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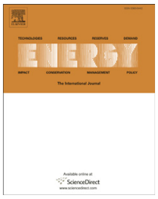

Prospective environmental and techno-economic assessment of steam production by means of heat pipes in the steel industry

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ABSTRACT

Many high-temperature processes in the steel industry discharge waste heat directly into the atmosphere without recovery of the dissipated energy. Additionally, the industry has been compelled to reduce its fossil energy consumption through increasing reductions in carbon emission caps. Accordingly, the development of new technologies, or new uses of the existing ones, for the exploitation of waste heat is of considerable importance. This study analysed the feasibility of using heat pipe technology for a novel use; the generation of steam by taking advantage of the energy contained in combustion fumes from reheating furnaces. To the best of our knowledge, the present study is the first to explore the technical viability of this technology under laboratory conditions, reaching efficiencies between 39.7% and 62.7%. The laboratory results were extrapolated to the conditions of a real steel plant, and it was estimated that 65% of its steam needs could be covered using heat pipes, leading to substantial savings in steam purchase and carbon taxes that ensure the economic viability of this technology. The environmental viability was confirmed through a comparative life cycle analysis. Notable reductions in environmental impacts were achieved, including a 97% reduction in CO2 emissions.

1. Introduction

The excessive emission of greenhouse gases (GHG) is presently a major concern in society, with the presence of CO_2 in industrial exhaust fumes being one of the greatest contributors to the environmental consequences of these discharges, most notably climate change. In particular, the iron and steel (I&S) industry accounts for about 4% of the anthropogenic CO_2 emissions globally, while the manufacturing industry accounts for about 23% [1].

The roadmap for moving to a competitive low-carbon economy, published by the European Commission in 2011, has been defined as the target for the steel industry, meaning the reduction of GHG emissions by 80%–95% of 1990 levels by 2050 [2]. Regardless of whether it is realistic to achieve these objectives, the steelmaking sector will require both technical and financial breakthroughs in technology to ensure the sustainability of their processes and products.

Significantly reducing GHG emissions to the atmosphere by the I&S industry not only entails a global benefit owing to the mitigation of climate change and its consequences (temperature and sea level rise) but is also advantageous from an economic point of view. Due to the carbon taxes imposed on these manufacturers, the decrease in CO_2 discharge to the environment promotes a significant enhancement in product competitiveness. The emission allowance trade is becoming a key player in steel manufacturing profitability due to the rapid rise in costs derived from CO_2 emissions in the past few years. Indeed, while in 2017 the average cost was 5,18€/ton carbon dioxide equivalent (CO_2-eq), prices have increased to up to 25€/ton CO_2-eq [3].

Consequently, I&S manufacturing industries are focusing their efforts on updating their processes to produce greener and more competitive products by means of reducing their carbon emissions. In this context, the production process for manufacturing steel is energy-intensive [4], and the energy is mainly obtained from non-renewable sources. The subsequent GHG emissions are a main concern for manufacturers who rely on devising energy-efficient alternatives to the current processes. Currently, the I&S sector accounts for nearly 20% of the world's total industry final energy consumption [4], but the high-temperature processes needed along

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Abbreviations

GHG	Greenhouse gases
CO_2-eq	Carbon dioxide equivalent
I&S	Iron and steel
HPHE	Heat pipe heat exchanger
NG	Natural gas
LD	Linz and Donawitz
WHR	Waste heat recovery
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
ROI	Return on investment
CG	Cogeneration
GWP	Global warming potential

Subscripts

air	Air
g	Saturated steam
$steam$	Steam produced
w	Saturated water

Key Parameters

Cp	Specific heat [kJ/(kg·K)]
Eff	Efficiency [%]
h_g	Enthalpy of the saturated steam [kJ/kg]
h_w	Enthalpy of the saturated water [kJ/kg]
$\dot{m}_{air}$	Mass flow rate of air [kg/s]
$\dot{m}_{steam}$	Mass flow rate of steam [kg/s]
P	Pressure [bar]
P_{sat}	Saturation pressure [bar]
$\dot{Q}_{air}$	Heat transfer from the air [kW]
$\dot{Q}_{steam}$	Heat transfer into saturated steam [kW]
S	Uncertainty
T	Temperature [°C]
T_{sat}	Saturation temperature [°C]
T_r	Reduced Temperature
T_{cr}	Critical temperature
v_g	Specific volume of saturated steam [m^3/kg]

Greek symbols

σ	Standard deviation
Δ	Difference

the production chain result in significant energy losses in hot output flows [5]. For instance, at the hot rolling facilities, the forming process, which ends with the production of steel coils or sheets, preheats the formats at 1200 °C and combustion fumes are directly released through the stack without utilising the residual heat [6].

To exploit the thermal potential of these exhaust fumes, waste heat recovery (WHR) has become an interesting strategy in the I&S industry, as described in previous studies [4–9]. Most heat recuperation systems are based on conventional systems, such as heat exchangers, recuperators, and regenerators, and their purpose is mainly to preheat the combustion air of the reheating furnace. Major limitations are encountered when these systems must function at very high temperatures or in adverse conditions with dirty flue gases [4,10,11]. Moreover, acid corrosion at low temperatures of flue gases because of the presence of H_2S or CO and the associated maintenance efforts hinder energy recovery [10].

Further, even when the sensible heat of the fumes is recovered to preheat streams, there remains an important waste heat potential in the I&S industry.

Accordingly, a technology called *heat pipes* has emerged as an attractive method for dirty gas-harnessing applications. A *heat pipe* is a passive heat exchanger that has the appearance of a common plate-finned water coil except that the tubes are not interconnected, and it is filled with a small amount of working fluid (usually water, methanol, or ammonium) that is selected based on the range of working temperatures.

The *heat pipe* is composed of three sections: the evaporator at one end, where heat is absorbed and fluid is vaporised; a condenser at the other end, where the vapour is condensed and heat is rejected; and between both of these there is an adiabatic section, where the vapour phase of the refrigerant flows in the core and liquid phase circulates in the opposite direction through the wick. The return to the evaporator of the liquid working fluid is achieved through a wick structure by capillarity such that the *heat pipe* can work in any position [12].

Heat pipes are classified into one of three types: *conventional heat pipes*, such as those previously described; *two-phase closed thermosyphons*, which lack a wick structure and use gravity to transfer the heat from a heat source that is located below the cold sink; and *pulsating heat pipes*, which force the working fluid to oscillate in the axial direction [13].

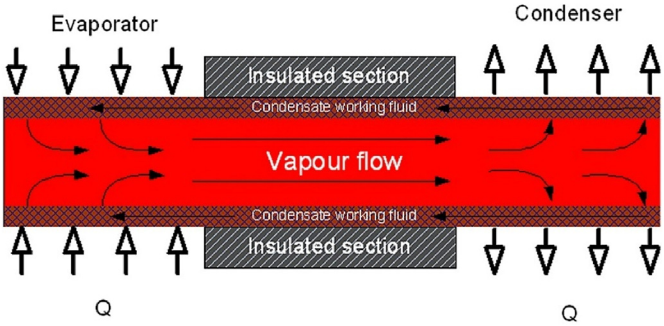


Fig. 1. *Heat pipe* working cycle [12].

Heat pipes provide the following major advantages: 1) high heat transfer efficiency (60–70%); 2) no need for additional power requirements, thus lowering the running cost; 3) higher safety standards due to the non-existence of cross-contamination between waste gas and the hot stream; 4) high corrosion resistance; 5) easy maintenance as damaged pipes can be replaced individually; and 6) ability to recover heat from gas or liquid sources [14].

Due to their convenience, these devices have been used for both commercial and industrial applications to reduce primary energy consumption. Recent developments have been made in several manufacturing fields to introduce these technologies to production processes. For instance, these devices have been proposed for inclusion in ceramic industries, where the firing stage is particularly energy-consuming [15–17]. Moreover, it has been claimed that the *heat pipe* devices can be coupled to an electric generator, thus, the recovered energy can be stored and transported to the suitable sinks [19]. This way, the geographical mismatches between supply and demand may be overcome. Additionally, *heat pipes* have been tested for other different uses, such as distilled water production in combination with solar still [20].

