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Techno-economic case study on Oxyfuel technology implementation in EAF steel mills – Concepts for waste heat recovery and carbon dioxide utilization

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ABSTRACT

Compared to integrated steel production via blast furnace and basic oxygen furnace, the electric arc furnace route saves energy and carbon dioxide emissions. While the major part of the energy is provided in the form of electric power, a substantial fraction of thermal energy is supplied by the combustion of direct fuels.

In the present study, we describe available options for increasing the energy efficiency and cut down on carbon dioxide emissions in electric arc furnace steel mills. Based on these technologies, we develop possible process layouts including the transition to Oxyfuel ladle preheating, on-site utilization of the CO_2-rich product gas and off-gas heat as well as the recovery of waste heat from the hot gas duct of the electric arc furnace for process steam production.

With the aid of an energy system model, a case study is carried out to determine the potential for fuel savings as well as carbon dioxide and waste heat utilization. In a technical assessment, we investigate the relationship between the storage capacities, the carbon dioxide and waste heat utilization ratios as well as the fuel and CO_2 emission savings. The subsequent economic analysis yields the optimum system layout under different framework conditions.

1. Introduction

The European steel industry had an annual final energy consumption of 309 TWh in 2018 (Eurostat (European Commission), 2020) and is today responsible for 4–7% of the anthropogenic carbon dioxide emissions in the EU (Pardo et al., 2015). Steel production using an electric arc furnace (EAF) enables both the recycling of steel scrap and the processing of directly reduced iron. Compared to the integrated steel production (blast furnace (BF)/basic oxygen furnace (BOF)) the secondary process route (scrap/EAF) reduces the CO_2-emissions by 63–73%. The application of the direct reduction route (DRI/EAF) results in a decrease of the CO_2-intensity of 41–68%, whereas direct reduction using hydrogen (HDRI/EAF) is expected to cut emissions by up to 99% (Toktarova et al., 2020).

However, the actual carbon dioxide emissions associated with the production of one ton of steel via the EAF route depend primarily on two main factors: The specific CO_2 emissions of the power grid (Sasiain et al., 2020) and the energy efficiency of the applied production processes (Quader et al., 2015). Within EAF steel production, particularly the generation of process heat from fossil fuels offers significant potential for reducing the energy consumption and thus the carbon dioxide emissions of the process.

1.1. Production process and energy consumption

Steel production via the EAF route consists of the main process steps melting, refining, steel and slag tapping, decarburization, ladle treatments and casting (Remus, 2013).

The EAF melts the introduced steel scrap through the input of electrical and chemical energy. In the refining process, the liquid steel is decarburized by oxygen blowing. Then, the steel is tapped into a preheated steelmaking ladle and unwanted scrap components are removed with the slag. For high-alloy steels, vacuum oxygen decarburization (VOD) is applied. Ladle metallurgy involves the process steps of desulphurization, alloying, homogenization and degassing and aims to adjust the required chemical composition (Remus, 2013). In the investigated mill, the steel is cast into ingots, which are heat-treated to enhance the material properties of the steel product. An alternative option is continuous casting to produce steel billets.

Most of these process steps require the input of substantial amounts of energy. According to literature, the mean specific energy consumption for EAF steelmaking amounts to 1178 kWh per ton of product (Arens et al., 2017). Depending on scrap and product quality as well as applied production processes, the production of one ton of steel requires about 5–65 m_N^3 of oxygen and 3–28 kg of coal (Remus, 2013).

A recent study conducted by the authors at an Austrian steel mill

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showed that about 58% of the final energy consumption is supplied in the form of electric energy, while the remaining 42% are provided by direct fuels (Fig. 1) (Dock et al., 2021). Electrical energy is mainly used to power the electric arc furnace, the ladle furnaces and the dedusting systems. Preheating of the steel mill ladles using natural gas burners is the second most energy-intensive process step. Further major natural gas consumers are the heat treatment furnaces and the process steam generation for vacuum treatments. The remaining minor electricity and natural gas consumers are subsumed under the term *others*. Pulverized coal is only used in the EAF and acts as a slag foaming agent.

Concerning the accounting of carbon dioxide emissions, the Greenhouse Gas Protocol (World Resources Institute and World Business Council for Sustainable Development, 2021) specifies three scopes. Scope 1 or direct emissions refers to greenhouse gases that are emitted by company-operated facilities. By multiplying the consumption values of the steel mill under consideration for natural gas and pulverized coal by their respective specific CO_2 emissions, we obtain scope 1 carbon dioxide emissions of the production process. Fig. 1 shows that ladle heaters are not only the biggest consumers of natural gas, but also the most important emitters of CO_2.

1.2. Decarbonization and energy efficiency measures

In EAF steel production, a major part of the process heat is generated by burning fossil direct fuels. Combustion processes, such as ladle preheating, are the main source of scope 1 CO_2 emissions in the considered steel mill (see 1.1). Moreover, individual processes, i.e. scrap melting in the EAF generate waste heat, which is currently not exploited, neither in the steel mill nor for external use.

In this article, we therefore focus on the implementation of the following energy efficiency measures, which we consider technically feasible under the given conditions:

- Oxyfuel-combustion,
- CO_2-capture and utilization (CCU),
- Waste heat recovery.

Properly deployed, these technologies have the potential to reduce not only energy consumption, but also production costs and carbon dioxide emissions.

1.2.1. Oxyfuel combustion

Compared to combustion with air, the Oxyfuel technology, the combustion of natural gas with pure oxygen, represents an effective measure to reduce fuel consumption and CO_2 emissions. First, the absence of nitrogen in the combustion process increases the thermal efficiency, because a higher portion of energy is transferred to the heating good instead of heating the nitrogen in the combustion air (Baukal and Baukal, 2013a). Second, the high concentration of the radiant gases CO_2 and H_2O in the Oxyfuel flue gas results in increased thermal radiation, thus improving the heat transfer (Baukal and Baukal, 2013b). Consequently, less fuel is required for a given heating load. In addition, scope 1 carbon dioxide emissions decrease proportionally to the decreasing fuel consumption (Baukal, 2013). However, the overall emission reduction depends on the applied oxygen production technology and the specific carbon dioxide emissions in the electricity mix.

Within the studies conducted by Stanger et al. (2015), Wall et al. (2013) as well as Gibbins and Chalmers (2008), Oxyfuel combustion is considered as key technology for capturing CO_2 from fossil-fired power plants. Burning coal or natural gas with pure oxygen produces a flue gas mainly consisting of water vapor and carbon dioxide, which is separated by dehydration (H_2O condensation) and purification. Stanger et al. (2015) give an overview over the technical advances in Oxyfuel technology for coal- and gas-fired power plants. Apart from demonstration on industrial level, the authors identify research needs in terms of higher integration, alternative oxygen sources, innovative combustion

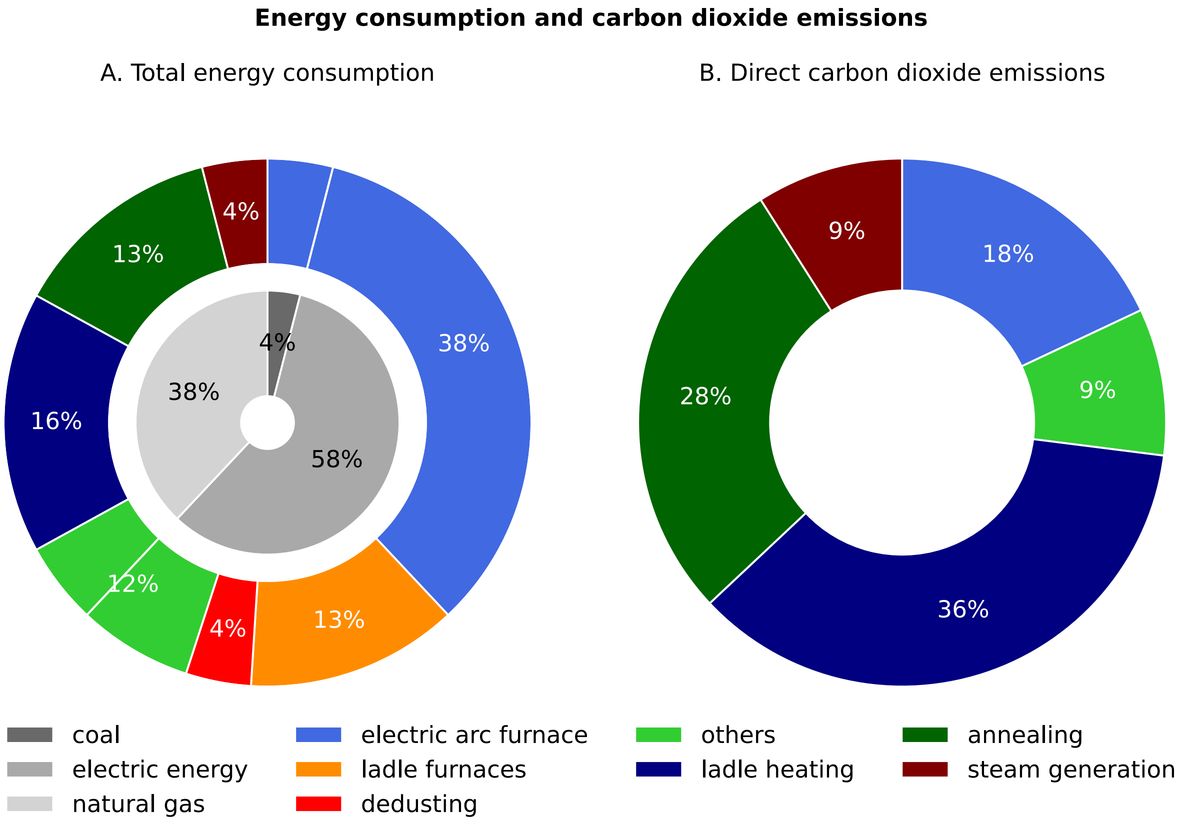

Fig. 1. Final energy consumption (A) and scope 1 carbon dioxide emissions (B) of main consumers in the electric steel mill.

processes as well as improvement of energy efficiency and reduction of installation costs and risks.

Regarding the steel industry, von Scheele (von Scheele and Palm, 2010) identifies the hot stoves of the blast furnace, the electric arc furnace, the reheating furnace, vessel preheating and strip processing as feasible areas of application for Oxyfuel combustion. According to his work, positive effects range from increased throughput capacities, fuel savings and increased material yield to reduced CO_2 and NO_X emissions. For vessel preheating, the fuel consumption and the associated CO_2 emissions may be reduced by around 50% (von Scheele and Palm, 2010).

