BILAGA 8

AP6 Report

Techno-economic analysis of thermal plasma torch application for heating furnaces.

Ilman Nuran Zaini

Weihong Yang

Department of Materials Science and Technology

KTH Royal Institute of Technology

Summary

In this report, a technical evaluation and economic analysis of plasma scenarios for the heating furnaces in the steel industries are carried out. The objectives of the techno-economic analysis is to evaluate the efficiency of different plasma system configurations and operating conditions, as well as to analyze the economic aspect of the process in regard to the other CO_2 mitigation process. The results show that the electric power consumption and price are the main major cost elements of the plasma scenario. A -/+ 25% change in the price of electricity will significantly change the total production cost (by 20%) and the CO_2 avoidance cost (by 70%). It is also estimated that that a decrease in the plasma torch efficiency from 90 to 80% may increase the CO_2 avoidance and total production cost up to 63% and 18%, respectively. Furthermore, compared to the post combustion CO_2 capture process and the hydrogen oxy-combustion, the installation of plasma torches to replace fossil-fuel burners can potentially has a lower total production cost, as well as CO_2 avoidance cost. At the highest value of plasma torch efficiency, the use of plasma torch cause an additional production cost of 62.6 SEK/t-steel. This number corresponds to the CO_2 avoidance cost of 761 SEK/t-CO_2.

Table of content

List of figures

List of tables

1 Introduction

1.1 Background

The electrification of furnaces in the steel industry faces a big challenge as a significant portion of high-temperature heat is required to meet the operational need. These requirements are challenging to comply with conventional electrified heating (e.g., resistance and induction heating). Hence, the use of plasma torches as the route for electrification is gaining interest. The main advantages of plasma torches compared to other alternatives are the high temperature in the plasma jet, the plasma's high energy density, and the possibility of using different plasma gases depending on the desired application. Replacing fossil fuel burners with plasma torches can also lead to lower operating costs and greenhouse gas emissions. Other advantages include controlled process chemistry, small installation sizes and rapid start-up and shutdown features.

In this report, techno-economic analysis of plasma-heated furnaces are carried out. The analysis modeling includes scenarios with a full plasma heating and combinations of plasma heating and gas burners. Furthermore, a simple economic analysis is carried out to compare the cost of operating plasma torches compared to other CO_2 low technologies.

1.2 Overview of the low emission heating technologies

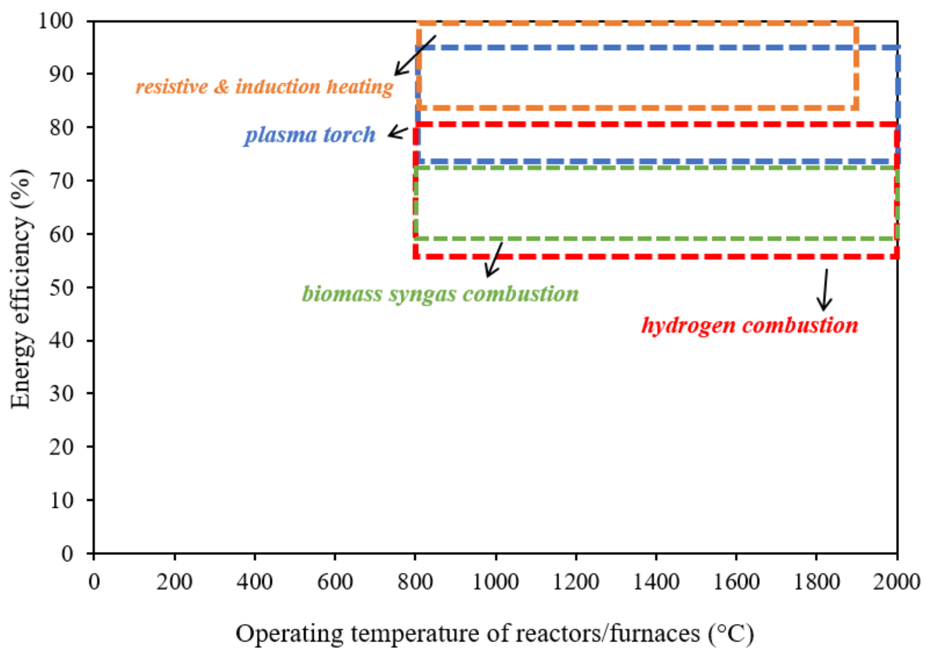


Figure 1. Comparison between different heating technologies.

In general, current research and development of alternatives heating technologies for decarbonization of steel industries mainly focus on the plasma heating, biomass syngas combustion, hydrogen combustion, resistive electrical heating, and induction electrical heating. Figure 1 shows typical energy efficiency and the possible operating temperature for those technologies. The figure is drawn based on the typical values of efficiency and operating temperature of current related technologies. For instance, current efficiency of the thermal plasma torches is in the range 75-95% depends on the type of plasma torch. DC plasma torches typically have a lower efficiency than the AC plasma torches due to the energy loss in the AC-DC rectifier. In the case of biomass syngas and hydrogen combustion, the energy efficiency is relatively low due to the energy loss during the fuel production (i.e., hydrogen electrolyzer and biomass gasification). Furthermore, despite their high energy efficiency, the application of resistive and induction heating to replace existing fossil-fuel burners might requires high capital cost for redesigning the existing furnace. This is different in the case of plasma torches, biomass syngas, and hydrogen burner as they are relatively easier to be installed in an existing furnace without any needs for redesigning the existing furnace. Therefore, in this report, an economical comparison of different heating technologies is presented without considering the resistive and induction heating.

Further lists of advantage and challenges in implementing the aforementioned technologies are presented below.

1.2.1 Plasma torch

Advantages:

- High operating temperatures
- High heating rates
- Flexible process gases.

Challenges:

- Significant amount of energy loss due to plasma cooling.
- Energy loss in the rectifier in the case of DC plasma torch.
- NO_X emission in the presence of air.
- Additional electricity power generation and grid capacity when applied to large scale furnaces.

1.2.2 Hydrogen combustion

Advantages:

- High operating temperatures
- High heating rates

Challenges:

- Relatively low efficiency in terms of the power-to-H_2 production process (56-80% [1]).
- Additional electricity power generation and grid capacity if the electrolyzer would be built on site to supply the H_2 to large scale furnaces.

1.2.3 Biomass-based syngas combustion

Advantages:

- High operating temperatures as syngas's adiabatic flame temperature could be higher than the natural gases.
- Possibility for a combination with existing LPG burner operation for an intermediate energy transition.

Challenges:

- High cost of biomass feedstock.
- Relatively low energy efficiency in term of biomass to syngas production (60-70%).
- Reliable source of biomass for long-term large scale processes.
- CO_2 post processing might be required for a carbon negative processes.

1.2.4 Resistive & induction heating

Advantages:

- No exhaust gases; hence, possibility for inert heating
- High thermal efficiency
- Possibility for local or spot heating
- Compact units

Challenges:

- May require a redesign of the existing furnace in the case of retrofitting.

1.3 Objectives

The objectives of the techno-economic analysis is generally to increase the general understanding of plasma technology in heating processes and propose a cost-effective technical solution. To achieve that goal, the objectives are further specified as follows.

- To evaluate the efficiency of different plasma system configurations and operating conditions.

Analysis of the economic aspect of the process in regard to the other CO_2 mitigation process and insentives.

2 Methods

In general, the work in this work package can be divided into two main parts. The first part is the process simulations of the plasma-based heating furnace system by using the process simulation software package Aspen Plus. Thereafter, in the second part of the work, economic calculations and analysis are carried out based on the results obtained from the process simulation. Figure 2 shows the overview of the scope of the works presented in this report.

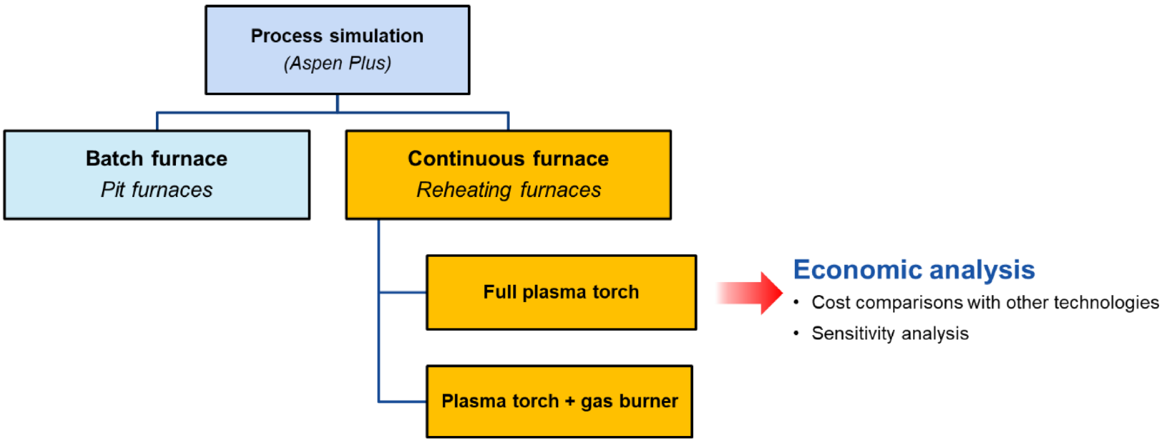


Figure 2. Scope of process simulation and economic analysis works.