In the I&S industry, the use of *heat pipe heat exchangers* (HPHEs) for heat recovery has also been reported. Water-water HPHE has been proposed to exploit the dissipated energy in the slag cooling process and the optimal operation conditions were previously investigated [22]. However, limited studies have investigated the application of air-water or air-air HPHE. Nonetheless, this technology has been used for years in the I&S industry in combustion air and gas preheating systems for hot blast stoves to recover the waste heat from their fumes (preheating temperature of about 200−250 °C) [23]. Table 1 summarises several studies on HPHE that included empirical efficiency values.

One of the possible applications of the recovered energy by HPHE could be the production of steam. Steam is a crucial energy carrier in the industrial sector as it allows the storing and transmitting of heat that is useable for industrial purposes. Currently, the consumption of steam accounts for around 10% of the total energy use in the I&S industry [26]. In I&S plants, steam is produced through one of three methods: offsite steam that is transferred into plants, steam generated using combined heat and power, and steam generated using conventional boilers [27]. Steam production by means of WHR systems has been achieved so far by waste heat boilers from medium-to-high temperature sources and heat recovery steam generators from high temperature sources [28]. Although they are simple systems, WHR boilers are designed for a process purpose, which is reducing the temperature of the off-gases. The quality of the steam is secondary. In contrast, steam generators are designed to obtain high quality steam, but it is a complex system that requires additional equipment requiring extra space and investment. There is no possibility of producing steam of the required quality with simple equipment.

Nonetheless, some efforts have been made to achieve the production of steam by steel gas combustion in cogeneration (CG) plants. However, self-sufficiency has not been achieved yet, and there is still a substantial need for an extra supply of energy that usually comes from natural gas (NG) with subsequent CO_2 emissions [29,30]. WHR techniques have thus arisen as feasible alternatives to avoid the consumption of fossil fuels for steam production. In this context, the possibility for producing steam by the exploitation of the waste heat from blast furnace slags, Linz and Donawitz (LD) converter slags, electric furnace slags, and LD gas has been investigated [31]. Another study also analysed the intermittent exhaust gas recovery of an electric arc furnace [32].

Although several WHR systems have been proposed for steam production in steelmaking facilities, the production through HPHE has not yet been investigated in any domain. As shown in Table 1, all previous studies only address the heating of water, except one study [16] that was dedicated to gas-gas exchange. Therefore, considering the benefits entailed by HPHE when recovering residual heat and the necessity for steam production in the I&S industry, this is a promising field. Moreover, this de-centralised clean method of steam production could be integrated with other heat-intensive industries or for different uses, such as a part of integrated clean hydrogen production systems providing feedstock for electrolysis processes. This means of energy production is of growing interest, as stated previously [33,34].

The present study aimed to assess the viability of the production of steam from a waste heat source by means of *heat pipes* in the steel manufacturing process from a technical, environmental, and economic point of view. In this latter regard, careful attention was paid to the economic implications regarding CO_2 emissions due to carbon tax. Since emissions play a crucial role in the viability of these technologies, the evaluation of this aspect when introducing the technology is key. This can be done by means of life cycle assessment (LCA), which has emerged as the reference tool for the evaluation of the environmental implications of products, services, or processes. LCA includes the environmental evaluation of the entire life cycle of a product from the extraction of resources, production, use, and recycling to the disposal of waste, including a record of all the inputs and outputs derived from it [35]. LCA can also be used to quantify direct and indirect energy consumed in a particular system [36], supporting policy management and technology investment decisions [37].

In the current context, LCA has already been used in several studies to test energy recovery systems [38−42], but to the best of our knowledge, this method has never been used for *heat pipes*. Therefore, the most important contributions that were expected to be achieved with this study were the demonstration of the application of HPHE for gas-to-liquid exchanges to produce steam capable of being used in industrial processes as well as the first LCA of this technology.

As this was a prospective analysis, this study is organised as follows: first, the conditions of reheating furnace fumes from a steel manufacturing process were replicated at a laboratory scale and a prototype of HPHE was installed to assess its capacity to produce steam in laboratory conditions. Then, the obtained results from the experiments were extrapolated to real production conditions at an industrial scale, and a full LCA was performed to precisely quantify the achievable savings in CO_2-eq emissions. Finally, the economic implications of the *heat pipe* for steam production installation in a real environment were evaluated, with special attention to the role of carbon taxes (see Fig. 1).

2. Materials & methods

2.1. Fume characterisation

In order to provide input data for the design of the HPHE, the characterisation of fumes from three reheating furnaces that released their exhaust fumes through two stacks was performed (TORW and TORE). Owing to confidentiality issues, the name of the facility is not disclosed. The variability of the temperature of the fumes was studied over a representative period and the

Table 1
Summary of studies on HPHE.

Source	Application	Range of heat source temperatures	Heat source	Heat sink	Heat exchanger type	Max. efficiency	Max. heat recovery
[24]	Study of effectiveness	Low (<100 °C)	Water	Water	Liquid-to-liquid	66%	
[16]	WHR in ceramics kiln	Medium (200 °C)	Flue gas	Air	Gas-to-gas	–	99.5 kW
[25]	Performance of an air-to-water HPHE	Low (100 °C)	Hot air	Water	Gas-to-water	65%	
[17]	WHR from a lab-scale ceramic kiln	Medium (<270 °C)	Exhaust gases	Water	Gas-to-water		63 kW
[20]	Preheating water for a solar panel from the exhaust of an indirect gas heater	Low (<100 °C)	Gas	Water	Gas-to-water	48%	
[22]	Iron and Steel heat recovery from slag cooling	Low (80 °C)	Water	Water	Water-to-water	66.1%	

temperature of the fumes released at the stack after the air preheater was between 300 and 500 °C (Fig. 2) with mean values of 383 °C and 359 °C.

The main fume properties for TORW that informed the setting of the experimental bench are shown in Table 2.

2.2. Heat pipe prototype description

The basis for the prospective assessment was a prototype installed in Asturias, located in the north of Spain. This equipment was designed to reflect the fumes featured in Table 2. HPHE performance is highly dependent on device geometry, fabrication materials, and the selected working fluid [43]. Therefore, a computational fluid dynamics analysis was performed before prototype fabrication for design optimisation, although details about the simulation are out of the scope of this article. The main HPHE design parameters are shown in Table 3 and these are extended on in the supplementary materials.

A general overview of the prototype is shown in Fig. 3. It mainly consisted of the following three modules: 1) A **hot air generator** module that supplied an air stream that simulated the combustion fumes (Fig. 4). This module was equipped with a fan with variable frequency drive and a heater with control for the regulation of the outlet temperature. The equipment was able to cover the complete range of temperatures of fumes at the stack (300 °C–500 °C), allowing to supply of a maximum air flow of 500 Nm^3/h at 100 mbar. 2) The **HPHE** system was made up of 12 stainless steel *heat pipes* of the thermosyphon configuration (Fig. 5a). 3) A **water tank** on top of the HPHE with a 12.5 L capacity was used (Fig. 5b). Water entered the system at 20 °C by means of a pump. It included a pressure control valve located inside the water tank, which allowed opening when the set pressure was reached (6 bar (g)). It also included a level meter, manometer, thermometer, pressure switch, and vortex flow meter to measure the saturated steam.

The equipment design did not allow the continuous injection of water. Consequently, when the pressure inside the tank reached 6 bar (g), the pressure valve opened and was regulated to maintain a constant flow rate of steam output until the pressure dropped up to 2 bar (g) when closed. Afterwards, it allowed an increase back to the target pressure. Although the steam generation could not be done continuously, carrying out the tests in this way allowed the measurement of the performance of the equipment. Table 4 shows the bench trial designed to test the industrial conditions.