In steel mills, ladle heaters are deployed to dry and preheat the steelmaking ladles prior to their utilization. As indicated in Fig. 1, they represent major consumers of natural gas and thus contribute significantly to the overall CO_2-emissions. According to Docquier et al. (2013), the conversion of a natural gas/air-fired ladle heating station to Oxyfuel-combustion results not only in fuel savings but also shorter heating times and higher achievable end temperatures. Due to higher preheating temperatures, the required tapping temperature decreases resulting in enhanced productivity, furnace life and energy efficiency. As state-of-the-art technology, Oxyfuel ladle heating is available from major equipment manufacturers such as Messer (Messer Americas, 2019) or Linde (Linde AG, 2017). Ladle heating with OXIPYR burners is expected to bring fuel savings of up to 55%, uniform heating, shorter heating cycles and lower NO_X emissions (Messer Americas, 2019). In order to lower the flame temperature and ensure uniform heating, the flame is diluted by flue gas, referred to as flameless Oxyfuel combustion. Similarly, substantially shorter heating times, fuel savings, extended refractory lifetime, and lower feasible EAF tapping temperatures have been reported for OXYGON burners compared to the combustion with air (Linde AG, 2017).

1.2.2. *Carbon dioxide utilization in steelmaking*

Combusting natural gas with pure oxygen generates a flue gas with a high concentration of carbon dioxide and water (see 2.2.1). Condensation of the water vapor produces a CO_2-rich gas that can be recovered for other processes. The separation and utilization of carbon dioxide from the flue gas transforms climate-relevant emissions into a valuable resource. In the iron and steel industry, carbon dioxide utilization has positive effects on metallurgical processes and has the potential to reduce overall carbon dioxide emissions (Wei et al., 2018). The review article by Dong and Wang (2019) discusses promising fields of application for carbon dioxide including top- and bottom-blowing in the BOF and the argon oxygen decarburization (AOD) converter, the ladle furnace and the EAF, injection into the blast furnace as well as CO_2 circulation in combustion processes. In light of the extensive research on the positive effects of carbon dioxide deployment in ferrous metallurgy processes, the authors project an overall CO_2 utilization potential of more than 100 kg/t of steel.

In their article, Zhu et al. (2020) review the beneficial effect of carbon dioxide on the EAF and BOF process and propose a route for the utilization of steel mill-generated CO_2. Laboratory (Li et al., 2017) and industrial scale (Lv et al., 2012) experiments were conducted to investigate the utilization of carbon dioxide in the basic oxygen furnace. BOF steelmaking involves dust production in the range of 13–32 kg/t of steel that consists mainly of iron and its oxides (Ray et al., 1997). Li et al. (2017) prove that the dust is generated as a consequence of the entrainment of carbon monoxide bubbles and evaporation of elements. The introduction of CO_2 as an oxidant allows decarburization while controlling the temperature of the steel bath. Using a mixture of oxygen and carbon dioxide as top-blowing gas in the converter and substitution of nitrogen and argon by carbon dioxide for bottom blowing reduces dust generation and iron loss, promotes the removal of nitrogen and phosphorous from liquid steel and saves oxygen. Zhu et al. (2020) assume a consumption of 10–13 kg CO_2/t of steel for top-blowing at 10 $\%_{vol}$ CO_2 and full substitution of oxygen by CO_2 for bottom blowing in BOF steelmaking.

Similarly, the electric arc furnace is a promising field of application for recovered carbon dioxide. According to Wei et al. (2018), current research focuses on the utilization of CO_2 for mixed blowing, submerged injection as well as bottom blowing in the EAF and the ladle furnace. In mixed blowing, instead of pure oxygen, an O_2/CO_2 mixture is injected into the EAF through a blowing lance. Compared to blowing with pure oxygen during the refining phase, endothermic reactions of CO_2 with elements in the liquid steel bath reduce the generation of hot spots and therefore limit the evaporation of iron and other elements (Wei et al., 2018). In their research article, Wang et al. (2016) establish an energy and material balance to investigate the impact of carbon dioxide injection into the EAF. The authors find that oxygen blowing with an increasing proportion of CO_2 increases the electric energy consumption. However, they argue that this effect is outweighed by enhanced decarburation and chromium retention. According to the literature, reasonable mixing ratios of carbon dioxide and oxygen range from 5 $\%_{vol}$ (Wei et al., 2018) to 50 $\%_{vol}$ (Wang et al., 2016) of CO_2.

Certain steel production steps such as vacuum treatments (VD and VOD) cause alkaline wastewater. Before discharge into a sewing system, the pH-value of the wastewater must be reduced to a neutral level. Water neutralization using carbon dioxide is an environmentally friendly alternative to conventional treatments based on mineral acids. Compared to acids, the advantages include safer handling, precise pH control, prevention of excessive acidification as well as low investment and operational costs (Messer North America Inc, 2021).

Furthermore, CO_2 serves as a neutralizer for the water in the cooling circuits of the steel mill. Since natural water tends to lime scale build-up, the cooling water needs to be treated to avoid plugging in the cooling equipment. Water hardness results from dissolved minerals such as calcium and magnesium. Carbonation of the cooling water with CO_2 represents an inexpensive and safe method to remove calcium and magnesium ions and reduce the pH-value to a neutral level (Ahn et al., 2018). Hart et al. (2011) describe the successful application of carbon dioxide to prevent scale build-up in a heat exchanger of a pulp mill.

1.2.3. *Waste heat utilization in steel mills*

In their review on energy use and energy efficient technologies, He and Wang (2017) describe the significant potential of waste heat utilization in the steel industry. For EAF steelmaking, they recommend the recovery of EAF waste heat for electricity production and cite energy savings of 130 kWh/t of steel. The electric arc furnace is not only the largest energy consumer, but also a considerable source of waste heat. In an electric arc furnace, the heat dissipated by the cooling system and the sensible heat of the off-gas account for 20–30% of the overall energy input (Steinparzer et al., 2014). For a 120 t furnace, the energy of the off-gas amounts to 226 kWh/t of steel at temperatures up to 1200 °C (Steinparzer et al., 2014), however typical outlet temperatures for EAF cooling systems lie around 50 °C (Gharib Mombeni et al., 2016).

Yang et al. (2018) elaborate on the possibilities to recycle the sensible heat of the EAF exhaust gas. Scrap preheating, steam production and eventual electricity generation via a steam turbine are presented as relatively mature technologies. However, fluctuations in EAF off-gas temperature and mass flow as well as its high dust content pose a challenge for steam and electricity generation. The authors consider the ejector pumps of the vacuum degassing system as potential consumers of the generated steam. Ramirez et al. (2017) present a waste heat recovery plant for the electric arc furnace of a special steel mill using Organic Rankine Cycle (ORC) technology. The furnace exhaust gas is used to produce saturated steam in a heat recovery unit. This steam supplies heat to an ORC process and a district heating network. In order to compensate for the discontinuous heat availability, the EAF and the consumers are decoupled by a steam accumulator. Due to the implementation of the plant, the authors estimate annual savings of 7990 t of CO_2 and 40 360 MWh of electricity and heat. Keplinger et al. (2018) present a dynamic simulation model for the recovery of EAF waste heat for steam production. The hot gas duct, which has the function to cool the off-gas for its subsequent treatment serves as a heat source. Due to the batch operation of the electric arc furnace, a thermocline storage is integrated into the system to compensate temperature and mass flow fluctuations. Depending on the load situation of the EAF, the waste heat steam generator is supplied with hot water from the storage tank or directly from the hot gas duct. Therefore, the cooling system is operated at an elevated water outlet temperature of 200 °C. Simulation results indicate that the presented concept is a feasible option for EAF waste heat recovery and that the thermocline storage system is capable of decoupling the time-variable heat supply and demand (Keplinger et al., 2018).

Waste heat recovery from ladle preheating has not yet been investigated to the same extent as for the electric arc furnace. Moch et al. (2008) conduct their research on ways to decrease energy consumption and emissions of ladle heaters. As part of the project, two ladle-heating stations are equipped with a rotating regenerator and a recuperator, respectively, for air preheating. Long-term observations indicate that these measures reduce natural gas consumption by 20–35%.

The authors are not aware of any studies on the utilization of waste heat from ladle heaters apart from air preheating.

1.3. Research need and structure of the work

The articles cited in chapter 1.2 demonstrate that the proposed technologies are suitable for reducing energy consumption and CO_2 emissions in EAF steelmaking. Scientific studies and implementation reports are available for Oxyfuel combustion, carbon dioxide utilization for steelmaking and water treatment processes as well as waste heat recovery in the steel industry.

However, to the authors' knowledge, at present there is no publication addressing the holistic implementation of the technologies mentioned in section 1.2 in an existing steel mill. We aim to understand, how energy saving and emission abatement technologies need to be integrated into the production processes to achieve the optimal effect for the overall energy system of an EAF steel mill. For this purpose, this study investigates the process integration of selected energy efficiency and CO_2 emission reduction technologies into an existing EAF steel mill.

The implementation of Oxyfuel and CCU technologies as well as waste heat recovery systems into batch production processes with highly fluctuating loads requires a time-resolved analysis. By using a steady-state simulation approach with a temporal resolution of 1 min, we integrate different feasible options into an energy system model of the steel mill and evaluate their impact in terms of overall energy efficiency, economic viability and carbon dioxide emissions.

Due to their significant natural gas consumption (see 1.1) and high operating temperatures, we focus on the conversion of air-fired ladle heaters to Oxyfuel-combustion. Within the present work, we investigate possibilities of waste heat recovery from the ladle heaters and the EAF as well as carbon dioxide separation and utilization in the steel production process. The objective is to develop viable concepts for reducing fuel consumption and CO_2 emissions in order to enable a low-CO_2 production process. Therefore, we compare the results of three integration scenarios on a technical and economic level.

In our study, we proceed as follows: First, we develop scenarios for the implementation of the presented technologies (2.1). Second, we introduce our model, which includes the energy system of the steel mill, Oxyfuel combustion, carbon capture equipment and storages (2.2). Additionally, we explain the cost-model used for our economic assessment. Based on each technology's potential, we carry out a technical (3.1) and an economic (3.2) assessment. A sensitivity analysis highlights the conditions under which investments in the examined technologies are economically viable (4). Finally, chapter 5 summarizes the key outcomes and gives a conclusion.

2. Methods

2.1. Scenario development

Due to long heating times and high operating temperatures, ladle heaters account for a major share on the final energy consumption of the steel mill. As stated in chapter 1.3, Oxyfuel-combustion offers the potential to significantly reduce the natural gas consumption of the ladle heaters. Therefore, this study focuses on the installation of Oxyfuel burners for preheating the steel mill ladles. As part of the burner conversion, the horizontal ladle heaters will be replaced by the vertical alternative. Measurements indicate that vertical heaters consume about one third less fuel due to improved flue gas routing in the ladle. The conversion from natural gas/air to natural gas/oxygen burners is associated with a considerable additional oxygen consumption (see Table 3). However, due to the metallurgical processes the steel mill already requires large volumes of oxygen, which are supplied by deliveries and storage tanks. Hence, we assume that the additional consumption through Oxyfuel combustion is met by the existing supply system.