2.1 Process modeling and simulation

The process simulation work consist of the simulation of a continuous type furnace and a batch type furnace. For each type of furnace, various possible configuration of plasma torch systems are presented and discussed.

The process simulations are carried out using the Aspen Plus version 9.0 (Aspen Technology, Inc.) process simulation package. The simulations are performed under the following general conditions and assumptions:

- The process is operated under steady-state conditions.
- Gases are treated as ideal gases, and the ambient pressure is 101.325 kPa.
- The property method selected is Peng-Robinson for the all-reactor modules.
- The efficiency of the compressor and pump are 90 and 75%, respectively [2].

2.1.1 Assumption of plasma torch operating conditions

Table 1. Assumptions of the operating condition of the thermal plasma torch.

Operating conditions	Values	Notes
Efficiency of the AC-to-DC rectifier	92.5%	Selected as an average value of typical efficiency of 90–95 %.
Maximum efficiency of the plasma torch	90%	The maximum value is based on the theoretical number suggested by ScanArc.
Total maximum power-to-heat efficiency	83.25%	Sum of rectifier and plasma torch efficiency.
Specific enthalpy of the plasma gas	2–4 kWh/m^3	Represents the working conditions according to ScanArc. During the pilot trials, the plasma torch was operated at an average value of ±3.8 kWh/m^3

In this report, DC plasma torches are selected for the process simulation and economic calculation works. A unit of DC plasma torch system typically consist of an AC-to-DC rectifier to supply DC electric power; a torch; and a tuyere. The operating parameters of the plasma torch used in the simulation were mainly determined based on the results of the previously conducted pilot trials within the PLATIS project. Further recommendations from ScanArc regarding the possible operating conditions for future application of the plasma torches are also considered in the simulation.

Table 1 summarizes those assumptions used in the process simulation.

2.1.2 Continuous furnace

The simulation of the continuous furnace is modeled based on the SSAB Borlange's reheating furnace as can be seen in Figure 3. From the data in Figure 3, scope and assumptions for the operating conditions of the simulated furnace were determined as described in Figure 4. In the process simulation, the new installed plasma torch system is assumed to replace the existing burners at the same heating zone and distribution. Hence, the process model is simplified by assuming that the temperature of the inlet part of the walking beam furnace is equal to 1000 °C (see point "A" in Figure 3). Correspondingly, this approach is implemented in the process simulation by setting the final temperature of the plasma gas at 1000 °C. Whereas, the plasma gas's temperature decreases to 1000 °C is a result of heating 192 t/h steel from 0 to 1200 °C, as well as the 5.4% of furnace heat loss as shown in Figure 4. Further details on the assumptions are summarized in Table 2.

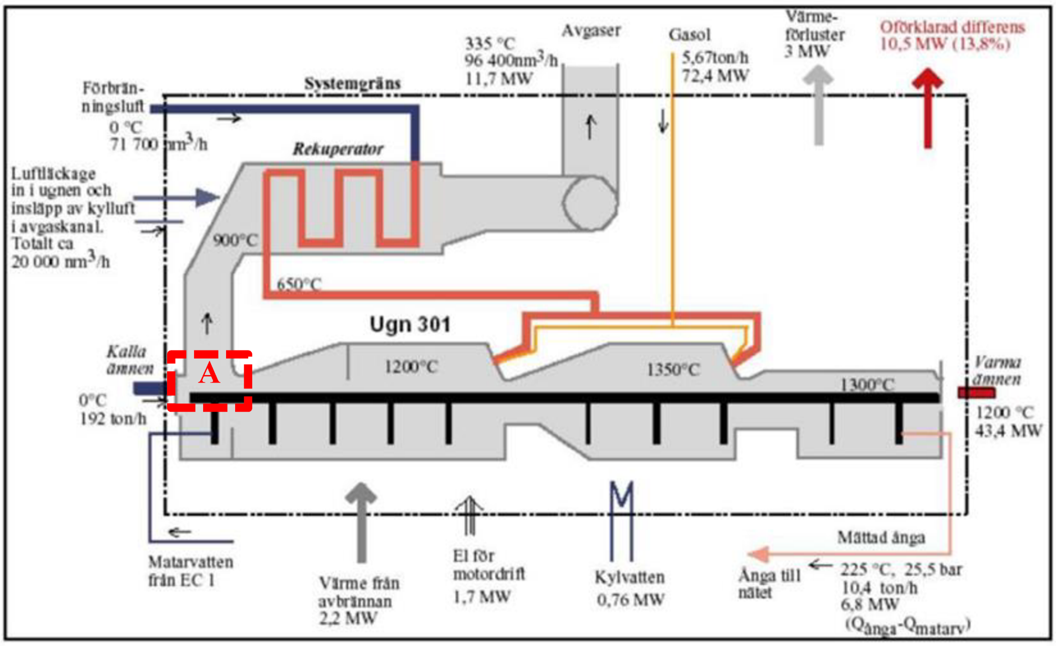


Figure 3. SSAB's Borlänge reheating furnace U301 circa 2000.

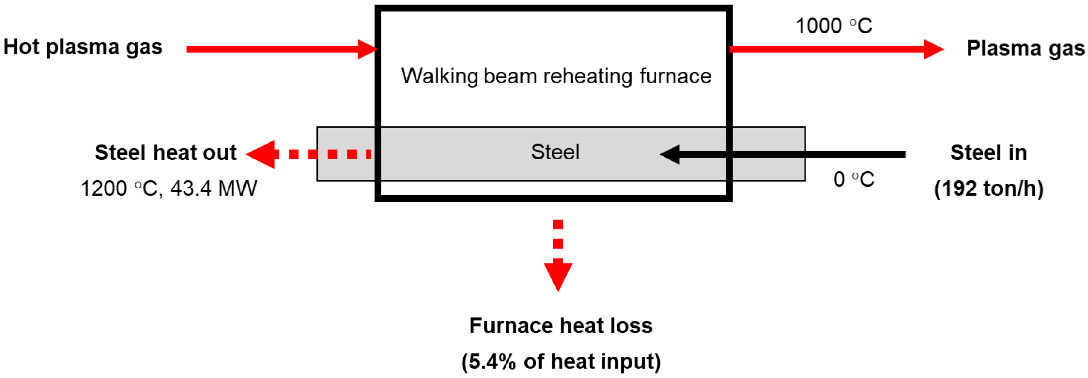


Figure 4. The scope and assumptions for the process simulation of the continuous reheating furnace.

Table 2. Assumptions of the operating condition of the SSAB's reheating furnace in the simulation of plasma torch scenarios.

Operating conditions	Values	Notes
Heat loss of furnace	5.4%	In respect to the total energy input. The value was used to represent the heat loss in the "walking beam" part only, excluding the recuperator etc.
Specific heat consumption for steel heating	226 kW/t-steel	The steel is heated from 0 to 1200 °C.

Final temperature of the plasma gas/flue gas after steel heating.	1000 °C	The value was used to determine the minimum required plasma power.

Based on the assumption described above, a process simulation model is constructed in Aspen Plus software. The flowsheet diagram of the model is shown in Figure 5.

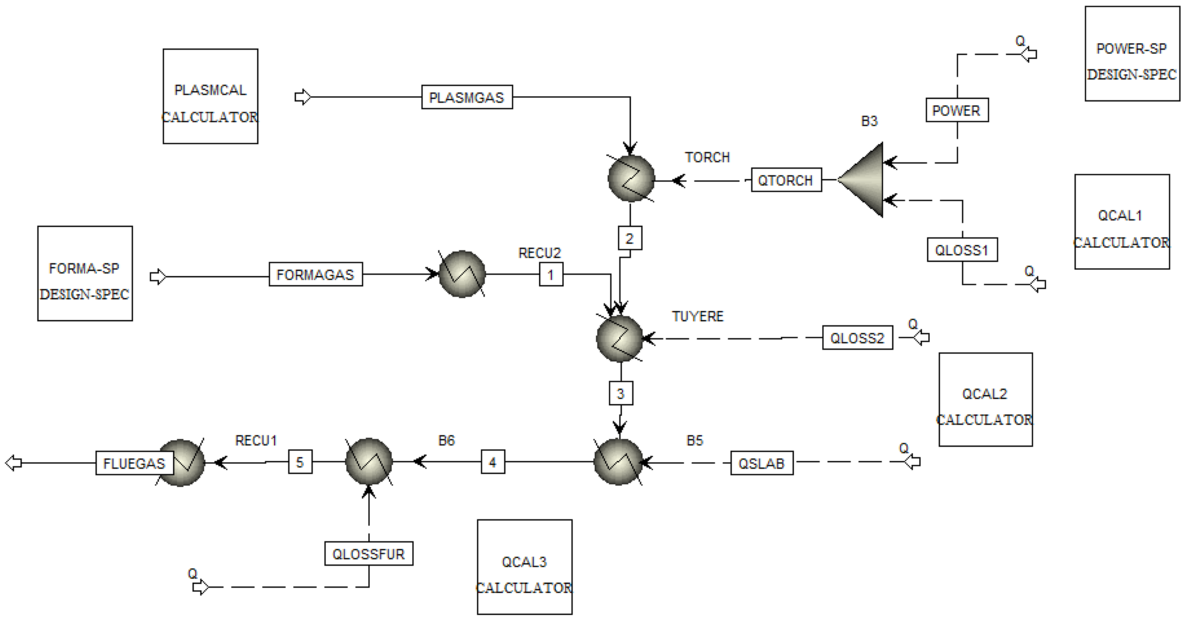


Figure 5. The developed process flow diagram of the continuous reheating furnace for plasma scenario.

