Integration of waste biomass thermal processing technology with a metallurgical furnace to improve its efficiency and economic benefit

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Abstract

The article presents innovative technology which integrates a metallurgical pusher-type furnace with a waste heat recovery system that consisted of a reactor for torrefaction and pyrolysis of waste biomass. The technology is designed for utilizing both liquefied and gaseous by-products (torgas, pyrolysis gas and condensate denoted as TPC) obtained from torrefaction and pyrolysis of waste biomass. TPC is considered to be applied as an additional fuel for a metallurgical furnace as an example of effective energy management in metallurgical industry. In detail, the technology contains waste heat recovery unit installed on the furnace smoke stack as the heat source for the pyrolysis/torrefaction reactor. The analysis was carried out for a pusher furnace, fed optionally with either natural gas or coke gas. Share of this gaseous/liquid TPC fuel from waste in the total fuel mixture fed to the furnace was varied from 5 to 15% by volume. Practical usefulness of TPC fuel was tested on a specially constructed test stand. Financial analysis in energy consumption and economy of using the obtained TPC fuel for co-combustion with coke gas in the metallurgical pusher furnace was carried out on the basis of data from a steel sheet roller combined with the pusher furnace located in one of large steel works. It was shown that the use of this TPC fuel derived from thermal treatment of waste biomass and other organic substances can be considered an effective method of reducing production costs in the analyzed steel company and can lead to increase in the attractiveness of their products and thus strengthen their competitiveness on the global market.

Graphic abstract

Keywords Pyrolysis · Waste biomass · Waste heat · Energy · Metallurgical furnace · Sustainable development

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Introduction

The noticeable climate changes force intensive efforts to reduce the effect of global warming, which in the first place translates into the development of modern, energy-saving technologies and stimulating the implementation of renewable energy sources and reduction of fossil fuel consumption (Raybould et al. 2020). Intensive development is observed in the field of renewable energies including solar, wind, tidal energy, fuel cells, biomass energy and waste heat (Lukáč et al. 2019). The development of these energy sources provides more efficient methods of both generating energy and reducing production costs as well as reduces or even completely eliminates the need for fossil fuels, which contribute to global warming (Rinaldi et al. 2020). Waste heat generated in almost every production processes deserves special attention. This heat can be reused for heating purposes or generating electricity. These and several other applications of waste heat recovery (WHR) are becoming common in industrial enterprises all over the world, also including metallurgical industry (Mellin et al. 2014; Proskurina et al. 2017). There are still obstacles, however, to the development of waste heat recovery technologies. One of them is difficulty in transporting heat over long distances, which limits the places where this heat can be used. Hence, heat consumers have to be located near the heat sources; otherwise, it is economically unjustified. Moreover, the subsidies for the recovery of waste heat are relatively small compared to the subsidies for new and renewable energy sources as well as the tax exemptions for companies implementing solar or wind energy.

Innovative strategies and technologies

There is probably enough evidence to state that the metallurgical industry is one of the most heat- and power-consuming branches of modern heavy industry, even though a number of innovative solutions have been introduced there. Apart from high pollutant emissions, the steel industry is also characterized by high energy consumption as discussed by Sun et al. (2020) and Zhang (2019). Taking into account the fact that effort on improving energy efficiency is one of the priorities of the EU energy policy, a number of countries have declared to implement measures concentrated on energy savings as their national targets in this field. The potential for improving energy efficiency can be found in the entire EU and global economy, but significant benefits are seen in the improvement in energy-consuming processes in steel production technologies.