The data acquisition system worked online and extracted the following parameters: Time elapsed until the system reached 6 bars of pressure; Time and quality of the steam produced; Temperature evolution of the outlet fumes and evolution of the recovered energy.

2.3. Thermodynamic analysis

As the equipment worked on a batch regime, an extrapolation considering whether the HPHE was in continuous operation was performed to obtain equipment efficiency. The efficiency was calculated for each reading (every 0.5 s) from the instantaneous power of the fumes and generated steam. The final result was set as the arithmetic mean. Calculations were performed according to those of a previous study [44] as follows: Thermocouples were placed at the outlet of the furnace and at the chimney of the fumes to measure the energy recovered by the *heat pipes*, and the following Equation (1) was applied:

$$\dot{Q}_{air} = \dot{m}_{air} \cdot Cp \cdot \Delta T \qquad \text{Equation 1}$$

where Cp is the calorific value of the air (1.012 kJ/kg·K) and ΔT is the difference in temperature between the inlet and outlet fumes.

In contrast, the pressure and flow rate of the saturated steam were measured such that other thermodynamic properties could be calculated to finally obtain the energy recovered. The temperature of the steam was not measured, so, to calculate the saturation temperature, Equation (2) was used, which depends on the saturation pressure (P_{sat}):

$$T_{sat} = \frac{234.04 \cdot (\ln P_{sat} - \ln 0.61091)}{17.625 - \ln P_{sat} - \ln 0.61094} \qquad \text{Equation 2}$$

The specific volume (v_g) was used to calculate the mass flow of the saturated steam. It was calculated with Equation (3), which depends on the reduced temperature (T_r), which is defined as T/Tcr (Tcr is the critical temperature 647.096 K).

$$\ln v_g = -7.75883 + 3.23753(\ln 1/T_r)^{0.4} + \frac{2.05755}{T_r^2} - \frac{0.06052}{T_r^3} + \frac{0.00529}{T_r^5} \qquad \text{Equation 3}$$

Finally, the energy recovered into the saturated steam was calculated using Equation (4):

$$\dot{Q}_{steam} = \dot{m}_{steam} \cdot (h_g - h_W) \qquad \text{Equation 4}$$

Where h_W is the enthalpy of the inlet water and h_g is steam enthalpy, which was calculated using Equation (5), as follows:

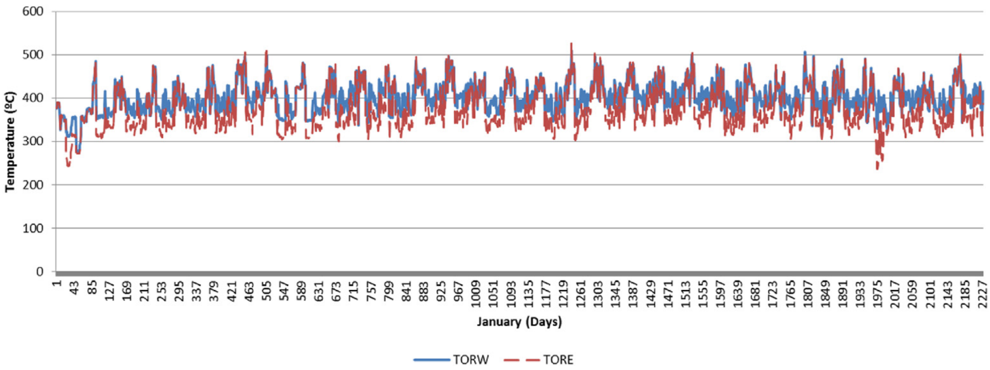


Fig. 2. Stack fume temperatures.

Table 2
Fume characterisation.

Mean T (°C)	Maximum T (°C)	Minimum T (°C)	Σ	Cp (kJ/kg K)	Flow (Nm^3/h)	Pressure (bar)
383.186	466.375	96.000	107.98	1.24	70,000	1

$$\ln h_g = \sqrt{64.87678 + 11.76476(\ln 1/T_r)^{0.35} - \frac{11.94431}{T_r^2} + \frac{6.29015}{T_r^3} - \frac{0.99893}{T_r^4}} \qquad \text{Equation 5}$$

2.4. Environmental analysis

The potential environmental benefits of the inclusion of this technology were tested using LCA. LCA was performed according to ISO 14040——2006 [45], taking into consideration the following stages: (1) goal and scope definition; (2) life cycle inventory (LCI) analysis; (3) life cycle impact assessment (LCIA); and finally, life cycle interpretation.

In the LCIA phase, all environmental loads associated with the production, use (under industrial conditions), and disposal of the equipment were quantified. To this end, environmental impacts were characterised using the impact analysis methodology ReCiPe [46]. This method provided impact indicators at two levels, midpoint and endpoint, through the quantitative modelling of environmental cause-effect mechanisms. Midpoints are quantifiable impacts that are distributed across 17 impact categories: particulate matter formation, ozone formation (human health), ionising radiation, stratospheric ozone depletion, human toxicity (cancer), human toxicity (non-cancer), global warming potential (GWP), water use, freshwater ecotoxicity, freshwater eutrophication, ozone formation (terrestrial ecosystems), terrestrial ecotoxicity, terrestrial acidification, land use, marine ecotoxicity, mineral resource depletion, and fossil energy consumption, which cover most of the environmental impacts that concern society. Midpoints quantify the effect on these categories and allow the emissions that influence them to be traced, although their interpretation is not easy [47]. Carbon footprint evaluation was performed through the ReCiPe midpoint indicator GWP. In contrast, endpoint indicators identify and define the damage caused so their interpretation is simpler, although with a greater degree of uncertainty. The ReCiPe method includes three endpoint impact categories: human health damage, ecosystem damage, and resource depletion. These three categories can also be integrated to render a single final score (single score endpoint ReCiPe).

This method has been selected because it integrates and harmonises the midpoint and endpoint impact indicators. In addition, it ensures that the different impacts are not assessed more than once in different indicators, thus, ReCiPe scores are extensively

Table 3
Main prototype's design parameters.

Number tubes (longitudinal x transversal)	6 × 2
Effective length of tubes (m)	0.41
length immersed in tubes (m)	0.3

Fig. 4. Hot air generator module.

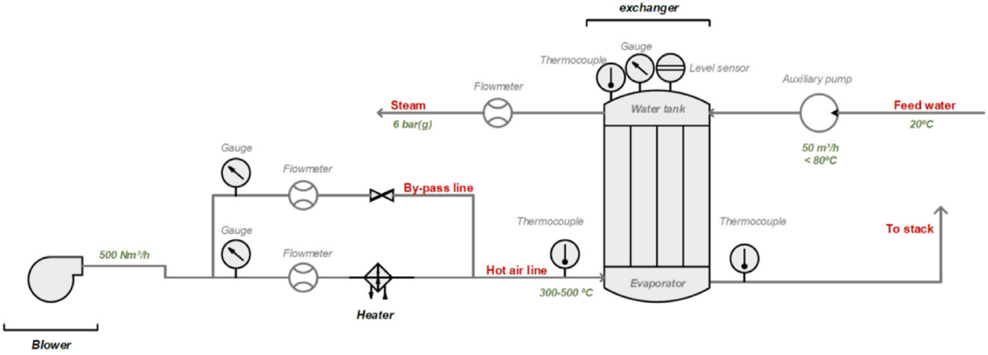
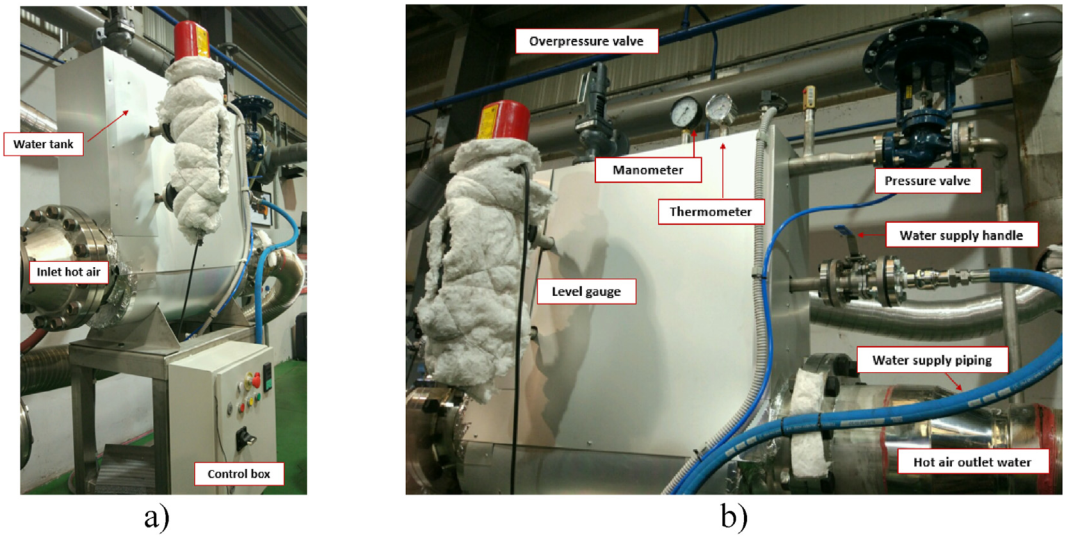