In addition to the full plasma torch scenario, further process simulation is carried out to investigate the performance of a plasma torch and gas burner combined heating process. This is done by adding an RGibbs block to simulate a chemically equilibrium combustion process. The gas burner is assumed to use a syngas produced from a biomass gasification with the composition is listed in Table 3.

Table 3. The composition of dry biomass-derived syngas [3].

Syngas components	Amount (vol.%)
H_2	27.5
CO	24.4
CO_2	45.8
CH_4	1.5
N_2	0.8

2.1.3 Batch furnace

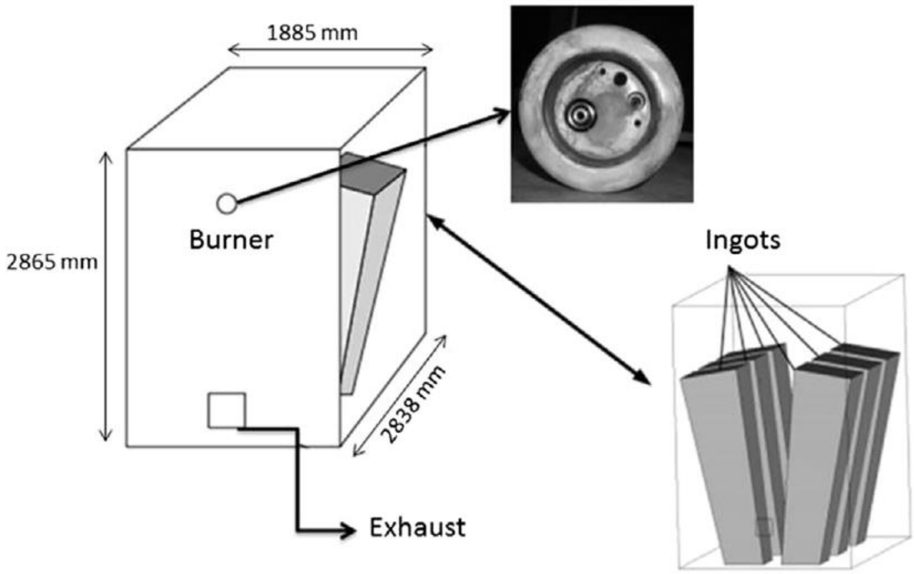


Figure 6. Soaking pit furnace configuration and arrangement of the ingots [4].

Table 4. Typical operating procedures of the existing soaking pit furnace (informations are provided by OVAKO).

Operation	Propane energy input	λ	Flue gas temperatures
Heating of the furnace			
At the initial temp. 900 °C	560 kW	1.02	~900 °C
At the target temp. 1200 °C	560 kW	1.02	~1200 °C
Soaking period	150 kW	1.02	~1200 °C

The OVAKO's soaking pit furnace is selected for the case study of the batch furnaces. The details information of the furnace are obtained from the readily available literature [4,5] and directly obtained from OVAKO. The furnace has the following dimensions: a length of 2865 mm, a width of 2838 mm and a height of 1885 mm, as shown in Figure 6. The 560 kW, oxy-fuel flameless burner as well as the exhaust channel are located at the furnace front wall, in order to reinforce a better flue gas recirculation. The burner thermal power is 560 kW. A total of six 4.2 ton ingots are normally heated inside the chamber. The ingots are heated from 900 to 1200 °C. The detailed typical operating procedures of the heating process is presented in Table 4.

Table 5. Heat flux parameters for the exterior walls.

Exterior walls	Heat loss (kW/m^2) [4]	Area (m^2)	Heat loss (kW)
Bottom	0.53	5.35	2.83
Longitudinal wall	0.45	8.13	3.65
Transversal wall	0.50	5.40	2.70
Lid	0.65	5.35	3.47
Total heat loss (kW)			**12.69**

For the process simulations, the exterior walls were treated as a heat sink with a fixed heat flux as described in Table 5. The simulation of the plasma torch scenario was then conducted in a steady state to represent two different moments as follows,

1. The moment when the furnace temperature just reaches the target temperature of 1200 °C.
2. The moment during the soaking period (constant temperature of 1200 °C).

This is done by assuming a plasma torch is installed in the same position as the existing gas burner. Also, the heat transfer characteristics on the ingot and the wall surfaces (Table 5) are assumed to be constant.

To be able to run the plasma scenario simulation, the information about the heat rate consumption of the ingot is needed. This is done by calculating the energy balance of the existing process through the following equation,

$$\dot{Q}_{fuel} = \dot{Q}_{ingot} + \dot{Q}_{loss-wall} + \dot{Q}_{loss-flue}$$

Where $\dot{Q}_{fuel}$ is the energy input from LPG (kW), $\dot{Q}_{ingot}$ is the heat rate consumption of the ingot (kW), $\dot{Q}_{loss-wall}$ is the heat loss through the furnace walls (kW) as described in Table 5, and $\dot{Q}_{loss-flue}$ is the sensible heat loss of the flue gas. From the calculation, the value of $\dot{Q}_{ingot}$ is known to be 444 kW at the moment when the furnace just reach 1200 °C, and 107 kW during the soaking period.

Thereafter, the plasma torch scenario is evaluated in term of the energy and mass flow during the heating process.

2.2 Economic calculation

2.2.1 Scope of analysis and assumptions

In this report, an economic analysis of a plasma scenario is performed based for the case of a continuous reheating furnace as described in section 2.1.2. The analysis is carried out based on the assumption that the new heating system is added to replace the existing burner in the furnace. Hence, the calculation of the capital cost (CAPEX) is determined by only considering the cost of the new added equipment excluding the capital cost of the existing furnace. In addition to the economic analysis of plasma torch system, analysis of other emerging CO_2 mitigation technologies are also carried out which include the post-combustion CO_2 process and hydrogen combustions. In general, the economic analysis is determined based on the following assumptions.

- *Scale of furnace*: The furnace is based on a SSAB's reheating (walking-beam) furnace as shown Figure 3. The existing furnace has a maximum burners capacity of 128 MW. An operating condition of 192 t-steel/h is assumed for the economic analysis.
- *Currency*: The results of the analysis are expressed in SEK applicable to 2021.
- *Lifetime of the new heating system (n)*: 20 years.
- *Discount rate of capital cost (r)*: 8%
- *Cost of electricity*: 0.45 SEK/kWh
- *Cost of LPG*: 0.42 SEK/kWh
- *Operating hours per year*: 8640 h

A scaling factor is used for converting the value of CAPEX obtained from literature based on the ratio of the capacity/scale which is formulated as follows.

$$Scaling\ factor = \left[\frac{Operating\ condition\ used\ in\ this\ study}{Reference\ operating\ condition}\right]^{0.6}$$

$$CAPEX\ for\ this\ study = CAPEX\ from\ reference\ x\ scaling\ factor$$

Nevertheless, for certain CAPEX parameters, the cost is assumed to be linearly increase with the production capacity such as the CAPEX of plasma torch (in SEK/MW). In this case, the total cost is calculated directly by multiplying the specific cost with the actual scale used in this study.

The cost of production for heating the steel is presented as the levelized total production cost which is formulated as follows,

$$Total\ production\ cost = \frac{C_{capex} * ACC + C_{opex}}{annual\ production\ of\ steel}$$

$$ACC = \frac{r * (1 + r)^n}{(1 + r)^n - 1} = 0.1018$$

where C_{capex} is the total capital cost; C_{opex} is the operating & maintenance cost; ACC is the annual capital charge; r is the discount rate; and n is the lifetime.

2.2.2 Reference furnace with plasma torch scenario

In the plasma torch scenario, the calculations are based on the additional cost of adding the plasma torch to the existing furnace as illustrated in Figure 7. In addition, the potential economic loss for halting the production line during the revamping process is not considered in the calculation. In this scenario, CO_2 is used as a plasma gas, which is fully recirculated throughout the heating process. No leak of CO_2 is assumed; hence, the system does not require a make-up CO_2. The recirculation of CO_2 is done by using a compressor with a maximum discharge pressure of 4 bar.

The economic evaluation of plasma torch scenario is determined based on the assumption as shown in Table 6. The price reference is obtained directly from ScanArc and other references.

Table 6. The assumed CAPEX parameters for plasma torch scenario.

Item	Cost	References
Plasma torch system	3 MSEK/MW	ScanArc
Electricity grid	0.38 MSEK/MW	
Project design and management	20% of CAPEX + 1 MSEK	[6]
Maintenance cost of plasma torches (annual)	3% of CAPEX	ScanArc

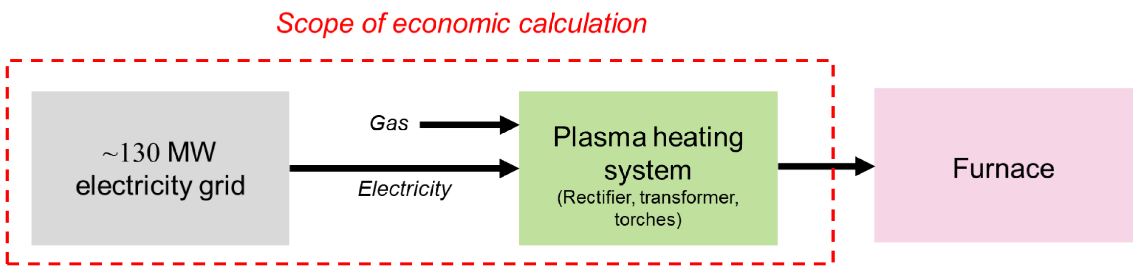


Figure 7. The scope of economic calculation for plasma scenario.