The metallurgical steel industry, due to its economic potential and importance for the economy, is classified as a strategic industry branch in several highly developed

countries. Steel products are among the basic materials used by most sectors of global and local economy. In order to meet high economic and ecological requirements, the steel industry is forced to modernize production processes. It is particularly important to search for new methods of reducing pollutant emissions and CO₂ from all processes in the technological chains; this mainly applies to steel works with a complete production cycle (Jerzak et al. 2014). The technologies currently used for steel production, despite plenty of ecologically focused investments, still have a negative impact on the natural environment, in particular regarding CO₂ emissions and energy consumption. Therefore, new solutions have been sought, including innovative future technologies developed under international programs for reducing CO₂ emissions (Zajemska and Poskart 2013). Noteworthy are optimization activities implemented in several steel works, which resulted in reduction not only in fuel consumption, but also in emissions as observed by Habashi (2011) and Lukáč et al. (2019). An example of such solutions implemented into practice is the use of low-emission burners and the use of the so-called producer gases, especially those rich in hydrogen (Kremer et al. 2001; Lee and Jou 2011; Li et al. 2011; Kirschen et al. 2005) combined with appropriate control of parameters for combustion process. (In particular, the equivalence ratio and temperature of input air are the most important.)

It must be stressed that promising technologies for energy savings and reduction in CO₂ emission relate to waste heat recovery systems for flue gases and slag in steel processing (Zhang et al. 2013). Li (2017) conducted theoretical analysis on the waste heat recovery system with various methods to recover heat from molten slag. He concluded that exergy efficiency of recovery this heat in the form of a superheated steam is 34.2%. Furthermore, he confirmed that combined multidisciplinary methods are more effective in heat recovery than single physical methods. Liu et al. (2014) proposed a gravity bed waste heat boiler with steam generation for recovering waste heat from high-temperature metallurgical slag particles. Summary of various heat recovery technologies and their usability can be found in article by Jouhara et al. (2018). He and his team conducted research focusing on the operation and performance of commonly used devices for waste heat recovery such as recuperators, various regenerators, air preheaters, regenerative and recuperative burners, plate heat exchangers, economizers and waste heat boilers. They analyzed several systems based on direct and indirect contact condensation recovery, transport membrane condensation, heat pumps, heat recovery steam generators (HRSGs), heat pipe systems, organic Rankine cycles (ORC) and the Kalina cycle. Furthermore, they also investigated effectiveness of new emerging technologies for direct heat to power conversion such as thermoelectric, piezoelectric, thermionic and thermo-photo-voltaic power

generation techniques. Finally, they came to conclusion that several specific cases should be analyzed individually without any key decisive indicators on favorable techniques and methods. They stated that improvements in energy efficiency by utilizing waste heat recovery in industrial processes are achievable based on different approaches and with the use of different state-of-the-art technologies.

There is no doubt that potential in energy savings is large and can be used with the involvement of relatively small resources in the scale of the entire undertaking. Among several mechanisms to increase energy efficiency, the mandatory energy monitoring and management system for the steel industry is proposed to be implemented as soon as possible as stated by Cheng et al. (2020), He and Wang (2017), Conejo et al. (2020). Opportunity to improve energy efficiency, aimed at reducing fuel consumption, is the use of the potential of post-processed gases, such as coke gas and gases from thermal waste processing (Jerzak et al. 2014). Particularly, noteworthy are by-products from biomass torrefaction/pyrolysis processing. These by-products are both gases and hydrocarbon-based vapors that condense to their liquid state when cooling them to ambient temperature. They are a mixture of torgas from torrefaction, pyrogas from pyrolysis process and a condensate denoted all as TPC fuel in this article. As a feedstock attractive from the environmental point of view, the raw material consisting of organic substances, including municipal organic waste, was used. Szwaja et al. (2019a) draw out attention to the TPC fuel, which, currently, is not effectively managed on industrial scale, unfortunately. In this case, significant energy savings can be achieved through skillful management in an energy system, which integrates other well-known technologies as follows: steel production line and torrefaction/pyrolysis technology for renewable fuel production from biomass as well as from other organic harmful waste including plastics.