Fig. 3. HPHE prototype configuration.



a) b)

Fig. 5. HPHE and water tank.

Table 4
Bench trial.

	Fume temperature (°C)	Fume flow (Nm^3/h)
Test 1	300	500
Test 2	400	500
Test 3	450	500
Test 4	500	500

used in the LCIAs [48–51]. The assessment was performed using the hierarchist perspective and normalisation values for Europe as the case scenario was located in Spain, and the hierarchist weighting set was applied as it was recommended by the authors.

2.4.1. *Goal and scope definition*

This study intended to assess the environmental benefits of producing steam by means of the WHR technology *heat pipes*. To calculate such benefits, the current means of production for the steam consumed in an undisclosed step of the steel manufacturing process were evaluated. Furthermore, the generation of steam in the same facility was simulated to be performed by a hypothetical HPHE designed to recover waste heat from reheating the combustion fumes of the furnace. The environmental profile of this steam production route was calculated. The difference between them represents the environmental benefit of the inclusion of the novel technology.

The chosen functional unit was 1 MWh of thermal energy used by the steel plant in the form of steam. This functional unit has been used in several LCAs performed for energy systems assessments [30,52–54].

2.4.1.1. Scenario descriptions. The chosen facility was part of the only integrated route steel plant in Spain, including all the facilities starting from ore charging to ironmaking and coke-making, and this facility produces more than 5 million tons of steel per year.

The reference facility obtained all steam from an external combined CG plant that produced electricity and steam from the energetic valorisation of steel gases. It combined CG technology in a simple cycle, with engines specially adapted for operation with a gas converter and steam generation in boilers that consumed mainly coke oven gas, LD converter gas, and NG in case of insufficient flow of steel gases. The LCI for the actual steam production means was published previously [30] and is included in the supplementary materials. It was assumed that steam production occurs under average conditions regarding natural and waste gas consumption.

The system boundaries that define the scope of the study are displayed in Fig. 6. In the CG process, together with steam, electricity was produced and considered in the analysis. Since was decided to solve the problem of impact assignment by extending the limits of the system, the generated electricity appears as avoided. Its impacts are particularised for the Spanish energy mix and updated for 2014. The NG consumed was modelled based on the Ecoinvent v3.01 database [55] but particularised in the case of Spain and updated in 2014. This database has been chosen for this study as it is the world's leading LCI database and has been used as a background source of data in many evaluations of renewable and novel energy uses [37,56–58].

The **HPHE scenario** assumes the hypothetical installation of the proposed technology by means of a bypass from the main exhaust pipe of the facility. As it can be seen in Fig. 7, the installation of HPHE would allow the production of a certain amount of steam in a clean way, reducing the demand of the utility from its usual supplier, the CG plant. Between the steel manufacturer and CG plant owner, there is an agreement to help the steel group to manage its environmental loads through the valorisation of steel gases so, regardless of the demand for steam from the steel manufacturer, the CG plant will always use all of the gases that it receives to avoid burning them in torch without use. The HPHE is an addition to the facility that does not change plant production conditions. Therefore, it was assumed that after the start-up of the HPHE, the facilities continued to operate under the same regime, with the only exception being the presence of the new equipment.

For the *HPHE* model, the following aspects were considered:

- Construction of *heat pipes* on an industrial scale
- Amount of steam obtainable from waste heat
- Device layout

The manufacturing of the equipment was modelled from an extrapolation of the design conditions of the prototype tested in the laboratory. Manufacturing was modelled from the materials and energy used. The scaling to industrial size was undertaken from an estimate provided by the designer of the prototype for industrial

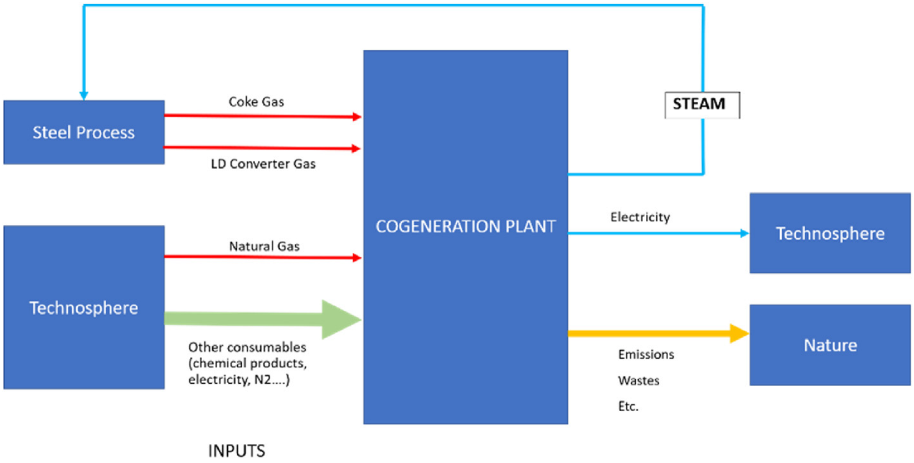


Fig. 6. Steel gas cogeneration process system boundaries. Adapted from Ref. [30].

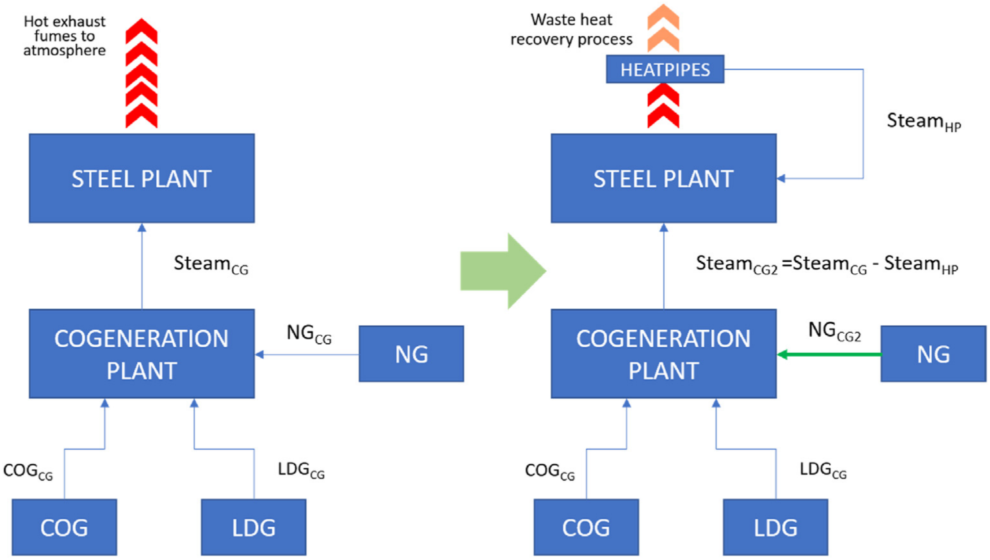


Fig. 7. Scenario descriptions: Current situation vs HPHE inclusion.

fume flow (70,000 Nm^3/h).