Additionally, we intend to exploit the CO_2-rich off gas generated by the Oxyfuel combustion process through the integration of a carbon dioxide separation and utilization system. Due to different types of deployed ladles and varying conditions of the upper ladle rims, a gap remains between the lid and the ladle, thus preventing airtight heating operation. However, the burner is operated at an overpressure, which will reduce the false air volumes to a minimum. In view of the proposed CO_2 application options, we assume that the gas treatment system generates a product gas of adequate purity, even in the case of minor false air inflow. For our case study, we consider the following in-plant carbon dioxide sinks: the neutralization of alkaline wastewater and cooling water in the cooling systems as well as the mixed injection of oxygen and carbon dioxide during refining in the electric arc furnace. Since both the wastewater neutralization and the cooling water conditioning using purchased CO_2 are already implemented in the considered mill, the existing infrastructure can be deployed in this case. In the latter case, the CO_2 is fed into the oxygen line ahead of the oxygen manipulator and then blown into the EAF through the injection lance. Prior to injection into the supply network and subsequent utilization, it is required to cool the exhaust gas, separate the water and compress the product gas to the operating pressure of the CO_2 supply network. To balance the fluctuating CO_2-demand, especially for mixed blowing in the EAF, we implement a buffer tank into the CO_2 supply system (see Fig. 2).

Condensation of the exhaust gas not only increases the carbon dioxide concentration in the product gas but also allows the recovery of waste heat. The ladle heaters are equipped with an exhaust gas condenser with an integrated heat exchanger that transfers the exhaust gas heat to the cooling water. Subsequently, the hot cooling water is used in the process steam boiler for feed water preheating. In an extended scenario, we evaluate the waste heat recovery from the hot gas duct at the electric arc furnace. The water-cooled duct dissipates the major part of the heat in the EAF exhaust gas. The recovered heat from the hot gas duct will be used for steam generation in the steel mill. For this scenario, the installation of a thermal energy storage is inevitable to balance the waste heat generation and steam demand (see Fig. 2).

As described in chapter 1.2.3, within the scope of their study, Keplinger et al. (2018) present a suitable system for the recovery of waste heat from the EAF hot gas duct for steam production. Increasing the water temperature and pressure in the cooling system requires the replacement of the duct. The additional equipment consists of a pressurized hot water storage, a kettle evaporator, pumps and a pressurization system.

In order to assess the technical and economic feasibility and the necessary framework conditions, we will investigate three scenarios:

- Scenario D: The starting point is a demonstration scenario in which half of the ladle heaters are converted to Oxyfuel technology. The

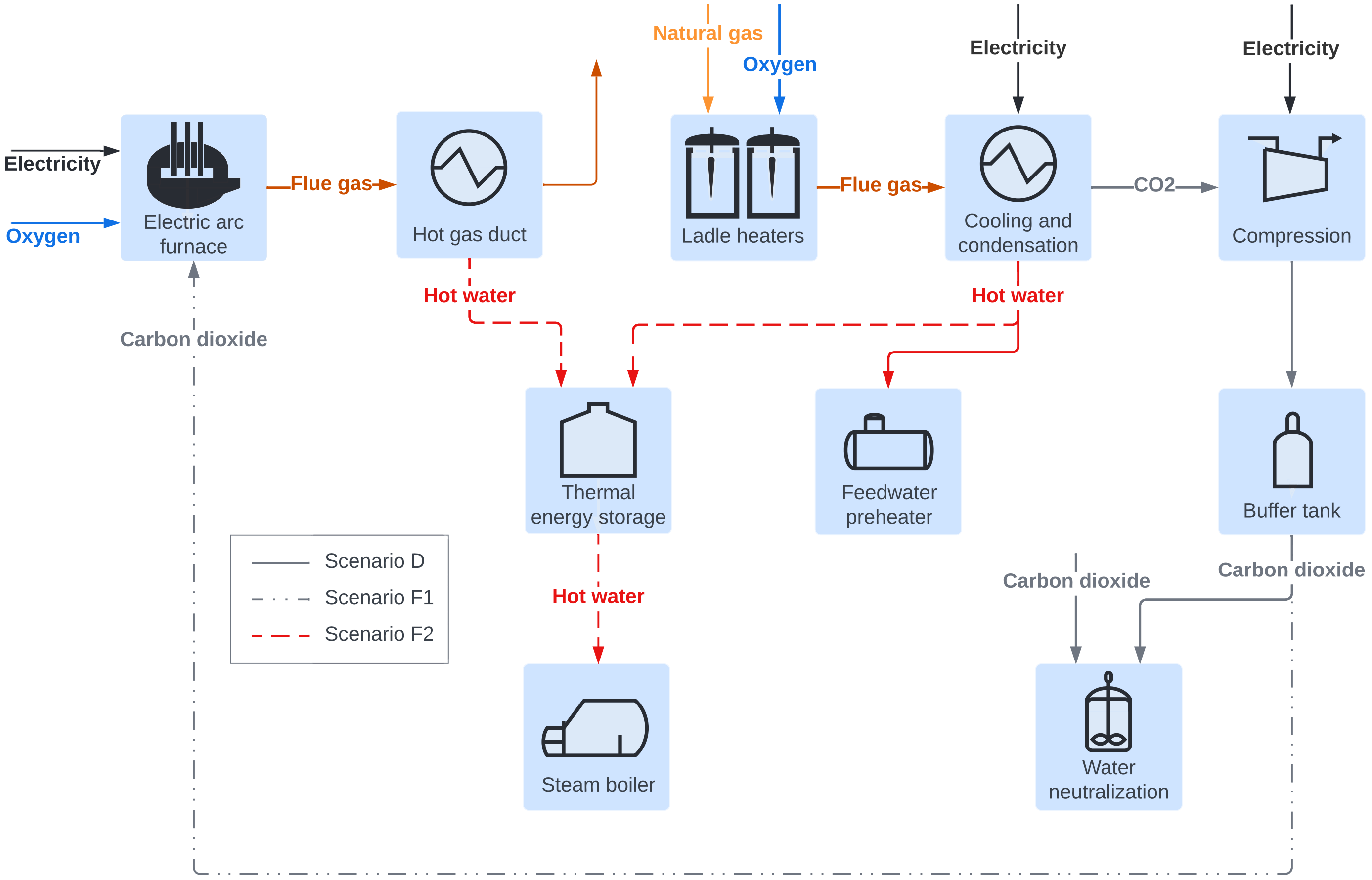

Fig. 2. Process layouts for the simulation scenarios.

generated carbon dioxide and waste heat are recovered and utilized plant-internally for water treatment. For this simulation, we stipulate that Oxyfuel ladle heaters, if available, are deployed preferentially.

- Scenario F1: In a first future scenario, we analyze the complete conversion of all ladle heaters to Oxyfuel technology. Analogous to the demonstration scenario, we aim to recover both CO_2 and waste heat. In addition to water treatment, the produced carbon dioxide is deployed for mixed blowing in the electric arc furnace.
- Scenario F2: The second future scenario, based on F1, deals with the additional recovery of waste heat from the EAF hot gas duct for steam generation.

Fig. 2 provides an overview over the considered waste heat and carbon dioxide flows. The simulation results are evaluated based on a reference scenario (R), which reflects the status quo in the steel mill. Table 1 summarizes the main features of the investigated scenarios.

2.2. Energy system model

In order to evaluate the implementation of efficiency measures in an existing EAF steel mill, we deploy the energy system model presented in a study by Dock et al., 2021. This preceding work describes the development of a model that generates time-resolved, synthetic load and waste heat profiles of sub-processes as well as the overall steel mill. The model covers the electric arc furnace, ladle furnaces, vacuum treatments, ladle heaters, annealing furnaces, as well as the dedusting and steam generation system. Due to its modular design, the model allows sub-processes to be added or system configurations to be modified. Therefore, we are able to represent different process designs and operational strategies within the scope of the present case study.

As part of this work, the energy system model is extended to include Oxyfuel combustion, production and demand profiles for carbon dioxide, buffer storages for carbon dioxide and thermal energy as well as a tool for basic economic analysis.

Table 1
Considered implementation scenarios.

	R	D	F1	F2
Number of Oxyfuel ladle heaters	0	2/4	4/4	4/4
Water neutralization	–	X	X	X
O_2/CO_2 mixed blowing	–	–	X	X
Feed water preheating (LH)	–	X	X	X
Steam generation (LH + EAF)	–	–	–	X

2.2.1. Ladle heating

In order to implement an Oxyfuel ladle heater in our energy system model, it is necessary to determine the actual flow rates of natural gas, oxygen, waste heat and carbon dioxide for every time step. We estimate these values by applying a simple process model based on the time-resolved thermal load and waste heat profiles of the mentioned steel mill model.

Our starting point is the following heat balance, where $\dot{Q}_{thermal}$ is the thermal power input, $\dot{Q}_{useful}$ the thermal power that is used to heat the ladle, and $\dot{Q}_{waste\ heat}$ the thermal power of the exhaust gas.

$$\dot{Q}_{thermal}(t) = \dot{Q}_{useful}(t) + \dot{Q}_{waste\ heat}(t) \tag{1}$$

Provided the fuel and the oxidant are supplied at reference temperature, the thermal power and the waste heat flow are defined by equations (2) and (3). $\dot{m}_{ng}$ and $\dot{m}_{fg}$ are the mass flow rates of natural gas and flue gas, NCV is the net calorific value of natural gas. $c_{p,\,fg}$, T_{fg} and T_{amb} are the mean specific isobaric heat capacity in $\frac{kJ}{kg \cdot K}$ as well as temperatures of the flue gas and the ambient air in *K*.

$$\dot{Q}_{thermal}(t) = \dot{m}_{ng}(t) \cdot NCV \tag{2}$$

$$\dot{Q}_{waste\ heat}(t) = \dot{m}_{fg}(t) \cdot c_{p,\ fg} \cdot \left(T_{fg} - T_{amb}\right)(t) \tag{3}$$

The mass flow of the flue gas can be determined by establishing the mass balance (4).

$$\dot{m}_{fg} = \dot{m}_{ng} + \dot{m}_{ox} \tag{4}$$

Derived from the reaction equation for the combustion of 1 kg of methane (5), which is the main combustible constituent of natural gas, the oxidant mass flow is calculated according to equation (6), where $x_{CH4,\ ng}$ and $x_{O2,\ ox}$ are the mass fractions of methane in the fuel and oxygen in the oxidant, and λ is the air-fuel equivalence ratio.

$$1\ kg\ CH_4 + 4\ kg\ O_2 = 2.75\ kg\ CO_2 + 2.25\ kg\ H_2O \tag{5}$$

$$\dot{m}_{ox} = \dot{m}_{ng} \cdot \lambda \cdot \frac{4 \cdot x_{CH4,\ ng}}{x_{O2,\ ox}} \tag{6}$$

Since the ladle heating program follows a specified temperature profile and we know the associated time-resolved thermal power input (equation (2)) and waste heat power (equation (3)), we are able to determine the time-resolved useful power (equation (1)). By applying the above equations and substituting air by pure oxygen as oxidant, we obtain the new mass flow rates for natural gas, oxygen, and exhaust gas resulting from the transition to Oxyfuel combustion. Combustion of natural gas with oxygen decreases the exhaust gas mass flow compared to combusting with air, while the useful heat profile determined by the heating program remains unchanged. This leads to a significant reduction in exhaust gas losses, thermal power input and thus natural gas consumption.