Products from thermal processing of biomass

Both torgas and pyrolysis gas, hydrocarbon vapors and char are products from the thermal treatment of organic substance in inert atmosphere at temperature range from 200 to 450 °C and residence time from 1 to 30 min. This treatment leads to evaporation, depolymerization and carbonization of the organic matter in the raw feedstock. Char is a solid product that is almost homogeneous with black color and rich of carbon. Gases/vapors from torrefaction/pyrolysis consist of condensing and non-condensing (gaseous) fractions (Bach and Skreiberg 2016). Condensed vapors are mainly water, organic substances and lipids, while the non-condensable fraction consists mainly of carbon dioxide, carbon monoxide and slight concentrations of hydrogen and methane (Michel and McCormick 2015; Sahoo et al. 2019). Typically,

approximately 70% of the initial biomass weight is retained as a solid product and 30% of the weight is converted to gases and condensates as follows (Bach and Skreiberg 2016; Michel et al. 2015; Sahoo et al. 2019):

- Solids: monosaccharides, polysaccharides, new polymers, carbon, mineral content (ash),
- Liquids: water, sugars, acids, alcohols, polyols, furans, ketones, toluene, benzene, lipids, terpenes, phenols, waxes, tannin,
- Gases: hydrogen, carbon monoxide, carbon dioxide, methane, higher light hydrocarbons.

Regarding gases efficiency, their yield can reach even more than 30% biomass feedstock and it depends on both the properties of raw biomass and the conditions of the process, in particular the temperature and pyrolysis time (Chen et al. 2015; Ren et al. 2013). Chen et al. (2015) observed higher yield of biochar in comparison with condensates at temperature over 230 °C. With an increase in torrefaction temperature from 220 to 280 °C, the non-condensable gas yield changed insignificantly, but biochar increased, whereas condensed substance (bio-oil) decreased by approximately 20%. As indicated by the study of the pyrolysis of sawdust pellets carried out by Ren et al. (2013), the share of combustible pyrolysis products may be significant. For the residence time of 15 min and the pyrolysis temperature of 270 °C, the share of CO was 42% and H₂—20.5%, while the CH₄ share was approximately of 25% at processing temperature of 310 °C.

Summary

At this point, it is important to draw a conclusion that there is not detailed information in the available literature on the system described in this article. This is an innovative energetic system that integrates two well-known technologies:

- Torrefaction/pyrolysis of organic wastes,
- Waste heat recovery from flue gases of the metallurgical pusher furnace.

The main objectives of the research works are the following:

1. Increase thermal efficiency of the pusher furnace, which contributes to higher energy savings, and improve financial condition of a company,
2. Provides opportunities for utilizing waste organics, especially municipal organic waste.

Novelty in the technology presented in the article is innovation that uses waste heat from a metallurgical pusher furnace to produce fuel that will supply the furnace and, in this case, will decrease energy consumption and contribute to CO₂ emission reduction. The technology uses the process of torrefaction and pyrolysis of energy crops and municipal organic waste (including plastics). Additional benefit from this technology is production of biochar.

Research methodology and test setup

The technology described in this article integrates waste heat recovery system installed on the pusher furnace smokestack with burners that heat steel sheets to temperature of 1300 °C. The main parts of this system are the following:

- A torrefaction/pyrolysis reactor that produces biochar and by-products (pyrolysis gas and pyrolysis oil),
- Furnace burners for combusting these by-products.

On the basis of border conditions, the process temperature inside the reactor varied in the range from 200 to nearly 400 °C; hence, both torrefaction and pyrolysis phenomena took place. As it was difficult to separately identify and describe each phenomenon, the parameters characterizing the process were temperature in the inlet and outlet of the reactor and the feedstock residence time in the reactor. Hence, the border conditions for the reactor were the following:

- Feedstock temperature at the inlet: 21 ± 1 °C,
- Gas temperature at the outlet: 375 ± 10 °C,
- Feedstock residence time in the reactor: 480 ± 20 s,
- Feedstock composition: waste biomass, optionally municipal organic waste with maximum 10% plastics

Fig. 1 Test bed diagram

waste (polypropylene, polyethylene), moisture content below 6%.

From technical point of view, the technologies for the torrefaction/pyrolysis and the devices are well known as well as principles of their operation. Hence, the main objective of the investigation was to present impact on financial savings obtained from implementing the technology into practice.

To achieve the main objective, two research tasks were conducted as follows:

- tests on the torrefaction/pyrolysis reactor to characterize the TPC fuel,
- feasibility study aided with experimental data from the real steel sheet rolling line with the pusher furnace.