The instrumentation of the equipment was not considered due to its low relevance to the total impact calculation. However, the pumping of water was considered and modelled, assuming the use of a 40 W pump with an 80% efficiency, an expectable equipment for such a task. The pump was estimated by engineering calculations to have an average electricity consumption of 38.86 kW/MWh$_{\text{generated steam}}$ (considering a performance equivalent to that obtained empirically).

The disposal of the equipment was not considered as it was entirely made of steel, which is considered 100% recyclable [59]. However, the impacts generated by the physical-chemical treatments for metal recycling were computed.

The amount of steam produced was calculated from the HPHE performance obtained under laboratory conditions. The inventory referring to the functional unit for steam production by HPHE means is shown in the supplementary materials section.

2.4.1.2. System limits. The environmental impacts derived from the construction and operation of a HPHE under industrial conditions were considered. Likewise, environmental loads derived from the production of steam that is currently consumed was accounted for in a previous study [30], which included the construction and operation of the CG plant [30].

The steel process was excluded from the system, neither the use of steam, the production of the energy recovered, nor the production of the steel gases were considered, as these can be considered to be a waste to be valorised, as in a previous study [30].

2.4.1.3. Sensitivity analysis. The performance of HPHE has been empirically evaluated in the laboratory and its efficiency is used to estimate steam production on an industrial scale. However, variations caused by a final design different from the one proposed, reduction of the heat transfer capacity due to fouling, or differences in the temperature of the recovering fumes caused by changes in the production system can lead to performance deviations from the experimental results. For that reason, a sensitivity analysis was performed considering variations in the steam generation rate of ±30%.

3. Results and discussion

3.1. Lab experiments

The proposed prototype allows the investigation of HPHE and its suitability to produce steam by exploiting waste heat from furnace stacks on an intermediate scale before proceeding to a large investment for full-scale implementation. Temperature tests were set between 300 °C and 500 °C according to fume temperatures.

Test 1: For a flue gas temperature of 300 °C, the test was stopped as the increase in temperature and pressure inside the water tank took too long. This was because the system was designed for higher fume temperatures (380 °C) and the evaporation-condensation cycle could not be achieved in continuous mode inside the *heat pipes*.

Test 2: The tank allowed four cycles of steam discharge until the water reached the lowest level allowed in the tank. Table 5 shows the saturated steam flow rate during each discharge (cycle) and its duration along with the heating time of the water inside the tank until the target pressure was reached (see Table 6).

The first interval of water heating was the shortest (85 min), while for the other instances, periods between 100 and 120 min were found (Fig. 8). Given the low warm-up time for the first cycle and the low amount of steam generated in this cycle, it was hypothesised that there was air inside the tank that could enter during the water supply, causing the pressure to rise faster than expected.

The heat transfer value from the fumes to the *heat pipes* obtained was 27 kW, and the recovered heat transformed into saturated steam was 11 kW. Therefore, the obtained efficiency at 400 °C was 39.7%.

Test 3: When fumes were set at 450 °C, the tank also allowed four cycles of steam discharge. In this case, the first cycle of water heating was the longest at 129 min, while the other intervals were maintained at around 50 min (Fig. 9).

The heat transfer value from the fumes to the *heat pipes* was 31 kW, and the recovered heat transformed into the saturated steam was 19 kW. Therefore, the obtained efficiency for 450 °C was 62.7%. Moreover, at 450 °C, the heating was faster, and the amount of steam produced in each discharge was higher.

Test 4: For fumes at 500 °C, the test was stopped due to water leakage and the obtained data were not valid.

Results of analyses of heat transfer rates and efficiency are summarised in Table 7. Such results are consistent with those reported previously (Table 1): 66% in Ref. [24], 65% in Ref. [25], 48% in Ref. [20] and 66.1% in Ref. [22]. It is important to highlight that all the previous results were obtained from low temperature heat sources, always below 270 °C, and that all were limited to heating water without reaching the vapour phase, while our results produced ready to use steam, which is more interesting for industrial processes.

Contrastingly, the efficiencies of the heat recovery steam generator, another technology of steam production from a WH source, were higher than those achieved by the HPHE (75–85% according to a previous study [60]). However, this technology requires several components to work and requires a further burner to enhance the standard of the recovered waste heat. Moreover, the system is extremely voluminous and requires on-site construction [28].

Table 5
Test 2 results.

Cycle	Heating time (min)	Discharging time (min)	Mass flow (kg/h)
1	85	2.6	13.4
2	121	2.3	21.3
3	100	2.3	22.4
4	121	2.4	15.7

Table 6
Test 3 results.

Cycle	Heating time (min)	Discharging time (min)	Mass flow (kg/h)
1	129	2.3	23.0
2	54	2.1	32.6
3	48	1.8	42.7
4	47	1.7	30.5

Therefore, the main advantage of this study was the successful application of HPHE in gas-to-liquid exchange applications as well as to produce steam with good results of up to 62.7% efficiency.

The HPHE performance increases with fume temperature as efficiency is markedly higher at 450 °C than at 400 °C. This effect was also reported in previous studies [24,61]. However, care must be taken during HPHE design to ensure the alignment of its optimal temperature ranges for both the external material and internal fluid, with the most likely temperature that the fumes will have. Even though HPHE efficiency would benefit from exposure to higher fume temperatures, it could result in serious damage to the equipment. Industrial conditions entail high variability in fume temperature, but damage could be prevented by the incorporation of air dilution systems.

Both Figs. 8 and 9 show that the obtained steam grades were low, and this limits the potential uses of the steam. The usual configuration to the I&S sites entails steam networks at different levels of pressure, generally with a high pressure one (about 20–25 bar) to cover the steel shop needs, and another at a lower pressure for other applications, mainly heating. In this case the trials were performed with the target of producing steam at 6 bars (g), corresponding to the low-pressure network. Some studies [27] have already warned about the difficulty on the utilisation of waste heat steam in the I&S industry due to the formation of droplets or moisture if heat loss occurs during transportation. This effect would cause further reduction in steam pressure, downgrading its quality. Therefore, the produced steam should be restricted to use in the same facility or nearby ones.

Finally, from Figs. 8 and 9 it can be seen that water evaporation takes some time and pressure decreases with time. This is due to equipment design and imposition to produce the steam discontinuously. In contrast, the obtained recovered energy (39.7% under design conditions) might seem lower than the delivered energy from the fumes. However, a previous study [62] stated that from the numerical analysis of an intermittent exhaust gas recovery of an electric furnace used in another study [32], only up to 24% of energy existing in the off-gas could be recovered to generate process steam, a notably lower efficiency than that obtained in the present study. Moreover, it is likely that these issues could be addressed through the installation of a preheating water system [63]. Therefore, this could assist the reaching of stable steam quality conditions and increasing heat transfer efficiency.

3.2. Environmental and economic assessment

Fig. 10 shows the compared results for the ReCiPe midpoint categories. The steam production through HPHE (av. performance) is shown in dark blue and the results with the current means of production are shown in dark green. Additionally, orange shows the results obtained through HPHE, assuming the maximum expected yield (+30% with respect to the experimental one) and in red colour the minimum expected yield (−30% with respect to the experimental one).