We obtain the mass flow rate of carbon dioxide ($\dot{m}_{CO2}$) in the exhaust gas from the mass balance for carbon dioxide (7), where $x_{CO2,\ ox}$ and $x_{CO2,\ ng}$ are the mass fractions of carbon dioxide in the oxidation medium and in the fuel. $x_{CH4,\ ng} \cdot 2.75$ represents the generation of CO_2 due to methane combustion.

$$\dot{m}_{CO2} = x_{CO2,\ ox} \cdot \dot{m}_{ox} + \left(x_{CO2,\ ng} + 2.75 \cdot x_{CH4,\ ng}\right) \cdot \dot{m}_{ng} \tag{7}$$

Fig. 3 shows the normalized natural gas and resulting carbon dioxide flow for ladle preheating with a conventional and an Oxyfuel burner.

2.2.2. Carbon dioxide utilization

In our study, the captured CO_2-rich product gas recovered from the Oxyfuel combustion is provided for neutralization in the wastewater treatment plant, injection into the cooling system and refining in the electric arc furnace. In order to determine the required capacity of the buffer tank, we consider the following carbon dioxide demand profile (Fig. 4).

The carbon dioxide demand profile was created by adapting the energy system model of the EAF steel mill (Dock et al., 2021). Its modular structure allows for implementation of the CO_2 consumers. CO_2 consumption occurs mainly during two process steps that are defined in the steel mill model: oxygen blowing at the EAF and wastewater discharge from the vacuum treatments. The required amount of CO_2 for wastewater neutralization is known from measurements, while that for EAF-injection is derived from the oxygen demand of the EAF using a fixed mixing ratio of 25 $\%_{vol}$ carbon dioxide.

An analysis of the third CO_2 sink, the injection into the cooling water of the EAF and various other installations, indicated a frequent consumption of small quantities for periods of less than a minute. Therefore, the total consumption was averaged over the operating hours of the individual installations and implemented into the model as a continuous demand.

2.2.3. EAF hot gas duct

Compared to the energy system model the authors presented in (Dock et al., 2021), the model of the EAF cooling system is modified to increase the accuracy of the simulation results. Instead of averaging the cooling power during an entire EAF production cycle, in the improved model used in this work, we represent the individual process phases in the load profile. Based on time-resolved measurements of the cooling power, we determined mean power levels for the process phases *melting* and *refining* as well as the time intervals between, referred to here as *power off*. The process phases as well as the associated cooling power levels are displayed in Fig. 5 B.

In order to model the fluctuating waste heat profile, the ordered duration line of the measured waste heat profile is divided into intervals, which are assigned to certain process phases based on the previously defined mean power levels. During the simulation, for every time step, a power value is drawn randomly from the distribution of power levels in the respective process phase. This results in the synthetic profile of the cooling power for one week presented in Fig. 5 A relative to the nominal EAF transformer power in kVA. A comparison of the sorted duration lines over 12 h of operation indicates the good agreement between the measured and simulated waste heat profile (see Fig. 5 B).

2.2.4. Carbon dioxide and thermal energy storage

Chapter 1.2 describes the need for storage systems to balance the temporal variability of both the demand and generation of waste heat and carbon dioxide. Both storages are implemented into the energy system model using the following properties: storage capacity, state of charge (SOC) at simulation start as well as associated sinks and sources.

According to equations (8) and (9), the SOC of the carbon dioxide (m) and the thermal energy storage (Q) are determined for every simulation time step (Δt). $\dot{m}_{inflow}$ and $\dot{m}_{outflow}$ refer to mass flow rates during feed-in and discharge of the carbon dioxide storage, while $\dot{Q}_{inflow}$ and $\dot{Q}_{outflow}$

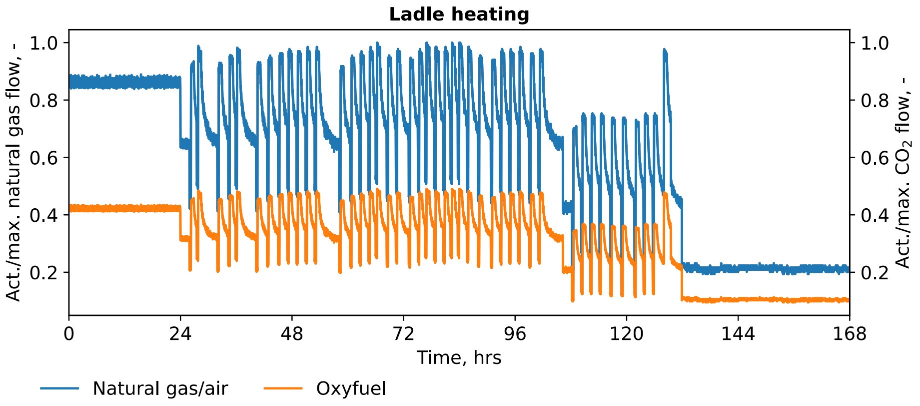

Fig. 3. Normalized natural gas and carbon dioxide flow profile of Oxyfuel and conventional combustion for ladle preheating.

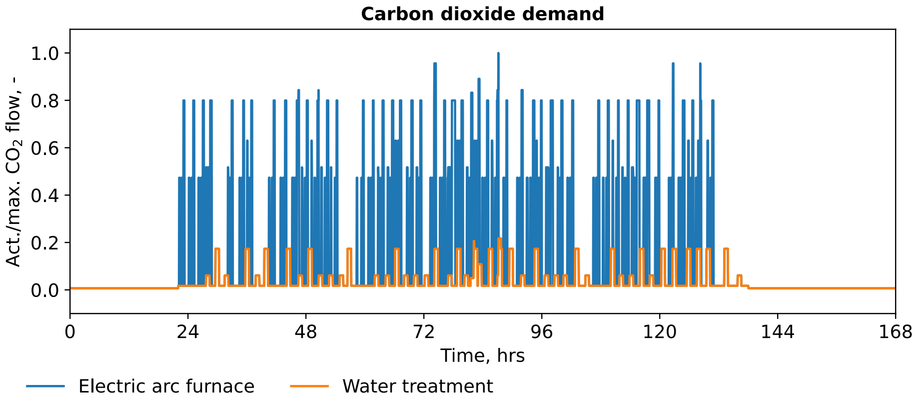

Fig. 4. Normalized carbon dioxide consumption profile.

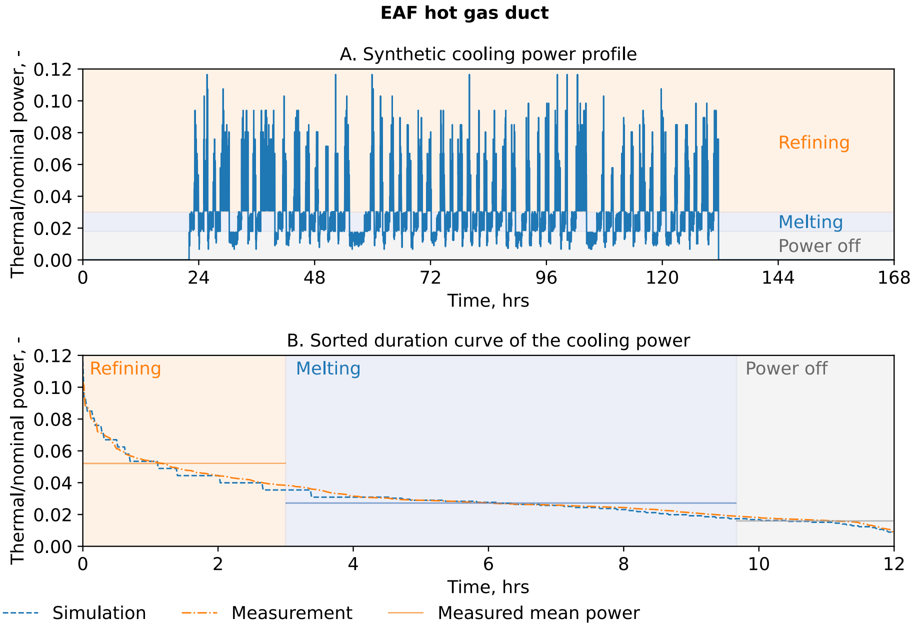

Fig. 5. Ordered duration line of the hot gas duct cooling power.

represent the heat flow rate for loading and discharging the thermal energy storage (TES). $\dot{Q}_{loss}$ denotes the loss rates of the TES (see equation (11)).

$$m(t) = m(t-1) + \left(\dot{m}_{inflow}(t) - \dot{m}_{outflow}(t)\right)\cdot\Delta t \tag{8}$$

$$Q(t) = Q(t-1) + \left(\dot{Q}_{inflow}(t) - \dot{Q}_{outflow}(t) - \dot{Q}_{loss}(t)\right)\cdot\Delta t \tag{9}$$

Assuming operation at constant pressure, the amount of stored energy (Q_{max}) in a sensible TES is given by the following equation (10), where m is the mass of the storage medium, c_p its mean isobaric heat capacity. T_{max} is the maximum and T_{min} the minimum storage temperature. The maximum storage temperature and therefore the storage capacity is limited by the evaporation temperature of the storage medium. Consequently, pressurized storage tanks allow operation at higher temperatures than atmospheric storages.

$$Q_{max} = m\cdot c_p\cdot(T_{max} - T_{min}) \tag{10}$$

We determine the energy losses of the TES using equation (11) (Verein Deutscher Ingenieure VDI-Gesellschaft Verfahrenstechnik Chemieingenieurwesen VDI-W ä rmeatlas, 2013). The heat loss rate ($\dot{Q}_{loss}$) is dependent on the overall heat transfer coefficient (k) and the surface of the storage tank (A) as well as the current temperature difference between storage medium ($T_{storage}$) and ambient (T_{amb}).

$$\dot{Q}_{loss}(t) = k\cdot A\cdot\left(T_{storage}(t) - T_{amb}\right) \tag{11}$$

2.2.5. CO_2 sequestration

In order to recover the carbon dioxide from Oxyfuel combustion, the flue gas has to be cooled. Therefore, the implementation of a cooling system is necessary, which causes additional energy consumption and costs. Part of the recovered heat is exploited by the steam boiler, while excess heat is dissipated in a cooling tower. The waste heat ($\dot{Q}$) is transferred to the cooling water, which has the volume flow rate $\dot{V}$, the density ρ, the specific heat capacity $\overline{c}_p$ as well as a temperature range between in- (T_{in}) and outflow (T_{out}). Given the temperature range, the required water flow is calculated by rearranging equation (12). Based on the volume flow rate, the electric power (P_{el}) of the circulation pump can be estimated according to equation (13) (Baehr and Kabelac, 2012), where η is the isentropic efficiency, $\dot{V}$ the volume flow rate and Δp is the pressure difference that the pump needs to provide.

$$\dot{Q} = \dot{V}\cdot\rho\cdot\overline{c}_p\cdot(T_{out} - T_{in}) \tag{12}$$

$$P_{el} = \frac{1}{\eta}\cdot\dot{V}\cdot\Delta p \tag{13}$$

After the flue gas treatment, the generated CO_2-rich product gas has to be compressed and stored in a buffer tank. To enable the flow to the consumers, the buffer tank has to operate at a higher pressure than the carbon dioxide network of the steel mill. In our study, carbon dioxide is stored between 5 and 20 bar, which implies a maximum output pressure of 20 bar. Therefore, we apply a two-stage compression of 1–5 bar and 5–20 bar, respectively, with the actual discharge pressure depending on the state of charge of the CO_2 tank. In the sequestration process, the compressor represents a significant energy consumer and thus cost factor that we want to integrate in our model. The electric compressor power (P_{el}) was calculated as indicated in equation (14) (Baehr and Kabelac, 2012) considering a pressure increase from inlet (p_{in}) to outlet pressure (p_{out}). Here, η is the isentropic efficiency, $\dot{m}$ the mass flow of product gas, κ its isentropic exponent and T its temperature in K.

$$P_{el} = \frac{1}{\eta} \cdot \dot{m} \cdot \overline{c}_p \cdot T \cdot \left(\left(\frac{p_{out}}{p_{in}} \right)^{\frac{\kappa-1}{\kappa}} - 1 \right) \tag{14}$$

2.2.6. *Cost model*

With regard to the formulated research demand (see 1.3), we will also approach the subject from an economic perspective. A simplified investment analysis will be carried out in order to identify the optimum system configuration for various underlying conditions.