The research methodology was based on the results from experimental studies on the torrefaction/pyrolysis of Virginia Mallow (*Sida hermaphrodita*) energy crops and organic municipal waste that contained plastics at percentage below 10% by weight. Based on the experimental results, the calorific value of the pyrolysis gas was calculated and then a feasibility study was carried out for the heating system of the metallurgical pusher furnace in order to improve its operating economy. For this purpose, the test stand shown in Fig. 1 was constructed. The torrefaction/pyrolysis reactor was built as a screw-type reactor, which was heated by waste heat of flue gases from the abovementioned furnace.

The chemical analysis was performed for the following:

- The raw feedstock—including dried shredded pieces of Virginia Mallow mixed with waste biomass collected by

Table 1 Physical–chemical properties of feedstock to the reactor that consisted of Virginia Mallow and waste biomass at ratio of 50/50%

Property	Unit	Value
Total moisture content	%	10.8
Moisture analytical content		6.3
Ash analytical content		1.7
Ash content at the tested sample		1.80
Volatile compounds analytical content		87.0
Carbon analytical content		44.5
Hydrogen analytical content		5.6
Nitrogen analytical content		1.0
Sulfur analytical content		0.1
Oxygen analytical content		40.8
Chlorine analytical content	%	0.02
Heat of combustion at analytical conditions	MJ/kg	17.65
Lower heating value at analytical conditions	MJ/kg	16.25
Lower heating value of the raw tested sample	MJ/kg	15.22

Fig. 2 **a** Test bed for TPC fuel combustion, **b** view at the diffusion flame through the technical viewing window. 1—Exhaust outlet, 2—flue gas measuring socket, 3—exhaust gas pipeline, 4—technical viewing window, 5—combustion chamber, 6—burner nozzle Ø18 mm, 7—mixing chamber, 8—gas connector, 9—air control valve, 10—gas control valve, 11—propane-butane gas control valve, 12—condensate drain valve

municipal cleaning services (leaves, straw, wood chips from parks, individual gardens, households, etc.),

- Torgas, pyrolysis gas and coke gas.

An analysis of vapors condensed to liquids from raw hot torgas and pyrolysis gas was partially performed.

Table 1 presents results from chemical analysis of the feedstock filling the reactor. It consisted of the Virginia Mallow and waste biomass collected by municipal cleaning service.

The detailed composition of the gas was determined from tests realized on the stand presented in Fig. 1. Detailed analysis was presented in the work by Rajca et al. (2020), while tests on TPC fuel combustion and flame investigation were carried out on the test stand shown in Fig. 2. In case of flame instabilities, propane-butane gas was used to enrich the combustible mixture and stabilize the flame from torgas/pyrogas combustion.

Gases and vapors (TPC) coming out of the pyrolysis reactor presented in the work (Szwaja et al. 2019b) through the nozzle (6) were delivered through the control valve (10) to the mixing chamber (7), where the air was delivered through the valve (9). Fuel-air mixture after flowing out the nozzle (6) was burnt in the combustion chamber (5). The flue gases through the pipeline (3) were thrown out to the ambient air. The flue gases measurement was performed with the aid of the MRU VarioPlus flue gas analyzer. In case of stabilizing combustion process, a propane-butane gas valve was included (11). Elemental analysis CHN of the samples was made with the aid of a LECO CHN628 analyzer. Higher heating value was determined with the aid of a LECO AC500 calorimeter. GC + MS Agilent in split mode was used to determine several specific compounds.

Table 2 Chemical analysis of gases from torrefaction/pyrolysis reactor filled with feedstock that consisted of Virginia Mallow and municipal waste biomass under various temperature conditions

Torgas/pyrogas content	Unit	Gas after thermal treatment		
		at 300 °C	at 350 °C	at 400 °C
H ₂	% v/v	0.28	0.57	0.68
CO		26.37	26.91	43.33
CH ₄		0.28	1.02	3.63
CO ₂		54.99	62.14	67.62
C ₂ H ₄		0.00	0.19	0.39
C ₂ H ₆		0.00	0.15	0.45
C ₃ H ₈		0.00	0.04	0.09
C ₃ H ₆		0.00	0.04	0.15
C ₄ H ₁₀		0.00	0.00	0.03
LHV by volume	MJ/Nm ^{3*}	3.46	4.11	7.63