2.2.3 Reference furnace with MEA post-combustion CO_2 capture scenario

The operating conditions of the reference plant is assumed based on the information presented in Figure 3. An adjustment on the fuel type from gasoline to LPG is made according to the latest operation of the furnace. Table 7 presents the assumed operating conditions used for the economic analysis. It should be noted that in the economical calculation, the fixed operation and maintenance cost of existing furnace (e.g., walking beam maintenance, labor, etc.) is excluded from the calculation. Hence, the total OPEX cost of the reference furnace only considers the cost of energy and the maintenance of the existing burners. The cost of burner maintenance is assumed to be 3% of the capital cost of burners. This is done by assuming the current price of burner equal to 0.32 MSEK/burner [6] as shown in Table 8.

Table 7. The assumptions of the reference plant's operating conditions.

Operating conditions	**Value**	**Notes**
Maximum capacity	128 MW	
Slab input	192 t/h	
LPG consumption	377 kWh/t-steel	
CO_2 emission	82.9 kg-CO_2/t-steel	Based on the specific LPG's CO_2 emission of 0.22 kg-CO_2/kWh [7].

Table 8. The assumption of burner's maintenance cost for existing furnace U301.

Number of burners	**CAPEX of burner**	**Maintenance cost of burner**
75[a]	24 MSEK[b]	0.72 MSEK/year

[a]information provided by SSAB Borlänge.
[b]assuming the price of the burners is the same (0.32 MSEK/burner [6]) regardless the capacity of each burner.

In the post-combustion CO_2 capture scenario, a process based on the amine-based technology is added at the end of the flue gas stream with monoethanolamine (MEA) as the solvent as illustrated in Figure 8. This technology is chosen as it is among the most adapted post-combustion CO_2 removal technologies. Figure 9 shows the typical process simulation diagram of an amine-based post combustion process. The capture plant consists of two main elements, the CO_2 absorber and the amine stripper. The CO_2 in the flue gas enters the absorber and contacts with the MEA aqueous solution flowing countercurrently to form a water soluble salt ("rich" MEA solvent). The rich MEA stream exits the absorber at the bottom of the column, which is then preheated before going to the stripper. In the stripper, with the further addition of heat (provided by the reboiler), the reaction is reversed. The CO_2 is released from the MEA and leaves through the top of the stripper column, whereas the 'lean' MEA is recycled back to the absorber.

.

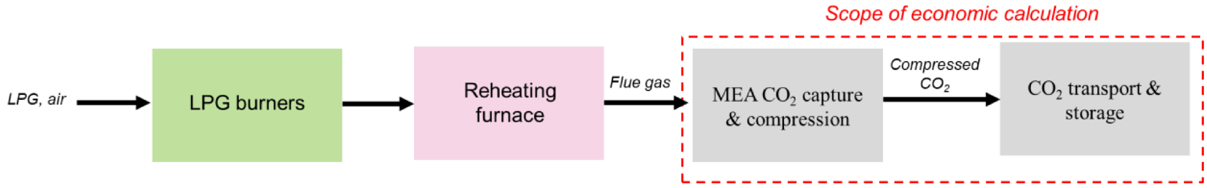


Figure 8. The scope of economic calculation for MEA scenario.

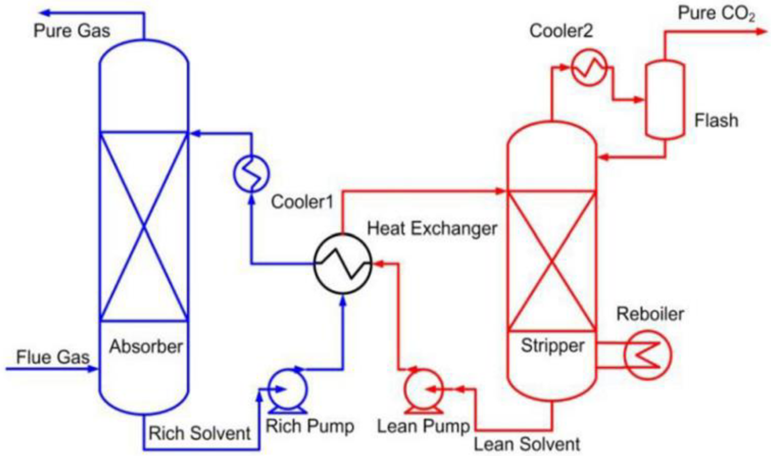


Figure 9. The process flow diagram of the basic configuration of an amine-based CO_2 capture process [8].

The CAPEX and the OPEX of the post-combustion CO_2 capture scenario are determined based on the cost and operating parameters as described in Table 9 and Table 10. In Table 9, the price obtained from the reference is presented for a CO_2 capture plant with 1 million t/year CO_2 capacity as originially presented in the reference. In this scenario, the values are then scaled to the average value of emitted CO_2 in the existing SSAB's reheating furnace as shown in Table 7.

Table 9. CAPEX of amine-based post-combustion CO_2 capture processes (capacity of 1 million t/year CO_2 capture) according to the reference [9].

Cost parameters	Price[a]	Notes
Pretreatment unit	48.2 MSEK	Blower, cooler column, packing, pump, storage tank, and cooler.
CO_2 capture unit	243.8 MSEK	CO_2 adsorber, absorber packing, washing columns, CO_2 stripper, reboiler, condenser, heat exchangers.
CO_2 compressor	197.3 MSEK	6 stages, 150 bar
Auxiliary	10.3 MSEK	Solvent reclaimer, solvent filtration

[a]Adjusted price to 2021.

Table 10. The assumption of the operating condition of the MEA CO_2 capture process.

Parameters	Value	Ref.
CO_2 capture efficiency	90%	[10]
Efficiency of the electric reboiler	100%	
Reboiler duty	3.6 MJ/kg-CO_2	[9]
CO_2 transport and storage cost	223.4 SEK/t-CO_2	[11]

2.2.4 Reference furnace with hydrogen oxy-combustion scenario

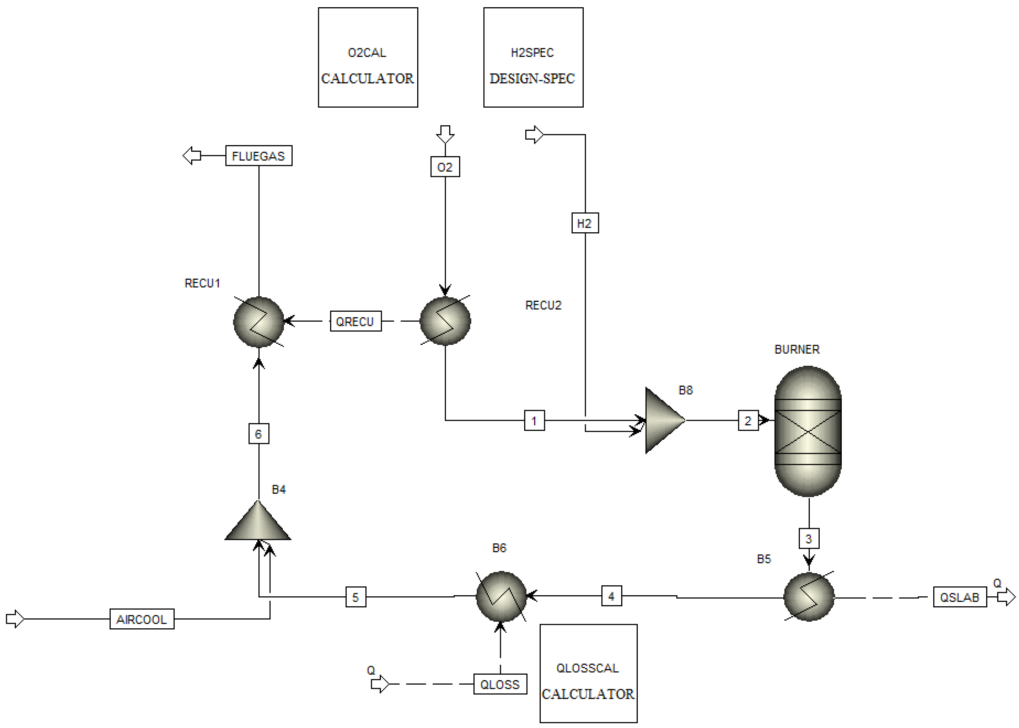


Figure 10. The process flow diagram of the hydrogen scenario developed in Aspen Plus.