In our analysis, we allocate the annually incurring costs to two cost centers: *ladle heating* and *steam generation* (Table 2). Considered expenses for *ladle heating* are the annual costs for fuel (c_{NG}), oxygen (c_{O2}), CO_2 emission allowances (c_{EA}) and electricity (c_{EE}) for product gas compression and the cooling system as well as capital costs (c_{IV}) for the proposed plant layout (15).

$$c_{tot} = c_{NG} + c_{O2} + c_{EA} + c_{EE} + c_{IV} - (r_{WHR} + r_{CCU}) \tag{15}$$

The savings generated in the steel mill by the utilization of waste heat (r_{WHR}) and carbon dioxide (r_{CCU}) are assigned to the cost center as revenues that are calculated using equations (16) and (17), where $c_{NG,\ SG}$ as well as $c_{EA,\ SG}$ are the fuel and emission allowance costs for steam generation, $c_{CO_2,\ WT}$ as well as $c_{O_2,\ EAF}$ are the carbon dioxide costs for water treatment and the oxygen costs for the EAF, and SR_{NG} as well as SR_{CO_2} are the substitution rates for natural gas and carbon dioxide.

$$r_{WHR} = SR_{NG,\ SG} \left(c_{NG,SG} + c_{EA,\ SG} \right) \tag{16}$$

$$r_{CCU} = SR_{CO2,\ WT} \cdot \left(c_{CO2,\ WT} + c_{EA,\ WT} \right) + SR_{CO2,\ EAF} \cdot c_{O2,\ EAF} \tag{17}$$

In scenario F2, the additional investment costs for waste heat recovery from the EAF hot gas duct as well as the costs for natural gas and emission allowances for steam generation are allocated to a separate cost center (*steam generation*).

For the calculation of investment costs of the implemented technologies, the *percentage on delivered-equipment cost* method (Peters et al., 2004) is applied. In a first step, the costs of the individual pieces of equipment are either derived from the regression models given in (Peters et al., 2004) or provided by our project partners. In the second step, the remaining direct and indirect plant costs such as installation (f_{inst}), instrumentation and controls (f_{contr}), piping (f_{pipe}), electrical installations (f_{electr}), engineering (f_{eng}) and construction (f_{constr}) are added to the equipment cost (E_n) by using multiplying factors (equation (18)).

Table 2
Cost centers including allocated costs and revenues.

Ladle heating	Steam generation
Operational expenditures	**Operational expenditures**
Natural gas cost	Natural gas cost
+ oxygen cost	+ emission allowance cost
+ emission allowance cost	
+ electricity cost	
Capital expenditures	**Capital expenditures**
Investment cost	Investment cost
Revenues	
- carbon dioxide revenue	
- waste heat revenue	
Total cost	Total cost

Table 3
Simulation results: theoretical potentials for natural gas savings, waste heat recovery and carbon dioxide utilization.

Scenario	Reference scenario	Demo scenario	Future scenario 1	Future scenario 2
Acronym	R	D	F1	F2
Share of Oxyfuel ladle heaters	–	50%	100%	100%
Natural gas consumption ladle heaters	100%	- 32%	- 46%	- 46%
Overall oxygen consumption	100%	+55%	+79%	+79%
Natural gas consumption steam generator	100%	- 14%	- 20%	- 100%
CO_2 consumption water treatment	100%	- 100%	- 100%	- 100%
O_2 consumption electric arc furnace	100%	- 28%	- 45%	−45%

$$I_n = E_n \cdot \sum \left(1 + f_{inst} + f_{contr} + f_{pipe} + f_{electr} + f_{eng} + f_{constr} \right) \tag{18}$$

Finally, we adjust the investment costs to the year 2021 using the chemical engineering plant cost index (CEPCI) (Access Intelligence LLC, 2021). Prior to the preparation of this study, we verified the plausibility of the calculated investment costs in cooperation with our industrial partners. A summary of the estimated capital expenditures is listed in the Appendix (A1, Table 5). According to the annuity method (19), the capital expenditures are determined by allocating the investment costs for the implemented equipment (I) over the payback period (n) based on a calculative interest rate (i).

$$c_{IV} = I \cdot \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \tag{19}$$

Prices for natural gas and European Union emission allowances are based on market data from the European Energy Exchange (EEX) (European Energy Exchange AG, 2021a). The oxygen and carbon dioxide price used in the study are provided by our project partner and represent the mean prices for the investigated steel mill in the year 2019. The assumed prices for energy and gases are summarized in A1, Table 4.

3. Results

This section covers the presentation of the simulation results and comparison with the reference case. First, we present an overview of the theoretical potentials (3.1.1) for natural gas savings, waste heat recovery and carbon dioxide utilization, followed by an analysis of the technical potentials depending on the capacity of carbon dioxide and thermal energy storages (3.1.2, 3.1.3). Finally, we determine the economically optimized system layout for each individual scenario (3.2).

3.1. *Technical assessment*

3.1.1. *Theoretical potential*

Table 3 summarizes the theoretical potential for natural gas and emission savings, as well as for waste heat and carbon dioxide recovery. Since the values were obtained from an existing steel mill and may not be published, they are stated here in relation to their respective reference values. Moreover, this approach facilitates scaling of the results to other steel mills. This potential determination does not include considerations regarding the temporal balance of supply and demand or technical limitations such as temperature levels, material properties, heat exchanger surface, carbon dioxide purity and losses due to storage and transport.

The simulation results indicate that the natural gas consumption for ladle heating decreases significantly for all scenarios. One reason is the higher combustion efficiency due to the conversion from natural gas/air-fired burners to natural gas/oxygen burners due to decreased exhaust gas losses. Secondly, the deployment of vertical ladle heaters leads to an enhanced transfer efficiency compared to the horizontal version. However, it must be noted that the energy consumption of the ladle heaters also includes the proportion required for ladle drying still using conventional natural gas/air burners.

The total natural gas consumption of the ladle heating processes decreases by 32% (D) and 46% (F) respectively, which corresponds to a reduction of direct carbon dioxide emissions by the same percentage. Further savings in fuel and carbon dioxide emissions are achieved by exploiting the exhaust gas heat of the ladle heaters. Starting from the demonstration scenario, the complete conversion to Oxyfuel ladle heaters equipped with waste gas heat exchangers will increase the amount of waste heat by 42%. The integration of the EAF hot gas duct into the system (F2) substantially increases the available waste heat compared to scenario F1.

Regarding the carbon dioxide balance, we can conclude that the generation of carbon dioxide at the ladle heaters is sufficient to cover the consumption for waste and cooling water neutralization in any case. Assuming mixed blowing of oxygen and carbon dioxide at 25 $\%_{vol}$ CO_2, the demand of the electric arc furnace is covered partially in scenario D and completely in scenario F1. However, the additional mass of oxygen required for the ladle heaters significantly exceeds the savings resulting from the potential substitution of oxygen at the EAF.

3.1.2. *Carbon dioxide utilization*

As mentioned, the ladle heaters produce sufficient carbon dioxide for the water treatment plant in all scenarios. Thus, we examine the utilization of the excessive amount of CO_2 for mixed blowing of carbon dioxide and oxygen at the EAF in scenario F1. However, due to the batch operation in the steel mill, the carbon dioxide demand for both wastewater neutralization as well as EAF blowing is subject to strong fluctuations. In order to balance the temporal variations in supply and consumption, the installation of a buffer storage is necessary.

By the integration of the storage sub-model described in chapter 2.2.4 into our energy system model of the steel mill and simulation for a range of different storage sizes, we can determine the CO_2 utilization ratio as a function of the installed storage capacity. With increasing CO_2 utilization ratio, the consumption of purchased carbon dioxide and oxygen decreases.

For example, the installation of a 200 kg storage tank, indicated in the diagram by the vertical line, enables the system to consume 34% of the CO_2 generated at the Oxyfuel ladle heaters in scenario D (Fig. 6A). This design can provide sufficient carbon dioxide for water treatment, thus making the purchase of CO_2 obsolete. Given the increased available volume of carbon dioxide from the higher number of Oxyfuel ladle heaters, the utilization ratio in the future scenarios amounts to 72% for the same storage capacity, whereas oxygen consumption at the EAF is cut down by 15% (Fig. 6B). Accordingly, the substitution ratios in the economic assessment will equal 100% for carbon dioxide and 15% for oxygen (see equation (17)).

3.1.3. *Waste heat recovery*

According to the proposed process design, the ladle heaters serve not only as a source for carbon dioxide but also for waste heat. Another potential heat source is the cooling water from the EAF hot gas duct. Due to the matching temperature level, we identified the steam generator as a suitable heat sink within the steel mill. By utilizing the available waste heat, we want to save natural gas in steam generation.

In order to balance fluctuations of heat sources and sink, the integration of a thermal energy storage is required. The installed storage capacity is a decisive factor that determines the share of recovered heat as well as the corresponding reduction in natural gas consumption and carbon dioxide emissions. In the following, we focus on the behavior of the thermal energy storage. Fig. 7 indicates the relationship between storage capacity, waste heat recovery and natural gas consumption of the steam boiler.

In the case of the waste heat recovery for feed water preheating in the demo as well as the future scenario, the storage capacity is limited by the volume of the existing feed water tank and its maximum temperature, which correspond to 650 kWh (vertical line). For this storage capacity, the natural gas consumption at the process steam boiler decreases by 10% (Figs. 7A) and 11% (Fig. 7B) while exploiting 72% and 55% respectively of the available waste heat.