* Nm³ stands for normal cubic meter at STP pressure and temperature conditions of 1 bar and 0 °C, respectively

Fig. 3 **a** Torgas/pyrogas content, **b** torgas/pyrogas heating value

Fig. 4 Fuel and heat management in the proposed system

Table 5 The measured composition of the coke gas fueled the furnace

Coke gas composition (%)	
H ₂	53.6
H ₂ O	7.7
CH ₄	23.7
CO	5.9
CO ₂	3.1
N ₂	3.1
C ₃ H ₈	2.9
LHV (MJ/Nm ³)	17.7

follows: preheating zone (to preheat the input material that are thick steel plates), upper and lower heating zones (to heat the steel plates from top and bottom) and compensating zone (to stabilize thermal stresses while the plates go to the roller to produce sheets from them).

The calculations presented in Table 4 were done on the basis of the furnace capacities, for which the heat demand was calculated taking into account the specific heat consumption.

Assumptions to calculations

The chemical composition of the gas obtained at various process temperature conditions presented in Table 2 was adopted for the calculations. Furthermore, the composition of coke oven gas presented in Table 5 was also used for the calculations. The assumptions in the following were taken into calculations:

- Continuous work of the furnace without any stops or break due to failure,
- First-order Newtonian interpolation method was used for predicting both energy savings and additional financial benefits for various steel material production in the range from 20 to 60 Mg/h,
- The price of coke gas taken for calculations was approximately 81 EUR/1000 Nm³.

For safety reasons, the burners installed in the furnace and the measurement systems for the coke gas did not allow for a deviation greater than $\pm 10\%$ from the calorific value LHV of 17.69 MJ/Nm³.

No assumptions were taken to simplify calculations of final results from tests on the reactor.

Table 6 shows the savings due to the use of TPC fuel obtained from thermal processing of Virginia Mallow mixed with waste biomass collected from municipal cleaning of city parks at three different temperatures.

Short summary of the data from Table 6 is presented in Fig. 6. As seen, the financial savings for the best scenario

can exceed 6,000 EUR monthly at steel sheets production output rate of 20 Mg/h. In case the furnace works at its nominal power and generates output of 80 Mg/h, then the financial savings can be around 22,000 EUR per month. Hence, the savings can significantly contribute to overall financial balance for the steel rolling technology in a company.

Discussion

The conception of integrating biomass thermal processing system with a metallurgical pusher furnace is shown in Fig. 7. As analyzed, the flue gases leaving the recuperator still have sufficiently high temperature to work as the heating source for the torrefaction/pyrolysis process at temperature of around 400 °C. The heat from the flue gas at temperature of approximately 430 °C is used to heat the biomass in the torrefaction/pyrolysis reactor. As result of torrefaction/pyrolysis process, the hot TPC fuel is generated and directly thrown by a blower to a main collector pipeline and finally to burners. An additional benefit of the proposed solution is the possibility of producing biochar. In addition, the furnace is equipped with a calorimeter that controls the air-to-fuel ratio and in case of higher TPC fuel production rate by the torrefaction/pyrolysis reactor. Then, a control system can automatically reduce primary gas (coke gas or natural gas) to burners.

Table 7 provides data on savings in coke gas (optionally natural gas) for heating the pusher furnace and CO₂ emission reduction obtained by implementation into practice the torrefaction/pyrolysis system to this furnace.

As depicted in Table 7, energy savings can reach 70 thousands GJ per year. This is approximately of 2.5% total energy (heat) demand by the rolling steel sheet production line that was under investigation. The average efficiency of the proposed technology was estimated at 10%. It was calculated with the aid of modeling heat transfer from flue gases to the reactor. The efficiency was defined as total chemical energy stored in a fuel (including both solid biochar and TPC) produced by the torrefaction/pyrolysis reactor divided by enthalpy change of flue gases before and after the reactor. Hence, this efficiency coefficient can be used by others to perform comparative analysis of our system with other systems. Assuming 25-year life time, the implementation of this technology can be considered a reasonable measure. Noteworthy is the significant amount of CO₂ emission reduction per year. It affects the carbon emission tax. Thus, if one assumes the carbon emission tax rate of 40 EUR/Mg, then this total annual tax can be reduced by more than 120,000 EUR as far as the coke gas (produced from coal gasification) is replaced by combustible gas from waste renewable organics/biomass.