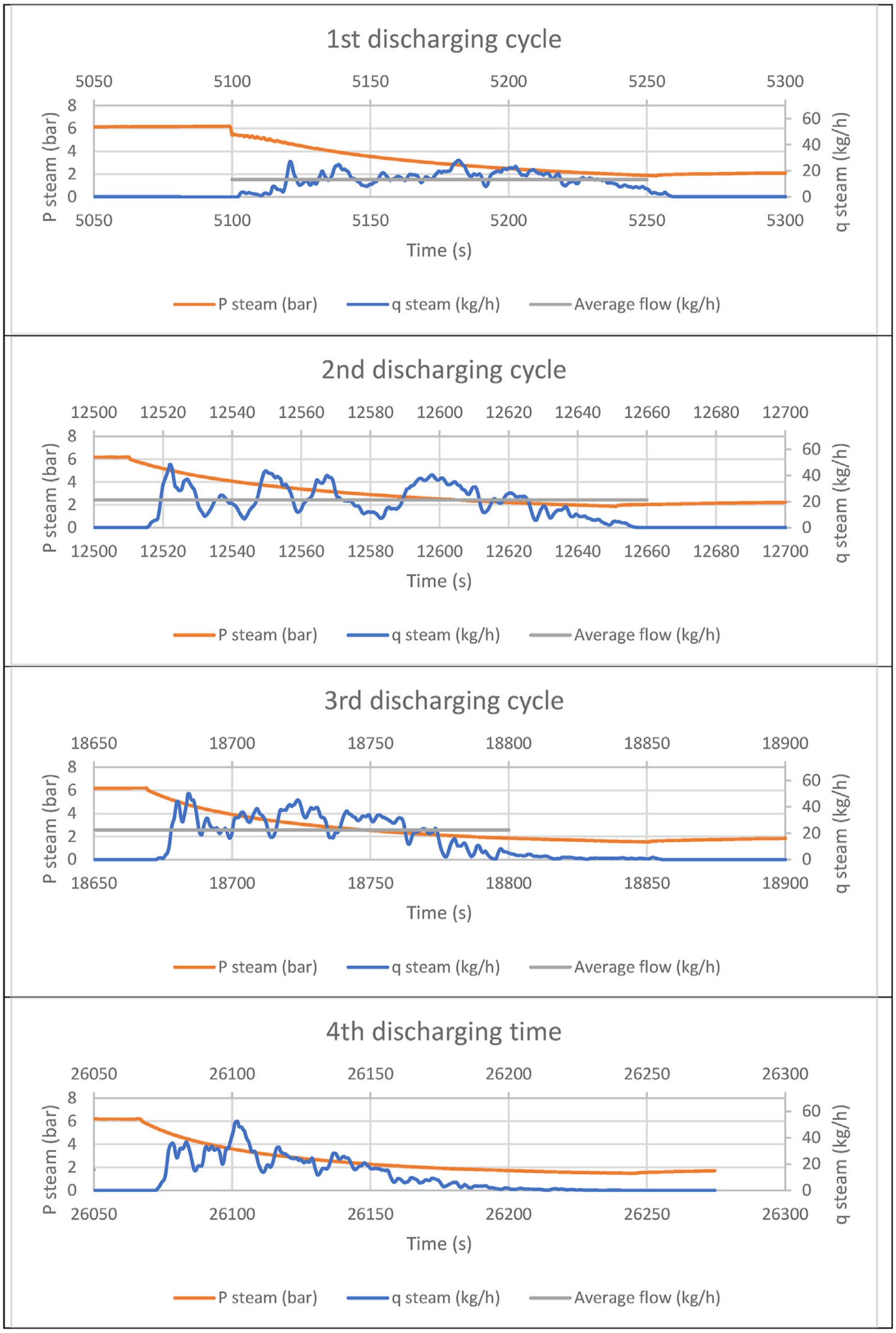


Fig. 8. Saturated steam flow rate obtained for the 400 °C trial.

Steam production with HPHE has lower environmental loads in the categories *Climate Change*, *Terrestrial Acidification*, *Photochemical Oxidant Formation*, and *Particle Matter Formation*. This is mainly due to the avoided emissions caused by the burning of NG over co-generation processes. For the same reasons, the *Fossil Fuel Depletion* category was lower for the HPHE scenario as less NG was required to be burned during co-generation.

The production of steam through *heat pipes* also had a lower impact for the category *Transformation of natural lands* except for the lower limit of equipment efficiency. This is because lower efficiencies to steam production result in higher relative electrical consumption as more water must be pumped for the same functional unit.

In contrast, the use of HPHE carried greater environmental burdens for the categories *Ozone Depletion*, *Freshwater Eutrophication*, *Marine Eutrophication*, *Human Toxicity*, *Freshwater Ecotoxicity*, *Marine Ecotoxicity*, *Ionising Radiation*, *Agricultural Land Occupation*, *Urban Land Occupation*, *Water Depletion*, and *Mineral Resource Depletion*. This is due in all cases to the fact that the co-generation also entails the net production of electricity whose avoided impacts must be discounted according to the Spanish energy mix, and are, therefore, reflected with negative values.

Fig. 11 shows the compared results for the three damage categories: *Human health*, *Ecosystems*, and *Resources*. It can be noticed

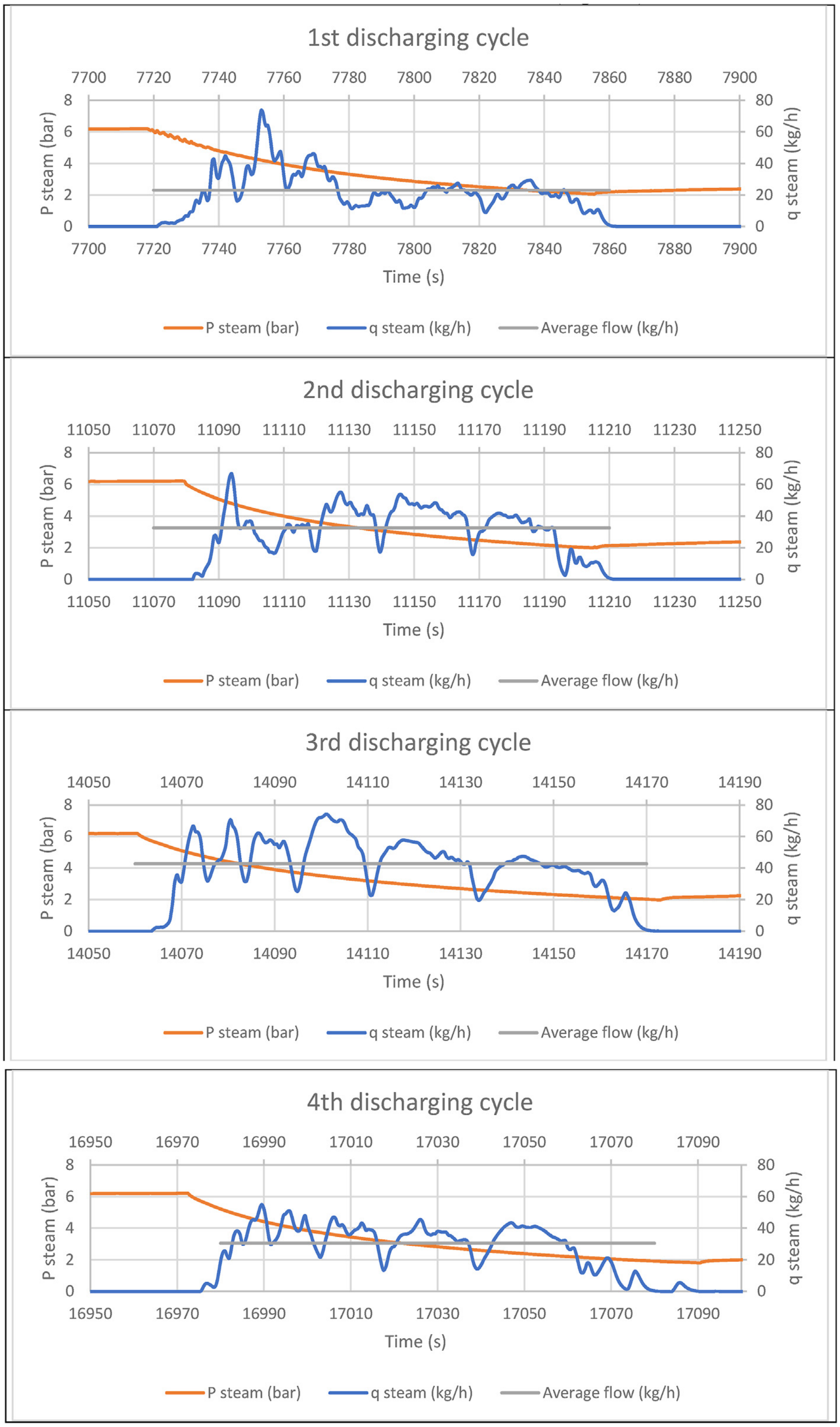


Fig. 9. Saturated steam flow rate obtained for the 450 °C trial.