The available amount of waste heat leads to a substantially higher heat recovery potential in scenario F2. The technical potential (Table 3) shows that the cooling water of the EAF hot gas duct as well as the ladle heater exhaust gas provide sufficient heat for the overall process steam generation. Assuming a storage capacity of 3000 kWh, Fig. 7 indicates natural gas savings of 97% for steam generation while exploiting 69% of

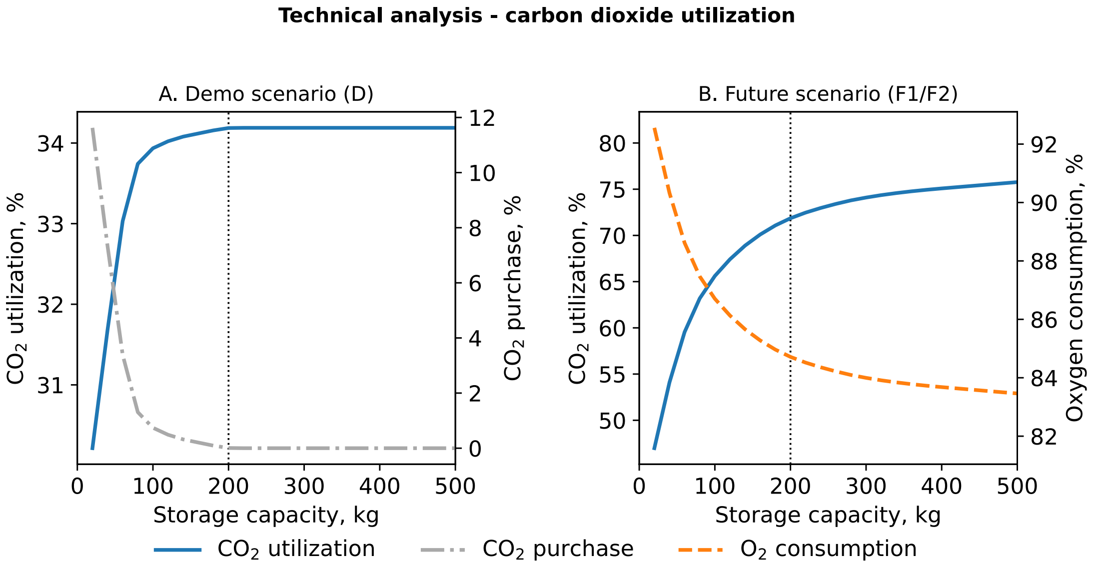

Fig. 6. Technical potential for carbon dioxide utilization for the demonstration scenario D (A) and the future scenarios F1 and F2 (B).

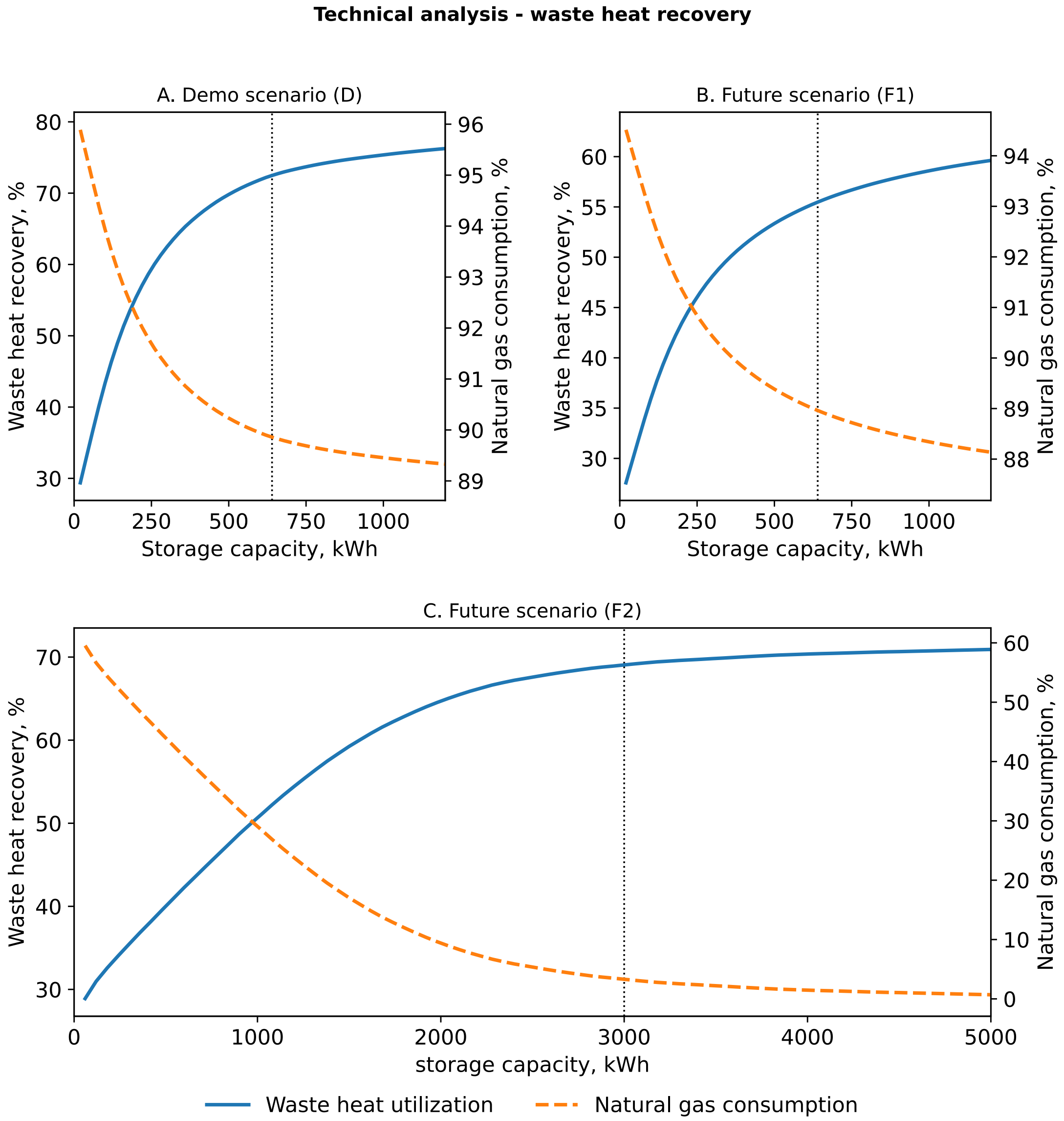

Fig. 7. Technical potential for waste heat recovery for the demonstration scenario D (A) and the future scenarios F1 (B) and F2 (C).

the available waste heat.

The presented calculations and diagrams (Figs. 6 and 7) demonstrate the technical potential for carbon dioxide and heat recovery. However, they do not provide any information about the optimal storage capacities. Therefore, we analyze the different options from an economic point of view in chapter 3.2. In order to identify the economically optimal system layout, we apply our cost model presented in section 2.2.6.

3.2. *Economic assessment*

The previous chapter (3.1) identified the advantages of Oxyfuel ladle heating in terms of fuel savings, the theoretical potential of carbon dioxide and waste heat recovery, and the technical requirements for their exploitation. In this section, we will investigate the conditions under which the presented technologies prove to be economically viable in the steel mill.

3.2.1. *Oxyfuel combustion and CCU*

By applying our cost model (section 2.2.6) to the investigated scenarios, we are able to determine the annual energy costs for the cost center ladle heating as a function of the CO_2 buffer storage capacity. In order to quantify the economic benefits of the respective investments in new equipment, we present the annual costs relative to the reference scenario, which represents the status quo.

The base case for the economic assessment rests on the following assumptions: the price for emission certificates amounts to 54 EUR/t of CO_2 (European Energy Exchange AG, 2021b), the natural gas price is 45 EUR/MWh (E-Control, 2022a), the payback period covers 10 years and the calculative interest rate is 4% per year (see A1, Table 4). In order to analyze the impact of the volatility of underlying parameters such as prices for natural gas and carbon dioxide emission allowances, we vary them one after another. Similarly, we present the cost savings for different payback periods and at different interest rates.

Fig. 8 compares the annual energy costs of the ladle heating system under the status quo with those resulting from an investment into Oxyfuel ladle heaters equipped with carbon capture and waste heat recovery units according to scenario D. The *X* marks the respective cost minimum with the corresponding CO_2 storage capacity and the predicted annual energy cost of the ladle heating system, the base case is denoted as BC.

For scenario D, the installation of the proposed Oxyfuel and CCU equipment including a buffer storage with a capacity of 120 kg of CO_2 under the previously defined base case parameters decreases the annual

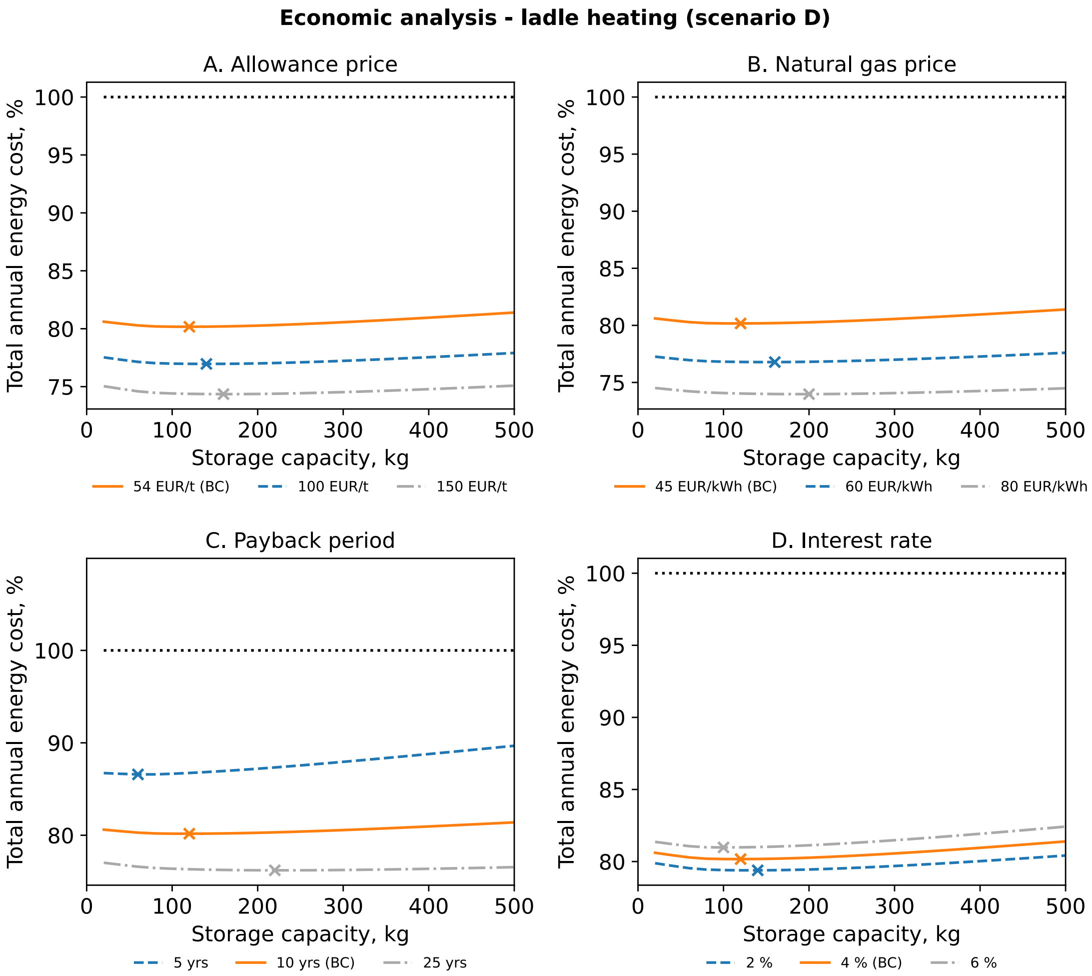

Fig. 8. Annual energy cost for ladle heating as a function of the CO_2 buffer storage capacity (scenario D).

energy costs for ladle heating by 20% (Fig. 8). In scenario F1, the analogous approach results in an optimum storage capacity of 180 kg and annual energy cost savings of 25% (Fig. 9).