Table 6 Savings in coke gas consumption under various TPC fuel replacements of 5, 10 and 15% at temperatures of 300, 350 and 400 °C

Heated steel output	Mg/h	80	60	40	20
5% TPC fuel replacement obtained at temperature of 300°C					
Total flowrate	Nm ³ /h	6772	5209	3647	2084
Flowrate of coke gas	Nm ³ /h	6434	4949	3464	1980
Flowrate of TPC fuel	Nm ³ /h	339	261	182	104
Savings in use of coke gas (hourly, daily and monthly)	Nm ³ /h	66	51	36	20
	Nm ³ /24h	1589	1223	856	489
	Nm ³ /m	47686	36682	25677	14673
	EUR/m	3144	2419	1693	967
10% TPC fuel replacement obtained at temperature of 300°C					
Total flowrate	Nm ³ /h	7069	5437	3806	2175
Flowrate of coke gas	Nm ³ /h	6362	4894	3425	1957
Flowrate of TPC fuel	Nm ³ /h	707	544	381	2
Savings in use of coke gas (hourly, daily and monthly)	Nm ³ /h	138	106	74	42
	Nm ³ /24h	3318	2552	1787	1021
	Nm ³ /m	99544	76572	53600	30629
	EUR/m	6563	5049	3534	2019
15% TPC fuel replacement obtained at temperature of 300°C					
Total flowrate	Nm ³ /h	7392	5686	3980	2274
Flowrate of coke gas	Nm ³ /h	6283	4833	3383	1933
Flowrate of TPC fuel	Nm ³ /h	1109	853	597	341
Savings in use of coke gas (hourly, daily and monthly)	Nm ³ /h	217	167	117	67
	Nm ³ /24h	5205	4004	2803	1601
	Nm ³ /m	156145	120112	84078	48045
	EUR/m	10295	7919	5544	3168
5% TPC fuel replacement obtained at temperature of 350°C					
Total flowrate	Nm ³ /h	6759	5200	3640	2080
Flowrate of coke gas	Nm ³ /h	6422	4940	3458	1976
Flowrate of TPC fuel	Nm ³ /h	338	260	182	104
Savings in use of coke gas (hourly, daily and monthly)	Nm ³ /h	78	60	42	24
	Nm ³ /24h	1884	1450	1015	580
	Nm ³ /m	56536	43489	30443	17396
	EUR/m	3728	2867	2007	1147
10% TPC fuel replacement obtained at temperature of 350°C					
Total flowrate	Nm ³ /h	7040	5416	3791	2166
Flowrate of coke gas	Nm ³ /h	6336	4874	3412	1950
Flowrate of TPC fuel	Nm ³ /h	704	542	379	217
Savings in use of coke gas (hourly, daily and monthly)	Nm ³ /h	164	126	88	50
	Nm ³ /24h	3926	3020	2114	1208
	Nm ³ /m	117774	90595	63417	36238
	EUR/m	7765	5973	4181	2389
15% TPC fuel replacement obtained at temperature of 350°C					
Total flowrate	Nm ³ /h	7346	5651	3955	2260
Flowrate of coke gas	Nm ³ /h	6244	4803	3362	1921
Flowrate of TPC fuel	Nm ³ /h	1102	848	593	339
Savings in use of coke gas (hourly, daily and monthly)	Nm ³ /h	256	197	138	79
	Nm ³ /24h	6144	4726	3308	1890
	Nm ³ /m	184324	141787	99251	56715
	EUR/m	12153	9349	6544	3739
5% TPC fuel replacement obtained at temperature of 400°C					
Total flowrate	Nm ³ /h	6690	5146	3602	2058

Table 6 (continued)

