavourable combination of prices is considered, reaching up to about -€450 million in profit in the worst cases. These results highlight how volatile the coke-making market is, and how heavily it can be affected by fluctuations in the energy prices, and they also explain the decision of many steelmaking plants of reducing or stopping their production in 2022, since having such an uncertain profit value could end up having disastrous consequences.

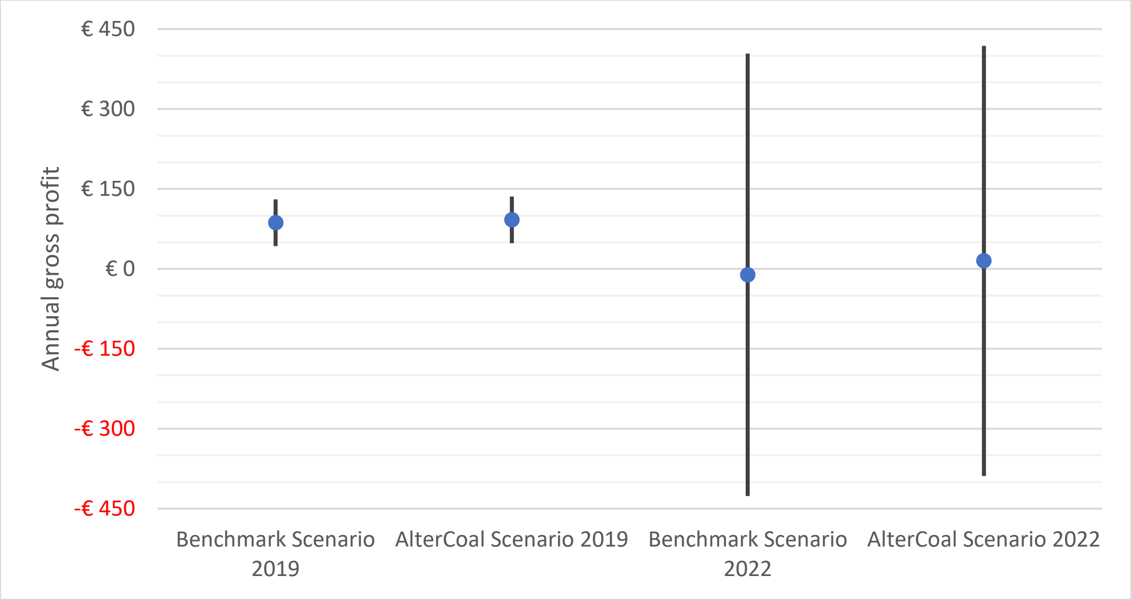

Figure 4. Uncertainty analysis results for both scenarios in 2019 and 2022. The blue points represent average gross profit value from the simulations, while the black lines represent the 95% confidence interval. The AlterCoal scenario outperforms the Benchmark scenario in both years.

Table 5. Summary of annual results of economic indicators for both scenarios

Year	Scenario	COGS* of coal distillation	COGS of gas cleaning	GR** of coal distillation	GR of gas cleaning	Maintenance-Labour costs	Gross profit
2019	Benchmark	€513,708,734	€50,856,760	€541,802,334	€132,591,110	€23,006,519	€86,821,430
	AlterCoal	€498,914,776	€52,438,963	€527,892,878	€138,484,318	€23,038,786	€91,984,669
	Net diff.	-€14,793,958	€1,582,203	-€13,909,456	€5,893,208	€32,267	€5,163,239
	Rel. diff.	-2.9%	3.1%	-2.6%	4.4%	0.1%	5.9%
2022	Benchmark	€1,313,906,904	€136,192,631	€966,092,473	€497,850,965	€24,986,618	-€11,142,716
	AlterCoal	€1,278,109,715	€140,354,141	€941,290,642	€517,161,527	€25,023,292	€14,965,021
	Net diff.	-€35,797,189	€4,161,510	-€24,801,830	€19,310,562	€36,674	€26,107,737
	Rel. diff.	-2.7%	3.1%	-2.6%	3.9%	0.1%	234.3%

*COGS: Costs of goods sold; **GR: gross revenues

Table 6. Summary of annual results of uncertainty analysis for both scenarios

Year	Scenario	Average Gross profit	Std Dev	Std Dev/average Gross profit	Positive profit ratio	Best scenario ratio
2019	Benchmark	€86,801,832	€22,337,588	26%	100%	0%
	AlterCoal	€91,965,184	€22,329,498	24%	100%	100%
2022	Benchmark	-€11,122,588	€212,074,727	1906%	48%	0%
	AlterCoal	€14,981,262	€206,145,112	1373%	53%	100%