For comparison purposes, the economics of the scenario where the existing burners are replaced with hydrogen oxy-combustion burners are analyzed. In this scenario, the combustion is assumed to use the existing heat recuperator of the reference plant as described in Figure 3. A process model is then developed in Aspen Plus (see Figure 10) to determine the minimum required amount of hydrogen and oxygen. As shown in Figure 10, the oxygen input is assumed to be preheated at 650 °C through the existing recuperator. An RGibbs block is then used to represent the hydrogen oxy-combustion burners to simulate an adiabatic hydrogen combustion process. The hydrogen is assumed to be fully reacted with 3% excess of oxygen. The flue gas consisting of H_2O and excess O_2 then heats the steel slab in the walking beam furnace. The final temperature of the flue gas after being used to heat the steel slab is assumed to be 1000 °C, which is the same temperature to that of plasma scenario.

The results of the simulation are presented in Table 11. As shown in the table, a H_2 amount of 8.2 kg/t-steel is required to heat the steel slab at the same operating temperature as the existing process. Correspondingly, an O_2 amount of 67.4 kg/t-steel is needed for a complete H_2 combustion with 3% excess of O_2. In addition, the specific energy consumption that is obtained based on the required amount of H_2 equals to 273.3 kWh/t-steel. This value is similar to the specific energy consumption value for an oxy-fuel combustion process reported by other references (260-285 kWh/t-steel [12]).

Table 11. The results of the process simulation for hydrogen scenario.

Parameters	**Value**	**Notes**
H_2 consumption	8.2 kg/t-steel	
O_2 consumption	67.4 kg/t-steel	
Specific energy consumption	273.3 kWh/t-steel	Based on the net heating value of H_2 = 120 MJ/kg

Based on the operating conditions described in Table 11, the economic analysis of the hydrogen scenario is determined by assuming the capital and operating cost values as shown in Table 12. In this scenario, the hydrogen is assumed to be green hydrogen produced and transmitted by the gas producer to the furnace site as illustrated in Figure 11. The distance between the hydrogen plant and the steel furnace site is assumed to be 50 km.

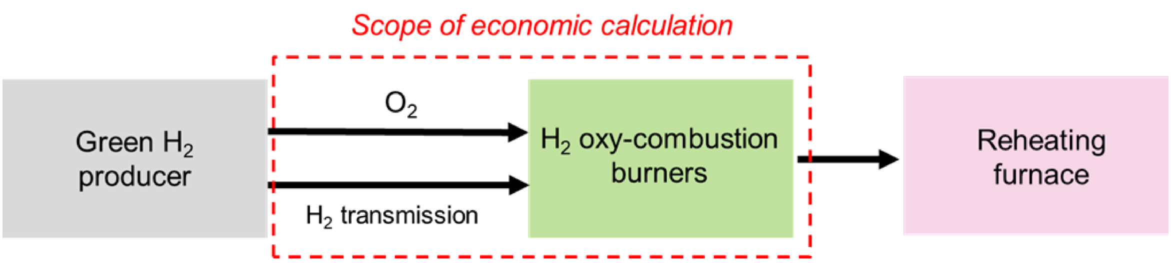


Figure 11. The scope of economic calculation for hydrogen scenario.

Table 12. Cost parameters for hydrogen scenario.

Parameters	Value	Notes
H_2 price	25 SEK/kg	Assumed to be an average price of green H_2 in 2021 based on the price range (~22–28 SEK/kg) reported by IRENA [13].
O_2 price	0.4 SEK/kg	Price provided by Linde.
Oxy-fuel burners	0.32 MSEK/burner	Price from [6].
Control system	2 MSEK/zone	Price from [6].
CAPEX of H_2 transmission	0.077 SEK/MWh_{H2}/km	New dedicated infrastructure. Includes pipeline and compressor. Price is taken from [1].

3 Results and discussion

3.1 Process evaluation of plasma scenario

In this section, the results from the process simulation are presented. Specifically, the results include the discussion on the several possible configurations of plasma torch heating system, as well as the effect of operating condition on the energy consumption for steel heating.

3.1.1 Continuous furnace

3.1.1.1 Fully plasma torch scenario

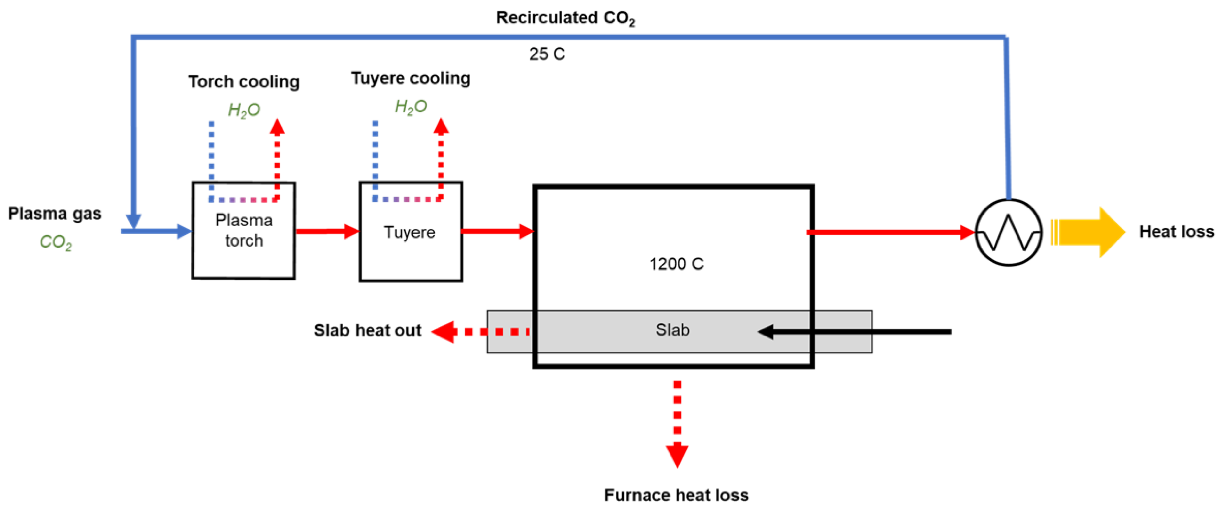


Figure 12. The illustration of the reheating furnace fully heated by plasma torches.

Figure 12 illustrates the process diagram a reheating furnace that is fully heated by plasma torches. This diagram shows the basic configuration in which no further heat recuperations are implemented. As shown in the figure, a stream input of plasma gas carrier is being fed into the plasma torches system in a relatively low temperature. Due to the limitation of the plasma torch, the plasma gas carrier should not have a temperature higher than 60 °C. The plasma gas carrier is then heated up as it goes pass through the plasma torch. A tuyere is installed at the end of the plasma torch, which mainly acts as a mounting platform for the torches. Cooling systems based on a water circulation are normally embedded into the plasma torch and the tuyere, which account for the main energy loss in the plasma torch system. The hot plasma gas then flows into the furnace chamber as a heating source with a maximum allowed specific enthalpy of 4 kWh/Nm^3 as explained previously. After the heating process, the flue gas (refer to the plasma gas after heating process) is cooled down to room temperature before being recirculated back to the plasma torch.

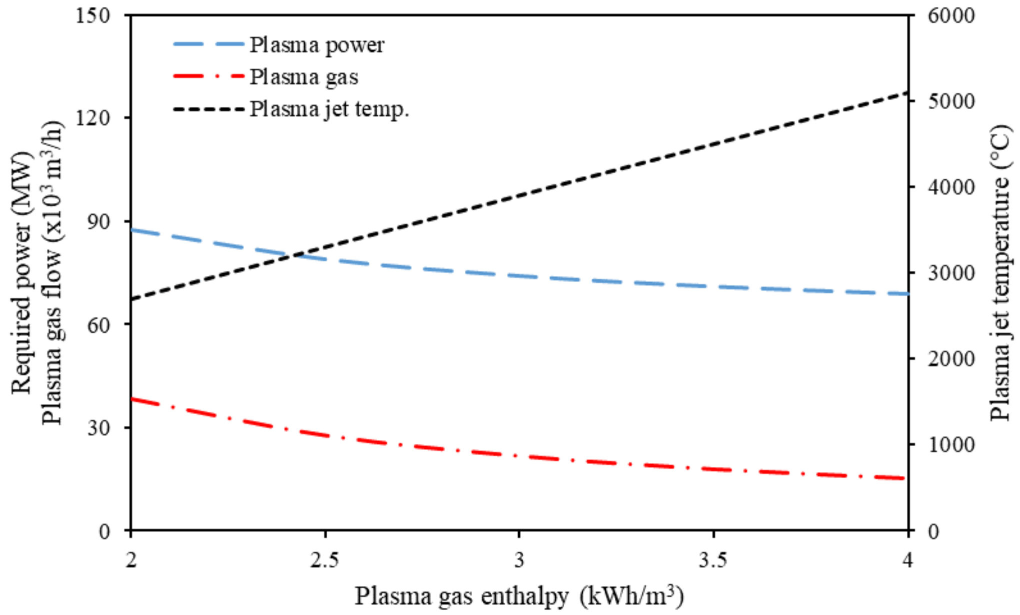


Figure 13. Effect of the plasma gas (CO_2) specific enthalpy on the operating condition of the plasma torches obtained at the maximum torch efficiency of 90%.

Figure 13 shows the relationship between the specific enthalpy of the plasma gas carrier and the operating conditions of the plasma torch system. As shown in the figure, the system requires the lowest electrical power input when it is operated with the highest plasma gas enthalpy of 4 kWh/Nm^3. At the higher enthalpy values, the temperature of the plasma jet would become higher as well. As a result, the furnace can be heated up to the required operating temperature with relatively lower electrical input.