Table 7
Heat transfer rates and efficiency.

Fume inlet temperature	Fume outlet temperature	Heat transfer value from the fumes	Heat transformed into saturated steam	Efficiency
400 °C	240 °C	27 kW	11 kW	39.7%
450 °C	260 °C	31 kW	19 kW	62.7%

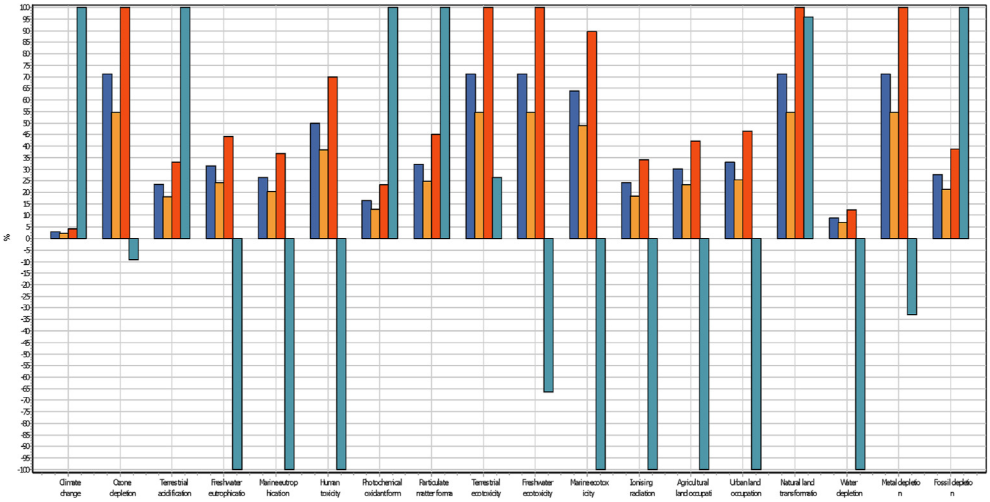


Fig. 10. LCIA results at the midpoint level (ReCiPe H/H).

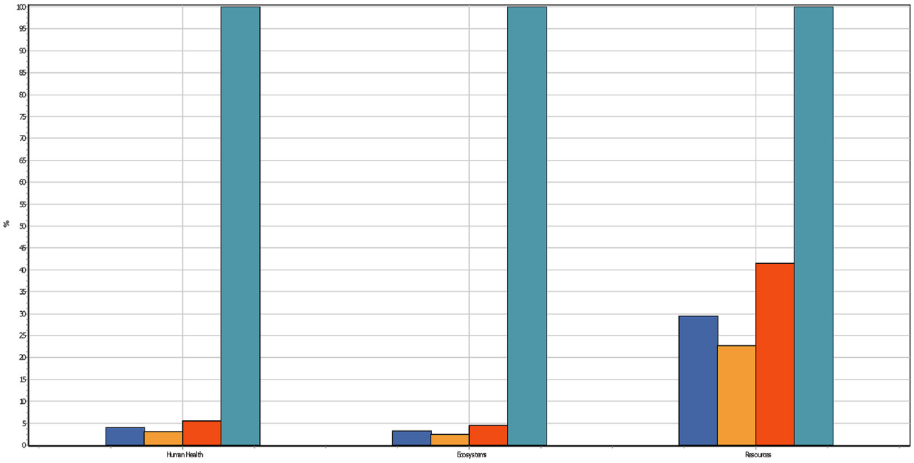


Fig. 11. LCIA results at the *endpoint* level (ReCiPe H/H).

Table 8
Results to single score ReCiPe (H/H.

	Pt. ReCiPe (H/H)	Impact reduction
1 MWh by *current means*	29.56	0%
1 MWh by *heat pipes (average yield)*	1.96	93%
1 MWh by *heat pipes (minimum yield)*	2.76	91%
1 MWh by *heat pipes (maximum yield)*	1.51	95%

that even for the most unfavourable efficiencies (red colour) the production of steam by the current means involves considerably more damage.

The damage categories are integrated to render a single final score (single score endpoint ReCiPe) that is used to ease the decision process. Results in Table 8 show reductions of the total environmental impact of over 90% in all scenarios. Moreover, it is important to mention that the current production regime using CG already represents an environmental improvement from steam boilers fired with NG, the traditional production means, with a worse profile.

Table 9
Carbon Footprint of steam production referring to the functional unit (ReCiPe H/H).

Current situation	674 kg CO_2-eq/MWh
Steam production by heat pipes (average yield)	19.6 kg CO_2-eq/MWh
Steam production by heat pipes (maximum yield)	15.0 kg CO_2-eq/MWh
Steam production by heat pipes (minimum yield)	27.5 kg CO_2-eq/MWh

Focusing on the GWP, Table 9 shows how the GWP of steam production by the *heat pipes* was markedly lower, representing on average only 3% of the current emissions profile.

Calculations with the average yield show that designed *heat pipes* would be able to provide 65% of the steam requirements of the industrial plant that would lead to reductions of about 335 ton CO_2-eq/month.

Contrarily, as stated in the Introduction, carbon taxes entail a markedly increasing share of steel production costs, and their reduction is key to ensuring its viability. Therefore, it is highly important to include proper quantification in the economic viability appraisal of this technology. Examples showing the inclusion of avoided CO2 and energy use in the evaluation of WHR novel technologies can be checked in previous studies [16,64].

Fig. 12 shows the annual return on investment (ROI) for average values of steam production yield-average steam purchase cost (ROI Av_Av), minimum values (ROI Min_Min), and maximum values (ROI Max_Max) and refer to the cost of CO_2 emissions. ROI was

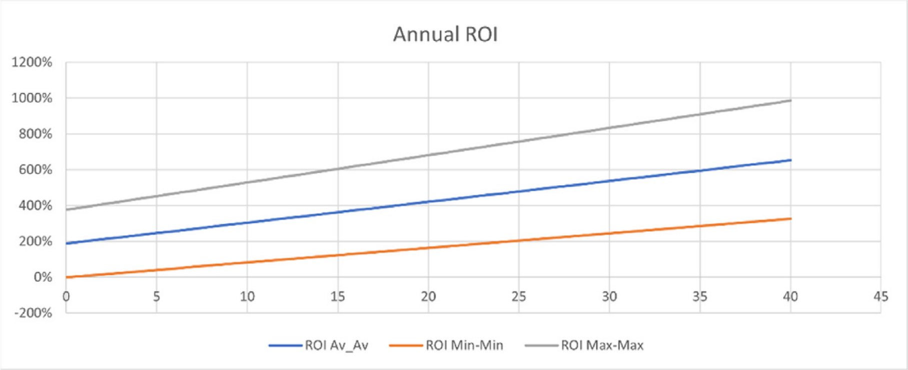


Fig. 12. Annual return on investment referring to carbon tax prices.

calculated according to the following formula:

ROI = Net ROI/Cost of investment × 100%

Where the cost of investment considers equipment manufacturing and installation costs (prorated considering a 10-year life expectancy period), cost of electricity for pumping, and annual maintenance. Likewise, the net return investment considers the avoided cost of purchased steam (average purchasing price) and avoided cost due to CO2 emissions.