3.2.2. *Waste heat recovery*

We apply a similar approach for the economic analysis of the waste heat steam generation system in scenario F2. However, in this case, the costs for investments, energy and carbon dioxide emission allowances are allocated to the cost center *steam generation*. In contrast to scenarios D and F1, in which the recovered heat is stored in the existing feed water tank, the amount of recoverable heat is dependent on the capacity of the implemented thermal energy storage. Therefore, Fig. 10 indicates the relationship between the storage capacity and the relative annual energy cost for different economic framework conditions.

As in section 3.2.1, we assume the base case parameters given in section A1, Table 4. Fig. 10B and C illustrate, that due to the high investment costs, this variant is only economically advantageous at natural gas prices exceeding 70 EUR/MWh or long assessment periods of more than 17 years. Considering a natural gas price of 80 EUR/MWh, the installation of a thermal energy storage with an economically optimized storage size of 2340 kWh results in an annual cost reduction of 10% for steam generation. Moreover, the natural gas consumption and the related CO_2 emissions of the steam boiler decrease by 94% (Fig. 7).

3.3. *Overall carbon dioxide reduction potential*

Our calculations demonstrate that exploiting the potential for carbon dioxide and waste heat recovery will lead to a significant reduction in fuel consumption and direct CO_2 emissions. However, the actual effect of the proposed measures is limited by the previously described technical (section 3.1) and economic (section 3.2) considerations, but still leads to significant emission reductions. Fig. 11 summarizes the savings in carbon dioxide emissions for the overall steel mill, which are achievable in the individual scenarios.

The transition to Oxyfuel ladle preheating, recovery of the waste heat for feed water preheating at the steam generator and utilization of the generated carbon dioxide for cooling water treatment and wastewater neutralization results in direct emission savings of 14% in the demo scenario. Additional plant-internal utilization of CO_2 for EAF blowing generates emission savings of 19% in scenario F1, considering the economic optimum at the defined base case (see 3.2). Assuming the base case with an elevated natural gas price of 80 EUR/MWh, the most cost-efficient variant of the EAF waste heat recovery system would save additional 7% of the annual carbon dioxide emissions of the steel mill. While the implementation of new Oxyfuel ladle heaters implies high investment costs, the measure results in substantial CO_2 emission savings. In contrast, the emission reduction by carbon capture and internal utilization as well as EAF waste heat recovery is comparatively low, despite significant effort in engineering, equipment as well as the related costs.

4. Discussion

According to our results, the application of Oxyfuel burners as well as the transformation from horizontal to vertical ladle heaters reduces the natural gas consumption and scope 1 carbon dioxide emissions for ladle

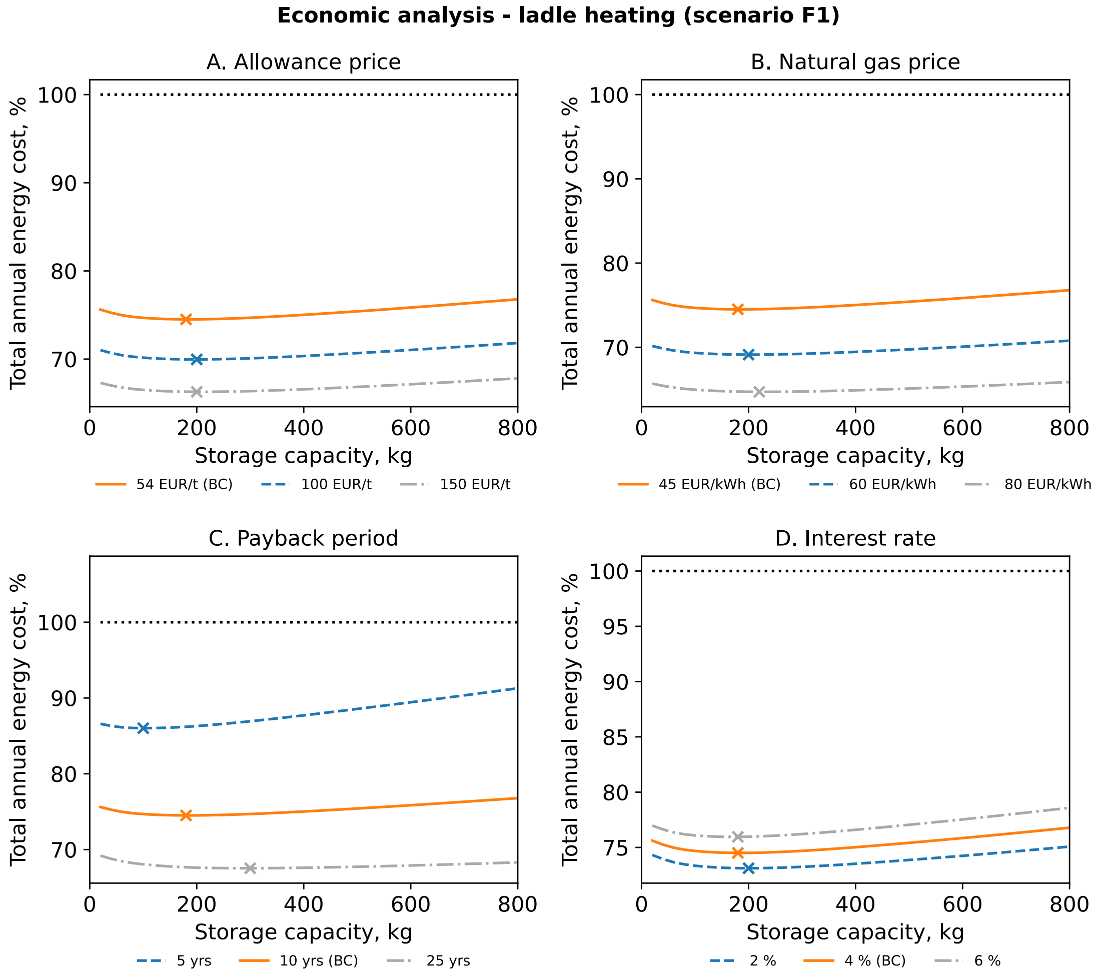

Fig. 9. Annual energy cost for ladle heating as a function of the CO_2 buffer storage capacity (scenario F1).

preheating in the considered steel mill by 32–46% (Table 3). The extent of the effective CO_2 emission cut is only dependent on the specific CO_2 emissions of the supplied oxygen. Moreover, our assessment of the demonstration scenario indicates that the implementation measures are economically advantageous considering reasonable framework conditions and a payback period of 10 years (Fig. 8).

The utilization ratio of recovered carbon dioxide varies significantly depending on the capacity of the buffer storage. To a certain extent, higher storage costs are compensated by savings of purchased CO_2 for the cooling systems and the waste water treatment plant as well as the partial substitution of oxygen by carbon dioxide in the electric arc furnace. If the carbon dioxide separation and utilization system is designed according to the economic optimum, up to 71% of the produced carbon dioxide can be exploited plant-internally (Fig. 6). In this way, the purchase of CO_2 for cooling water treatment and waste water neutralization is avoided and the oxygen consumption of the electric arc furnace is reduced by up to 15%. Additional emission and fuel savings are achieved by recovering the ladle heater waste heat. The existing feed water tank of the steam boiler provides a heat sink with sufficient storage capacity (Fig. 7).

The electric arc furnace produces a substantial amount of waste heat at high temperature levels. However, the recovery is difficult due to a lack of suitable heat sinks in our case study. With regard to temperature and amount of required energy, solely the process steam boiler offers potential to exploit the heat produced by the EAF hot gas duct. However, due to the batch operation both at the EAF, which acts as the heat source, and at the vacuum treatment units, which are the biggest steam consumers, heat generation and demand fluctuate substantially. Therefore, the implementation of a thermal energy storage is crucial. In order to cut down on fuel consumption and CO_2 emissions of the steam generator by 95%, the installation of a pressurized hot water storage with a capacity of 2500 kWh is required. The complexity and the extent of the necessary equipment of the proposed heat recovery system lead to high investment costs. Hence, this plant is only economically feasible considering long payback periods or high natural gas prices (Fig. 10). Theoretically, it would be possible to produce the process steam almost exclusively via waste heat recovery (Fig. 7).

Since the carbon dioxide introduced into the electric arc furnace is released into the atmosphere as part of the furnace exhaust gas, it does not contribute to the mitigation of scope 1 CO_2 emissions. However, depending on the oxygen production process and the supplied energy, substituting oxygen at the EAF could reduce costs as well as indirect (scope 3) emissions. The potential energy and emission savings resulting from the mixed blowing of oxygen and carbon dioxide into the electric arc furnace will be the subject of subsequent studies. In order to investigate the achievable concentration of CO_2 in the product gas of the proposed CCU plant in an industrial environment, a demonstration project will be carried out following this study.