Table 13. Comparisons of flue gases flow obtained from different fuels and oxidizers with net energy input of 57.3 MW.

Fuel/energy	**Oxidizer/ plasma gas**	**Fuel amount (kg/h)**	**Oxidizer/plasma gas input (Nm^3/h)^a**	**Flue gas mass flow (kg/h)**	**Hot flue gas (Nm^3/h)^b**
Plasma	CO_2	-	15137	29972	72245
LPG	Air	4451	55337	73622	275196
LPG	O_2	4451	11274	20562	74648
Hydrogen	Air	1719	45659	59953	259106
Hydrogen	O_2	1719	9492	15282	90256

^{a}at 25 °C, 1 bar

^{b}wet gases, at 1000 °C and 1 bar

As shown in Figure 13, the volume flowrate of the CO_2 needed for plasma gas carrier is 15137 Nm^3/h at 25 °C. The volume flowrate of the flue gases inside the furnace is an important factor that should be considered when changing the fossil fuel burner with plasma torch. The different amount of flue gases after changing the system to plasma torch could affects the operability and the performance of such heating furnace. Table 13 shows the comparisons of flue gases flowrate obtained from different fuels and oxidizers. The flowrate of the flue gases are obtained by performing combustion simulations with a net energy input of 57.3 MW. This energy input value is equal to the value in the plasma torch scenario with the highest plasma gas enthalpy of 4 kWh/Nm^3 and plasma efficiency 90%. As shown in the table, the volume flowrate of the CO_2 plasma gas carrier at 1000 °C (gas temperature after heating process) is comparable to the flue gases obtained from oxy-fuel combustion of LPG or hydrogen (~75000 Nm^3/h wet flue gas). However, the value is significantly lower (3.5 times lower) compared to the air-fuel combustion (>250000 Nm^3/h wet flue gas).

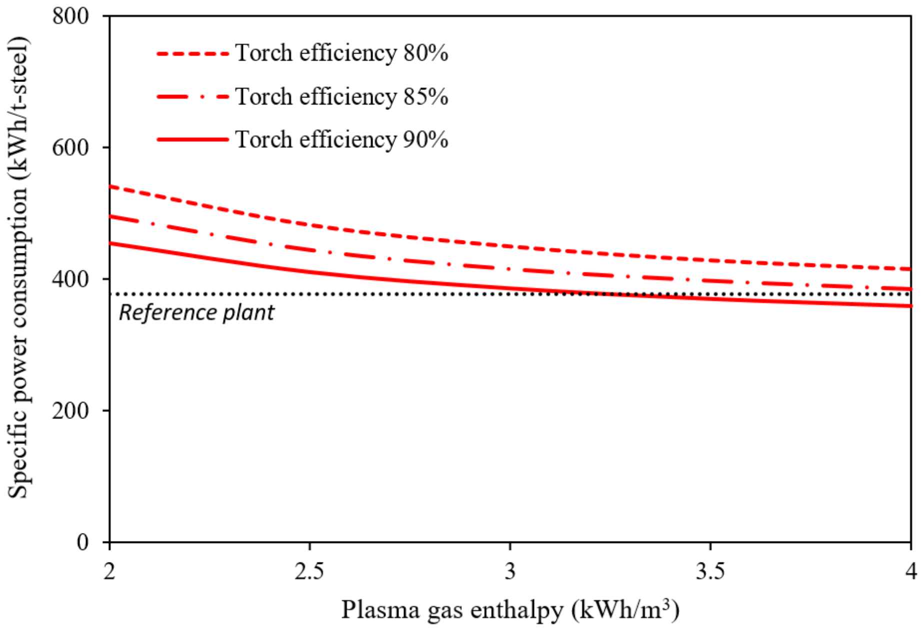


Figure 14. Specific power consumption for steel heating at different operating conditions of the plasma torch with CO_2 as plasma gas.

Figure 14 presents the specific energy consumption of the plasma torch heating system at different operating conditions. As shown in the figure, the calculation results indicate that the specific energy consumption of the plasma-based furnace is similar to that of existing furnace, when it is operated at a specific gas enthalpy higher than 3 kWh/Nm^3 and plasma torch efficiency higher than 85%. The highest furnace efficiency is equal to 63% that is obtained at plasma torch efficiency 90% and specific plasma gas enthalpy 4 kWh/Nm^3. Figure 15 shows the energy flow diagram of the furnace at the highest level of efficiency.

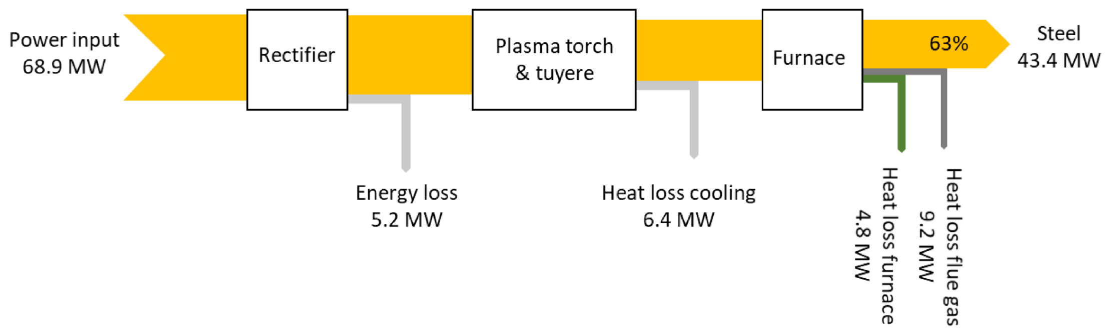


Figure 15. The energy flow diagram of the plasma-heated reheating furnace with a plasma torch efficiency 90% and a specific plasma gas enthalpy 4 kWh/Nm^3.

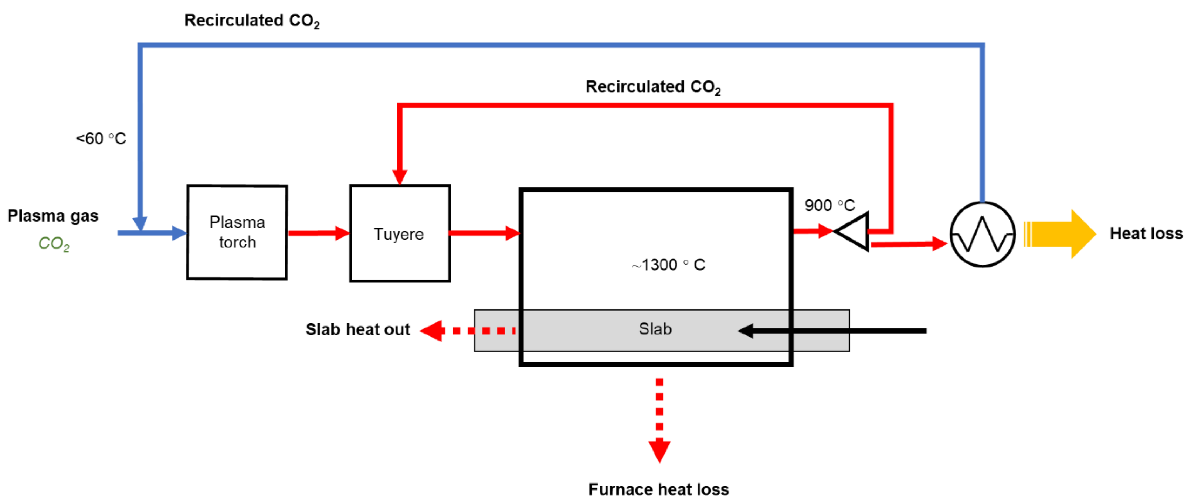


Figure 16. The schematic diagram of a plasma heated reheating furnace with recirculation of hot flue gases to the tuyere's forma gas.

Beside the primary plasma gas carrier to the plasma torch, a secondary plasma gas carrier can be also injected directly into the tuyere at a high temperature (can be up to 800 °C). This gas is called normally as the forma gas. The forma gas can consist of a wider range of gas compounds such as H_2O that is typically could not be handled by the plasma torch itself. Nevertheless, the injection of a secondary gases into the tuyere causes a decrease in the specific enthalpy of the plasma gas mixtures. As a result, the furnace efficiency also decreases.