Annual ROI is positive for all scenarios but the most unfavourable case, when the carbon price is set to 0 combined with the lowest steam production yield and the lowest steam purchasing cost, shows an ROI of −0.03%. As expected, the higher the cost of carbon tax, the higher the ROI due to the avoided emissions. In early 2020, the CO_2 European Emission allowances reached 25.15€ [65], https://markets.businessinsider.com/commodities/co2-european-emission-allowancesresulting in an ROI of 204% for the most unfavourable scenario and 758% for the most favourable one, proving the financial viability of the installation of HPHE for steam production in the I&S sector. Fig. 13 shows that the cost distribution was dominated by the avoided steam purchase while avoided carbon tax represented 29% of the costs in absolute value (taking a reference value of 25.15€/ton of CO_2). This fact enhances the importance of including carbon accounting for the investment evaluation of industrial WHR equipment.

Fig. 12 shows that even for the hypothetical scenario of carbon tax suppression, the financial viability of the technology is practically ensured. However, this event is highly unlikely due to the strong support to the carbon pricing instruments by the EU. In fact, the legislative framework of the EU ETS for the next trading period (phase 4) increases the pace of annual reductions in allowances to 2.2% as of 2021 [65], therefore, it seems likely that carbon prices will continue increasing.

3.3. *Uncertainties associated with the experimental results*

The efficiency of the HPHE was calculated as the ratio between the heat transfer in the steam and that of the air supplied. For the calculation of the heat transfer of the air, it was measured as follows: The flow rate in an orifice plate was the differential of pressure, and the differences were between temperatures of the air before and after the HPHE. For the calculation of the heat transfer in the produced steam, it was measured as follows: The flow rate and pressure of the steam produced. Therefore, uncertainties of the key measuring devices are shown in Table 10.

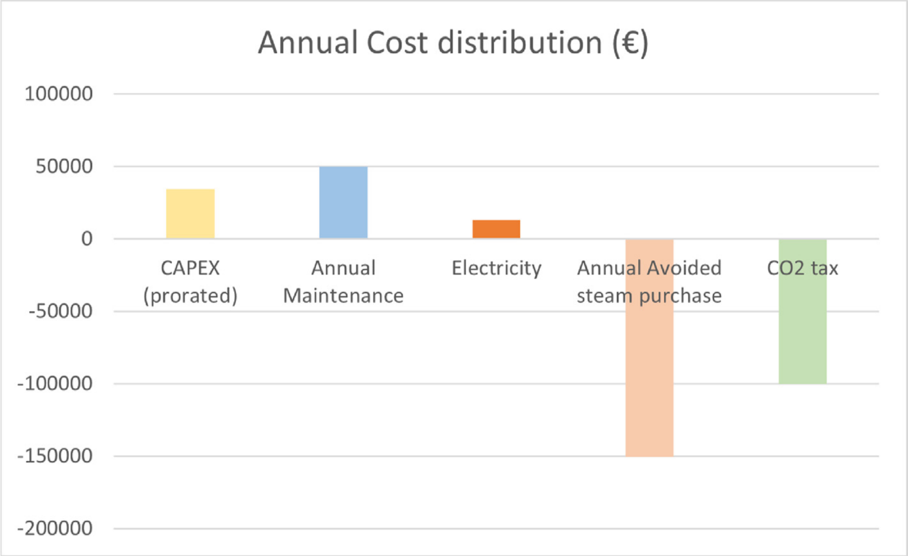


Fig. 13. Distribution of cost for the average values of steam production yield and steam purchase cost. Carbon tax fixed for 25.15€/ton; average values of steam production yield and average steam purchase cost.

Table 10
Measurement uncertainties of the key measuring devices.

	Measuring device	Measurement uncertainty
Temperature measurement (air)	Thermocouple type K	±1.5 °C at 450 °C and ±1.3 °C at 225 °C
Pressure differential transmitter	HK-Instruments DPT-3 Wire	±1.5%
Flow rate measurement (steam)	Vortek Instruments: M22 InLine MultiParameter Vortex Flow Meter	±1% of the rate
Pressure measurement (steam)	WIKA A10	±0.5%

Regarding this information, for the theory of uncertainty [66], the following formulations were applied to obtain the uncertainty of the power and efficiency:

$$S_{\Delta T} = \sqrt{(S_{T,in})^2 + (S_{T,out})^2} \qquad \text{Equation 6}$$

$$S(\dot{Q}_{air}) = \dot{Q}_{air} * \sqrt{\left(\frac{S(dP_{air})}{dP_{air}}\right)^2 + \left(\frac{s(dT)}{dT}\right)^2} \qquad \text{Equation 7}$$

$$S(\dot{Q}_{steam}) = \dot{Q}_{steam} * \sqrt{\left(\frac{S(\dot{m}_{steam})}{\dot{m}_{steam}}\right)^2 + \left(\frac{s(P_{steam})}{P_{steam}}\right)^2} \qquad \text{Equation 8}$$

$$S(Eff) = Eff * \sqrt{\left(\frac{S(\dot{Q}_{air})}{\dot{Q}_{air}}\right)^2 + \left(\frac{s(\dot{Q}_{steam})}{\dot{Q}_{steam}}\right)^2} \qquad \text{Equation 9}$$

Finally, the uncertainties are shown in Table 11.

Absolute maximum error 400°CAbsolute maximum error 450 °C.

4. Conclusions

In the course of this research, *heat pipes* were successfully applied for gas-to-liquid exchange to produce useable steam for industrial processes. Moreover, this study showed that the production of steam from a waste heat source by means of *heat pipes* into the steel manufacturing process is a clean technology that is also technically and economically viable.

This technology was tested in the laboratory by simulating the conditions of the off-gas from the reheating furnaces of a step of the steelmaking process, obtaining efficiencies up to 62.7%. When the results were extrapolated to the conditions of a real plant, it was found that up to 65% of its demand could be covered, notably reducing the need to purchase it from external suppliers or production in boilers.

Additionally, a prospective LCA, the first one for *heat pipe* technology, was carried out, reflecting the conditions on an industrial scale. The environmental advantages of the inclusion of the said technology were demonstrated, mainly due to the savings in burning NG to generate the steam necessary for the production process. Notably, this production route was compared against conditions of CG with waste steel gases, a system with a significantly lower environmental load than traditional steam boilers, obtaining reductions of more than 90% of the impact generated during their production. This aspect is intensified when the focus is placed on greenhouse gas emissions, since production using *heat pipes* reduces these emissions by 97%.

Table 11
Experimental uncertainties.

$\boldsymbol{S(\dot{Q}_{air})}$	kW	±0.55	±0.49
$\boldsymbol{S(\dot{Q}_{steam})}$	kW	±0.22	±0.31
$\boldsymbol{S(Eff)}$	%	±1.3%	±2.1%

Finally, an economic analysis of the investment showed that even without considering the effect of savings on carbon tax, the technology is economically viable owing to savings in the purchase of steam. This point is strengthened when the costs saved by the avoided taxes on GHG emissions are considered, such as the CO_2 European Emission allowances, representing about 29% of the costs in the absolute value of their inclusion with the starting prices of 2020. Therefore, the inclusion of carbon accounting within the feasibility studies of this type of technology is essential.

Credit author statement

Rocío Llera: Conceptualization; Investigation; Writing - Original Draft, **Miguel Vigil**: Conceptualization; Investigation; Methodology; Supervision; Writing - Original Draft, **Sara Díaz-Díaz**: Conceptualization; Investigation, **Gemma Marta Martinez-Huerta**: Supervision; Writing - Review & Editing.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2021.122334.

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