Heated steel output	Mg/h	80	60	40	20
Flowrate of coke gas	Nm ³ /h	6356	4889	3422	1956
Flowrate of TPC fuel	Nm ³ /h	334	257	180	103
Savings in use of coke gas (hourly, daily and monthly)	Nm ³ /h	144	111	78	44
	Nm ³ /24h	3463	2664	1864	1065
	Nm ³ /m	103882	79909	55936	31964
	EUR/m	6849	5269	3688	2107
10% TPC fuel replacement obtained at temperature of 400°C					
Total flowrate	Nm ³ /h	6892	5301	3711	2121
Flowrate of coke gas	Nm ³ /h	6203	4771	3340	1908
Flowrate of TPC fuel	Nm ³ /h	689	530	371	212
Savings in use of coke gas (hourly, daily and monthly)	Nm ³ /h	297	229	160	91
	Nm ³ /24h	7134	5488	3841	2195
	Nm ³ /m	214028	164637	115246	65855
	EUR/m	14112	10855	7599	4342
15% TPC fuel replacement obtained at temperature of 400°C					
Total flowrate	Nm ³ /h	7106	5466	3826	2186
Flowrate of coke gas	Nm ³ /h	6040	4646	3252	1858
Flowrate of TPC fuel	Nm ³ /h	1066	820	574	328
Savings in use of coke gas (hourly, daily and monthly)	Nm ³ /h	460	354	248	141
	Nm ³ /24h	11034	8488	5941	3395
	Nm ³ /m	331021	254632	178242	101853
	EUR/m	21826	16789	11752	6716

Fig. 6 Monthly financial savings in EUR for two steel sheets production output: **a** 20, **b** 80 Mg/h **Fig. 7** Conception of the integrated system that consisted of a metallurgical furnace and the torrefaction/pyrolysis system**Table 7** Annual savings obtained from implementation of the proposed technology to the pusher furnace in the steel works

		Material production (Mg/h)	
		20	80
Annual savings in coke gas demand	Nm ³ /year	1,220,000	3,970,000
Annual savings in coke gas purchase	EUR/year	80,600	262,000
Annual energy savings	GJ/year	21,600	70,300
Annual CO ₂ emission reduction	Mg/year	993	3,230
Annual savings in CO ₂ tax	EUR/year	39,700	129,000
Potential annual savings in natural gas equivalent	Nm ³ /year	618,000	2,000,000

Practical application and future research prospects

The proposed technology can be implemented into practice as additional measure regarding waste heat utilization, which can result in both fuel savings and CO₂ emission reduction and finally increase financial profit for a company. It requires that the temperature of the waste heat should not be lower than 350 °C. Therefore, the best idea of practical implementation of this technology is integrating it with a flue gas outlet system in steel manufacturing process. Hence, steel works can primarily benefit from this solution. Future research works will be focused on design and construction of both a mill and an auger-type reactor that can work with plastic waste as a feedstock.

Conclusions

Presented technology integrates a pusher furnace heat recovery units with the system for biomass/waste biomass torrefaction/pyrolysis process. As a result, several benefits can be achieved as follows: utilization of waste biomass, increase in overall efficiency of the furnace, reduction of fossil fuel-based CO₂ emission into natural environment and improvement in economic balance of the furnace. The annual energy payback of the specific furnace was approximately of 2.5% referred to total energy consumed by the furnace. The economic analysis shows that the use of TPC fuel in the co-combustion process with coke gas in this furnace is a profitable undertaking. The proposed technology uses waste biomass as energy source. Hence, its usage as feedstock to the torrefaction/pyrolysis reactor integrated with the pusher furnace is promising idea for future. As calculated, with annual steel sheets production of 500,000 Mg, savings in energy can amount to approximately 80,000 EUR and savings referred to CO₂ reduction can reach 120,000 EUR. Summing up, the proposed technology can remarkably contribute to reduction in energy consumption by a metallurgical pusher furnace and bring financial benefits to a steel manufacturer.

Authors' contributions SS contributed to methodology and conception, MZ was involved in conception and data processing, MS prepared the draft and analyzed the data, and AM performed experimental tests and economic data analysis.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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