Finally, we discuss our results applying a sensitivity analysis. Fig. 12 demonstrates the extent by which the overall result, hence the total energy cost reduction, changes in response to individual parameter variations. The presented analyses are each built on the base case assumptions from the economic analyses in chapters 3.2.1 and 3.2.2. Introducing a 40% funding ratio ensures an economic benefit within a payback time of 10 years for the implementation of the heat recovery system (see Fig. 12). In both cases, the natural gas price and the payback

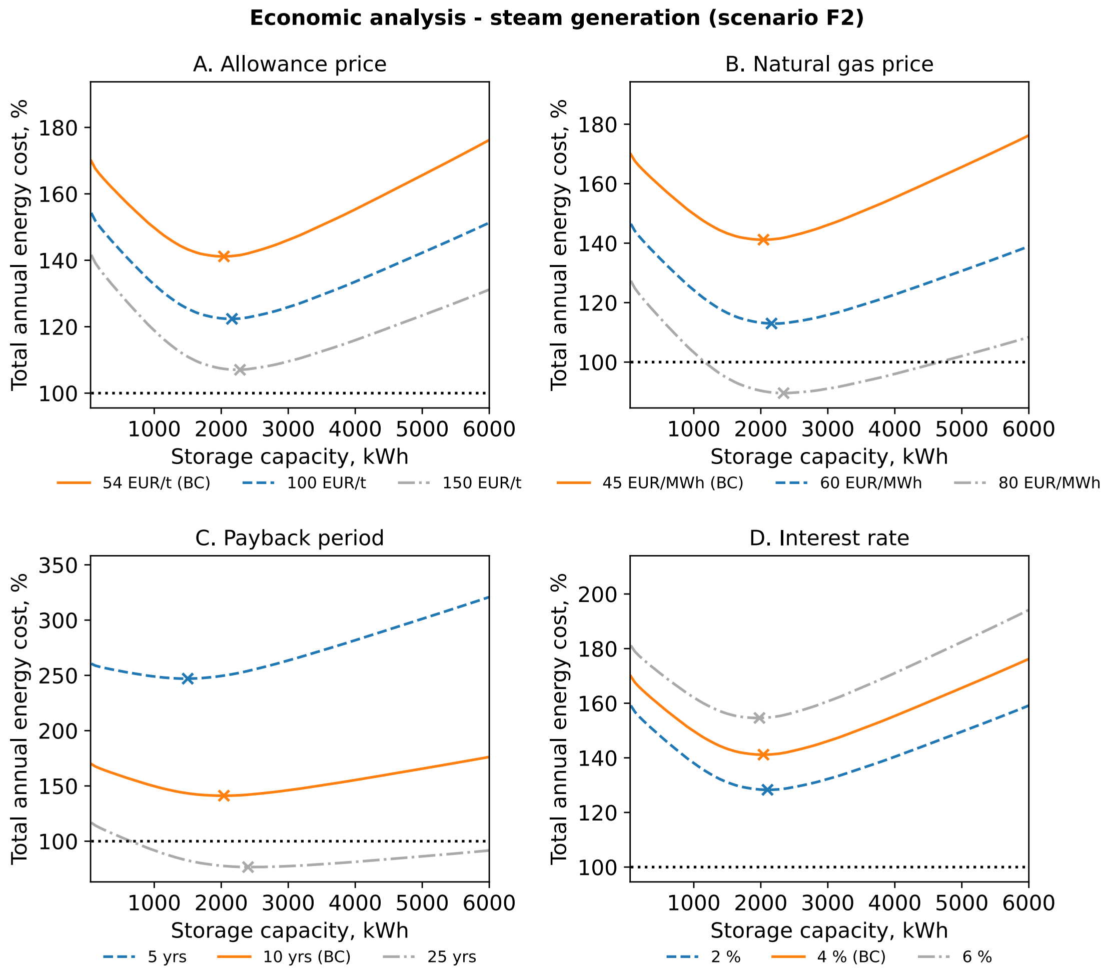

Fig. 10. Annual energy cost for steam generation as a function of the thermal energy storage capacity (scenario F2).

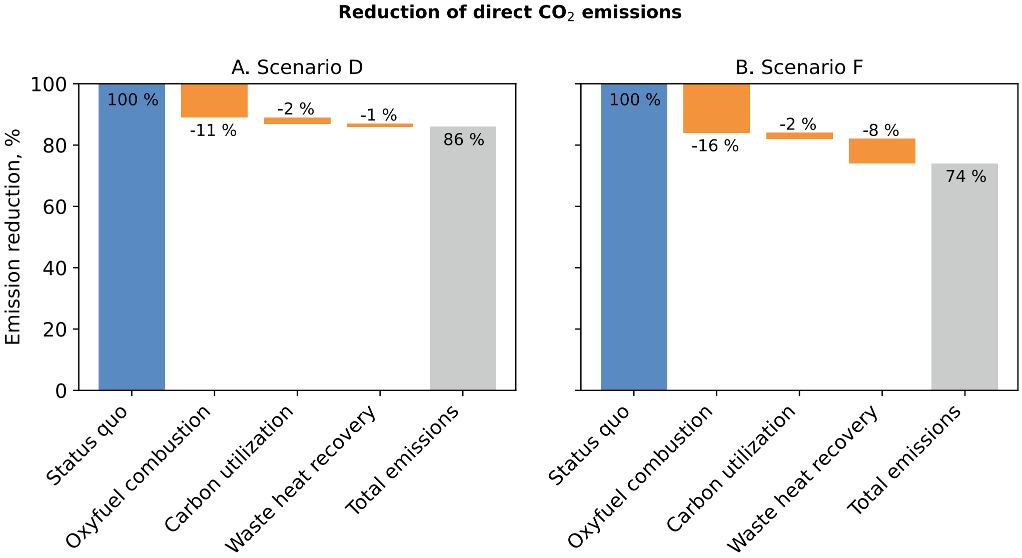

Fig. 11. Reduction of carbon dioxide emissions by scenario.

period have the strongest impact on the economic viability which calls for lifetime-based investment concepts. The CO_2 emission allowance price ranks only third, followed by the interest rate. However, it must be emphasized that emission allowance prices, as a policy instrument, represent the greatest uncertainty of all the analyzed parameters. In order to reach a net-zero-emission energy system by 2050, the IEA's World Energy Outlook 2021 (International Energy Agency, 2021) anticipates carbon prices of 120 EUR/t in 2030 and 230 EUR/t in 2050, which significantly exceed the range of variation considered in the sensitivity analysis.

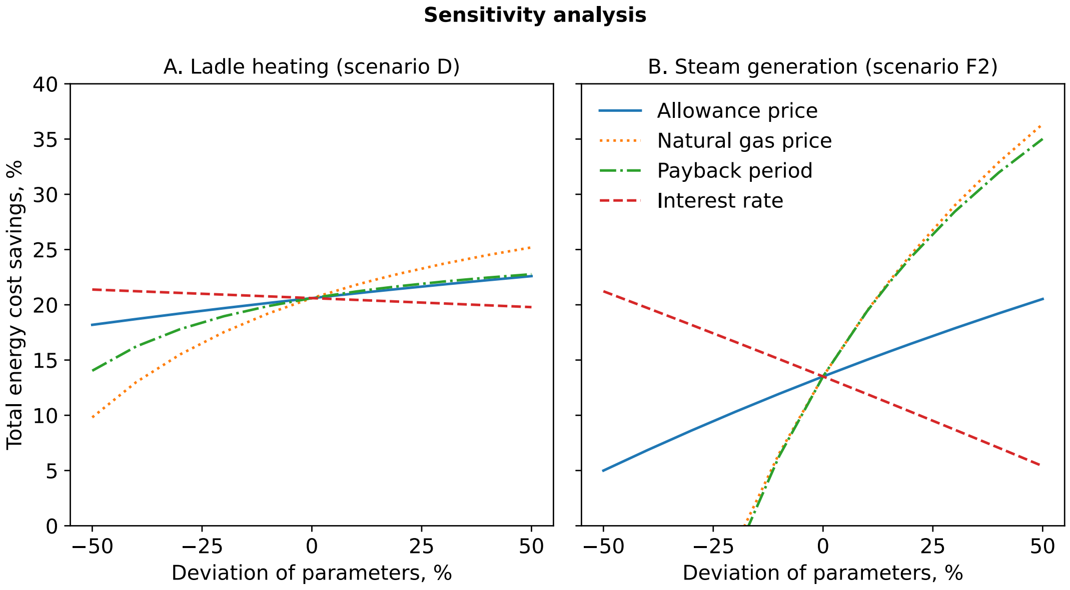

Fig. 12. Sensitivity analysis of the economic benefit for ladle heating (A) and steam generation (B).

5. Conclusion

The case study demonstrates that the implementation of the proposed technologies in the investigated steel mill leads to a significant reduction of energy consumption and direct carbon dioxide emissions. On the one hand, the transition to Oxyfuel burners reduces the natural gas consumption and related carbon dioxide emissions. On the other hand, the internal recovery of CO_2 further decreases emissions and saves the external purchase of carbon dioxide for the water treatment processes and enables the mixed blowing of oxygen and carbon dioxide at the electric arc furnace. Additional savings can be achieved by exploiting available waste heat sources such as the EAF or the ladle heater offgas for water preheating or process steam production.

The first finding of our investigation is that the investments in decarbonization technologies are not only enhancing the overall energy efficiency but, in view of increasing prices for CO_2 emission allowances, also financially viable. However, this does not apply to all measures: the waste heat steam production from the EAF exhaust gas will not be profitable in the medium term. Therefore, the holistic analysis and thorough assessment of potential implementations on a system level is of utmost importance.

Second, the economic evaluation as well as the sensitivity analysis indicate that the substantial capital expenditures required for the implementation of novel energy-related technologies entail long payback periods, even at high fuel and emission allowance costs. From this fact, we conclude that investments in energy efficiency and decarbonization measures do not necessarily become economically feasible through an increase of the costs for carbon dioxide emissions alone. In spite of profitability, the currently demanded amortization periods have an inhibitive effect on investments and hold the risk that investment decisions are delayed or not made at all.

Third, the investigated steel mill provides a considerable waste heat potential which can only be used to a limited extent mill-internally due to its comparably low temperature level and highly fluctuating output. In this case, external recipients such as neighboring industrial companies or district heating systems are essential to enable the efficient and economical utilization of waste heat.

Finally, the authors point out that due to its high degree of electrification, the decarbonization of EAF steelmaking is particularly dependent on electricity from renewable energy sources. Research is therefore needed not only with regard to efficient fuel utilization and avoidance of direct carbon dioxide emissions but also in terms of providing flexibility options for the increased integration of volatile renewable energy sources.

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.

Acknowledgments

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A1. Cost data

Table 4
Energy cost

Cost component	Unit	Cost	Reference
Electric energy	EUR/MWh	127	E-Control (2022b)
Natural gas	EUR/MWh	45	E-Control (2022a)
Oxygen	EUR/t	80	provided by industrial partners
Carbon dioxide	EUR/t	90	provided by industrial partners
Emission allowances	EUR/t	54	European Energy Exchange AG (2021b)

Table 5
Capital cost

Cost component	Unit	Cost	Reference
Oxyfuel ladle heater	EUR	100	provided by industrial partners
CO_2 sequestration	EUR/(kg/h)	2350	provided by industrial partners, (Peters et al., 2004)
EAF waste heat recovery	EUR/kW	590	provided by industrial partners, (Peters et al., 2004)
CO_2 storage	EUR/kg	780	provided by industrial partners, (Peters et al., 2004)
Thermal energy storage	EUR/kWh	360	provided by industrial partners, (Peters et al., 2004)

A2. Simulation data

Table 6
Simulation parameters

Parameter	Unit	Scenario D	Scenario F	Reference
Economic parameters				
Payback period	a	10	10	own assumption
Interest rate	%	4.0	4.0	Greiml et al. (2021)
Steam generator				
Feed water temperature	°C	105	105	process requirement
Steam temperature	°C	190	190	process requirement
Steam pressure	MPa	2.0	2.0	process requirement
Thermal energy storage				
Min. temperature	°C	15	200	process requirement
Max. temperature	°C	105	240	process requirement
CO_2 buffer storage				
Min. pressure	MPa	0.5	1.0	process requirement
Max. pressure	MPa	1.0	2.0	own assumption
CO_2 capture unit				
Compressor efficiency		0.6	0.6	own assumption
Sequestration efficiency	–	0.8	0.8	own assumption
Heat recovery efficiency	–	0.9	0.9	own assumption

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