4.4.Sensitivity Analysis

The results of the sensitivity analysis, which aimed to identify the most influential variables on the economic model, are presented in Table 7 for both scenarios in 2019 and 2022. For 2019, the GP of both scenarios is most significantly influenced by the prices of coke and coking coal. A 50% increase in coking coal price has a substantial impact, leading to a decrease of 255% in the GP of the BS, and 233% in the GP of the AS, while a 50% increase in coke price produces an increase of 307% in the GP of the BS and 282% in the GP of the AS. This pronounced effect is primarily attributed to the essential role of these products in the process: the large input of coal and the resulting output of coke during coke-making, which is the main goal of coke-making plants. Additionally, natural gas price and electricity price also exert a considerable influence on the gross profit. Natural gas sets the COG price and the steam price, as COG replaces natural gas for heating purposes, and as steam is produced by burning COG, while electricity is extensively consumed in the COG cleaning stage. In contrast, the other evaluated prices have minimal impact on the process economics, as a variation in 50% on the prices of CO_2 emission allowances, benzene, and tar, affect the GP in less than 15%. From these results, it becomes clear that the economics of the AS is less sensitive to changes in prices of coking coal and coke, the two most relevant streams of the process, than the BS, making it a more robust scenario.

In 2022, the most influential parameters on the gross profit for both scenarios are again coking coal, coke, electricity, and natural gas prices. However, this time their impact is even more substantial, with a 50% increase in coking coal price leading to a decrease in the GP of 4,243% in the BS, and of 3,078% in the AS. This increased effect can be attributed to the significant rise in coke, coking coal, and natural gas prices between 2019 and 2022, as shown in Table S2 and Figure S3 from the Supplementary Materials. Additionally, benzene and tar prices become more relevant for both scenarios in 2022, again because of their rise in price during that period.

The price of CO_2 emissions allowances, which was of insignificant effect in 2019, became a strong variable in 2022 for the BS, increasing 26 times its effect on the GP, which is attributed to the price increase of emissions allowances between 2019 and 2022, from 24.8 €/ton to 82.0 €/ton. Since the AS produces less emissions, the increase of the price of CO_2 emissions is smaller, about 20 times from 2019 to 2022. This reflects the importance of finding innovative ways to reduce CO_2 emissions, as the impact that they have on the process economics will keep increasing since the available emissions allowances will decrease every year, as determined by the European Union (European Commission, 2020).

It is clear from these results that the GP of the BS in 2022 is overly sensitive to all considered price evolutions, which again explains the decision of many steelmaking plants of reducing or stopping their production in 2022. It also confirms the importance of finding cheap substitutes for coking coal, which reduces considerably the sensitivity of the process to this variable. It is crucial to highlight that, in all considered cases, the AS consistently performs better than the BS.

Table 7. Summary of sensitivity analysis results. Corresponds to the variation in gross profit when prices of selected streams are decreased or increased in 50%, for Benchmark Scenario and AlterCoal scenario, in 2019 and 2022.

Year	**2019**				**2022**			
Scenario	Benchmark		AlterCoal		Benchmark		AlterCoal	
Price variation	-50%	+50%	-50%	+50%	-50%	+50%	-50%	+50%
CO_2	4%	-4%	3%	-3%	107%	-107%	71%	-71%
Benzene	-7%	7%	-7%	7%	-86%	86%	-67%	67%
Tar	-12%	12%	-12%	12%	-213%	213%	-176%	176%
Electricity	26%	26%	26%	26%	544%	544%	416%	416%
Natural gas	-31%	31%	-31%	31%	-1,034%	1,034%	-813%	813%
Coking coal	255%	-255%	233%	-233%	4,692%	-4,692%	3,378%	-3,378%
Coke	-307%	307%	-282%	282%	-4,243%	4,243%	-3,078%	3,078%

5. Conclusions

In this paper, a techno-economic assessment was conducted from the point of view of an average European coke-making plant. Two scenarios were evaluated: the Benchmark scenario (BS), which corresponds to the production of coke from fossil coals, and the AlterCoal scenario (AS), where 2 wt% of the coal blend is replaced by pellets made from non-recyclable waste plastics (AlterCoal®).

Direct CO_2 emissions were lower in the AS compared to the BS by 11.2%, mainly due to the biogenic carbon present in the AlterCoal® pellets, which are discounted from the total emissions in the AS. In 2019 and 2022 the gross profit of the AS was higher than that of the BS, which arises from the reduction of coking coal required, the use of cheap AlterCoal® pellets, and the increased production of clean COG.

The uncertainty analysis revealed that the AS is less uncertain than the BS, both in 2019 and 2022. The sensitivity analysis identified key profit drivers: in 2019, coke, coking coal, electricity, and natural gas prices were critical, while in 2022, these remained critical, and tar, benzene, and CO_2 allowances gained prominence.

To finalize, it is important to highlight that the presented approach diminishes the dependence of European steel plants on coking coal, promoting economic flexibility and environmental sustainability, making it a comprehensive and forward-thinking solution for the steelmaking sector.

CRediT authorship contribution statement

Mario Ávila: Writing – original daft, Conceptualization, Formal analysis, Methodology, Investigation, Data curation, Visualization, Software. **Inge Bellemans**: Writing – review and editing, Methodology, Conceptualization, Supervision, Validation, Project administration. **Sofie Verbrugge**: Writing – review and editing, Methodology, Conceptualization, Supervision, Validation. **Kim Verbeken**: Writing – review and editing, Supervision, Validation, Project administration, Resources, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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