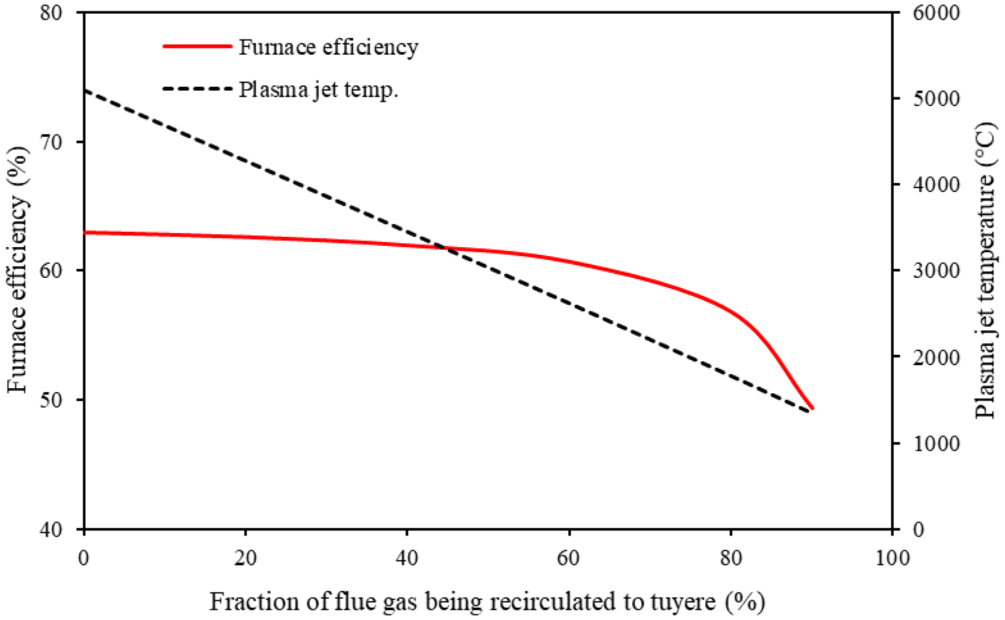


Figure 17. The furnace efficiency obtained at different amount of flue gases being recirculated to the tuyere (plasma gas specific enthalpy = 4 kWh/Nm^3; torch efficiency = 90%).

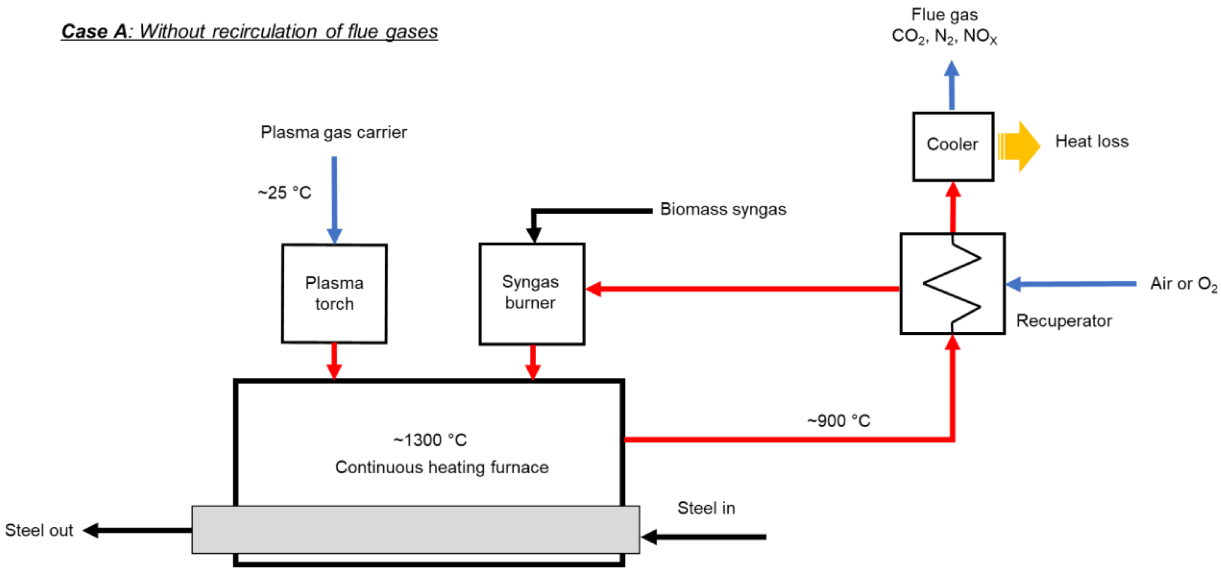
Figure 17 shows a possible configuration in which a fraction of the flue gas is recirculated as a forma gas input to the tuyere, while the rest of the flue gas is recirculated as a gas input to the torch. In this configuration, the heat loss due to the flue gas cooling can be reduced. Nevertheless, the amount of required electric power increases with the amount of flue gases being used as forma gas. Figure 17 shows the furnace efficiency obtained from different amount of forma gas. The results in the figure is obtained by assuming that the heat loss in the tuyere is constant to the plasma torch's power. As shown in the figure, the furnace efficiency decreases with the increases of the flue gas amount going into the tuyere. This is mainly due to the increase in the required plasma power to maintain the same furnace's operating temperature. As there are more forma gas with relatively lower temperature, the final plasma jet temperature decrease with the raise of the forma gas proportion.

From the explanation above, it can be concluded that injecting a secondary gas into the tuyere should be avoided to maintain a high heating performance. Nevertheless, the use of forma gas could be useful in some cases. An example is the injection of secondary air for NO_X reduction in the case of air-based plasma torch. Another example, is the use of H_2O for special processes as it can not be injected into the plasma torch directly.

3.1.1.2 Combined plasma torches and gas burners

In the plasma scenario, another possible configuration is the combination between plasma torches and gas burners. The use of biomass-based syngas in the burners would be beneficial considering that it is arguably a carbon neutral energy sources. The combination also has a benefit of more flexible operating conditions that can be adjusted based on the price and availability of the electric or biomass sources. The use of biomass syngas can be important as a transition phase toward a full a CO_2-free process.

Figure 18 presents different options of the combination scenario based on the recirculation of the flue gas. As shown in the figure, Case A presents a process in which all flue gases are released to the atmosphere and new gas stream input is added as the plasma gas carrier. Meanwhile, Case B presents a process in which a part of the flue gas is recirculated and used as the plasma gas carrier input. The benefit and drawbacks of those cases are listed further below.



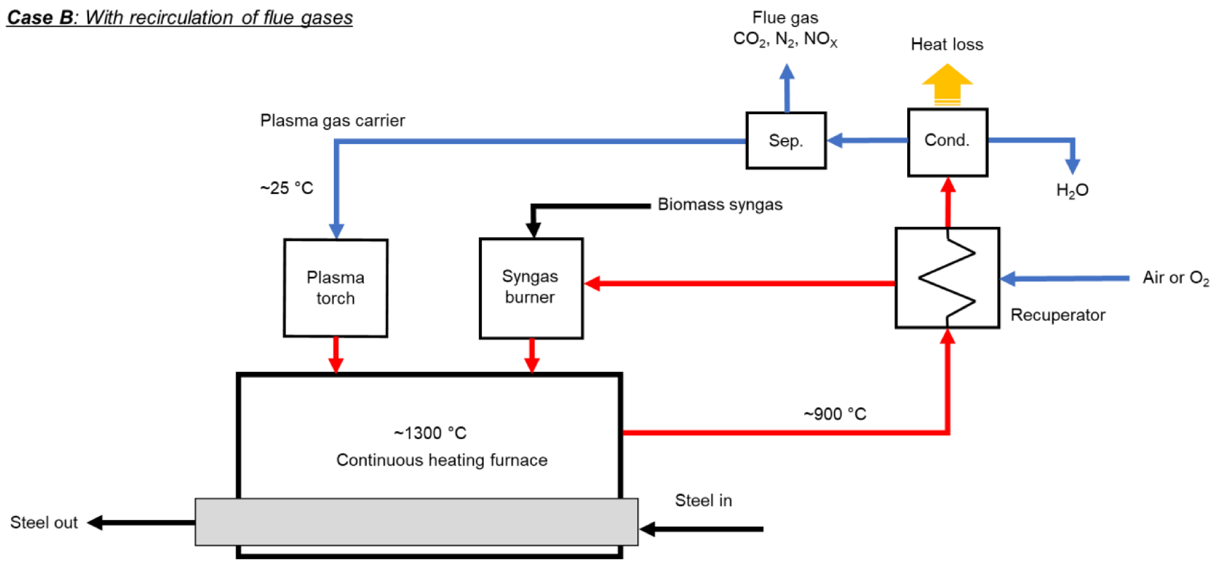


Figure 18. Possible combination between syngas burners and plasma torches without (Case A) and with (Case B) recirculation of flue gases.

Case A

- The choice of the plasma gas carrier is limited to air, O_2, or N_2. The use of those gases can potentially generate a higher amount of thermal NO_X following the higher operating temperature of the plasma torch. Thus, optimization or even a special NO_X treatment of the flue gas might be required.
- No gas separator and compressor are required at the end of the flue gas stream, which can lower the capital cost.
- The flue gas does not to be cooled at a very low temperature (< 60 °C); hence, no extra cooling is required.

Case B

- There is an option to use CO_2 as the plasma gas carrier. The CO_2 is obtained by separating and recirculating a part of flue gas. The use of CO_2 as a plasma gas carrier can limit the NO_X formation.
- Gas separator and compressor are required at the end of the flue gas stream, which can increase the capital cost. The separator is especially important if the burner uses air as the oxidizer. The presence of N_2 in the recirculated flue gas might decrease the plasma torch performance.

- The flue gas has to be cooled to separate the water content as it harmful to the main plasma torches.

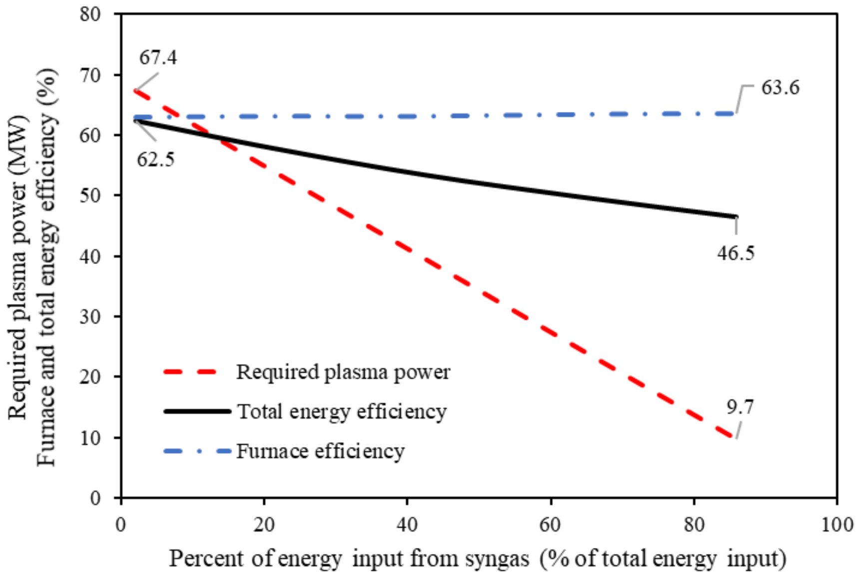


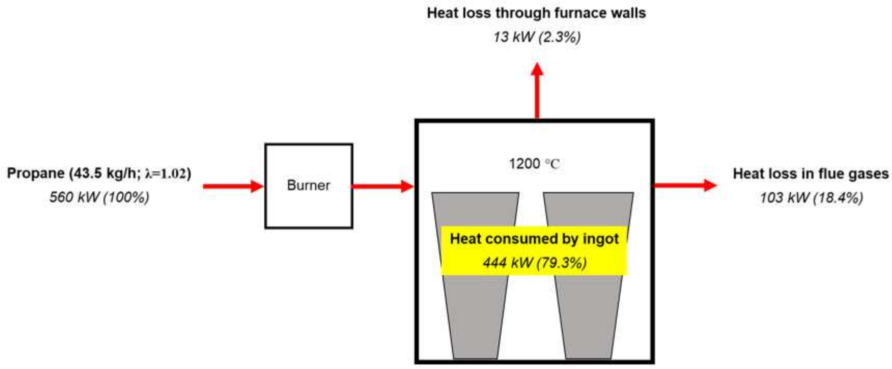
Figure 19. Effect of the share of energy input from biomass syngas on the required plasma power, furnace efficiency, and the total energy efficiency.

Figure 19 shows the effect of the share of energy input from biomass syngas on the required plasma power, furnace efficiency, and the total energy efficiency. The results are obtained by assuming the highest plasma torch efficiency and CO_2 as plasma gas carrier as described in Figure 15. As shown in the figure, the furnace efficiency is slightly increase with the increase of energy share from biomass syngas. At approximately 85% of biomass energy share, the furnace efficiency is 63.6% which is slightly higher than the full plasma scenario (63%). This trend is mainly due to the gas burner that has a higher thermal efficiency than plasma torches. Nevertheless, the use of biomass syngas has a low total energy efficiency (as calculated by the formula below) due to the low energy efficiency of the biomass gasification process. An increase of biomass energy share from 0 to 85% decrease the total energy efficiency from 63 to 46.5%.

$$Total\ energy\ efficiency = \frac{Heat\ to\ steel\ slab}{Biomass\ calorific\ value\ +\ plasma\ power\ input}$$

3.1.2 Batch furnace

Existing oxy-fuel burner



Plasma scenario

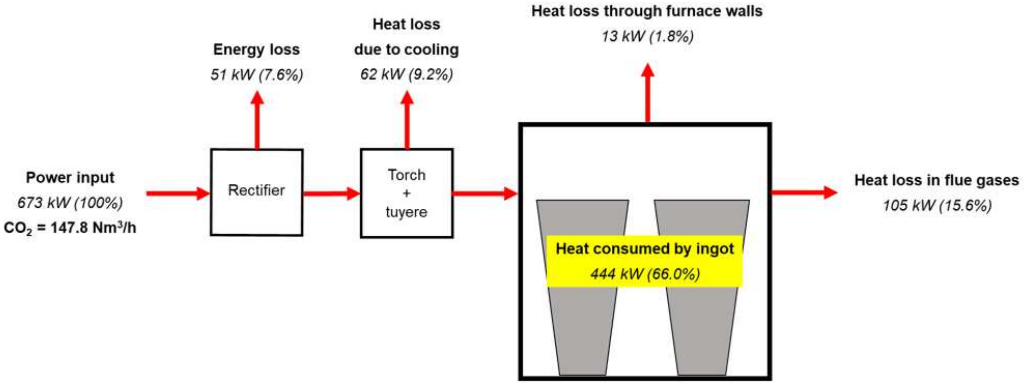
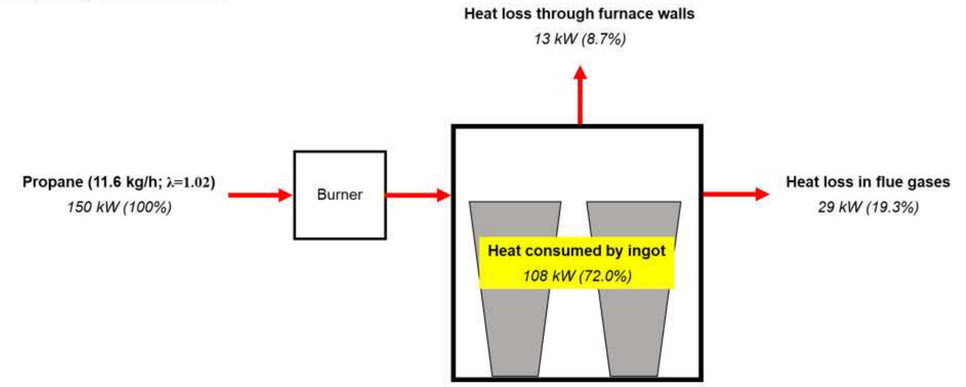


Figure 20. The energy flow diagrams of the soaking pit furnace with the existing oxy-fuel burner (upper), and the simulated plasma torch (lower), at the moment it reaches target temperature of 1200 °C with a net input energy to the furnace of 560 kW.

Figure 20 shows the energy flow diagrams of the OVAKO's soaking pit furnace with the existing oxy-fuel burner and the simulated plasma torch. The figure illustrates the energy balance at a point where the furnace just reach its target temperature of 1200 °C after the heating process from 900 °C. The simulation of the plasma scenario is performed with assumptions of plasma gas specific enthalpy 4 kWh/Nm^3, torch efficiency 90%, and CO_2 as the plasma gas carrier. As shown in the figure, a higher amount of energy input is required in the plasma scenario to maintain the same operating temperature. This is due to the higher amount of energy loss in the rectifier and the cooling system of the torch and tuyere. At this point, the estimated furnace efficiency for the plasma scenario is 66%, which is lower compared to the oxy-fuel burner (79.2%). In addition, a CO_2 flow if 147.8 Nm^3/h is required in the plasma scenario. However, it should be noted that the heat transfer phenomenon inside the furnace is not considered in the simulation work, which actually affects the efficiency and the total required heating time in the real applications.

Existing oxy-fuel burner



Plasma scenario

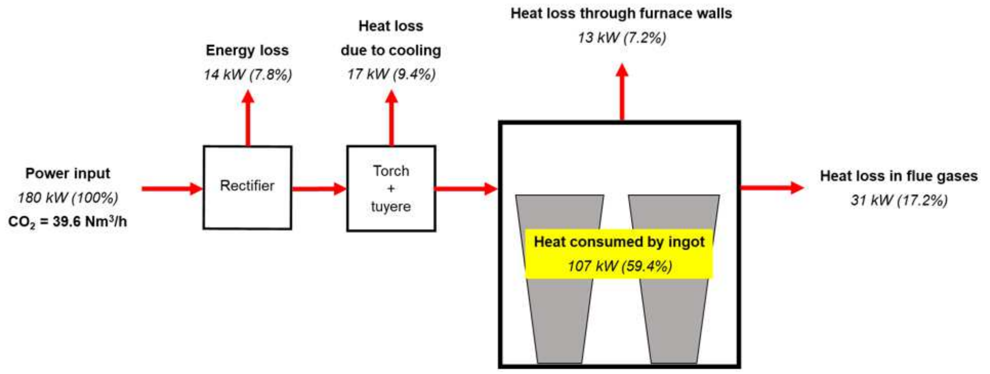


Figure 21. The energy flow diagrams of the soaking pit furnace with the existing oxy-fuel burner (upper), and the simulated plasma torch (lower), during the soaking period at 1200 °C with a net input energy to the furnace of 150 kW.

Figure 21 shows the energy flow diagrams during the soaking period at a constant temperature of 1200 °C. During this moment, the energy input is decreased from 560 kW to 150 kW. At this moment, the estimated furnace efficiency for the plasma scenario is 59.4%, while the efficiency of the oxy-fuel burner is 72.0%. A CO_2 flow if 39.6 Nm^3/h is required in the plasma scenario during this period.

3.2 Economic evaluation

3.2.1 Cost comparisons

In this report, an economic analysis of a plasma scenario is performed based for the case of a continuous reheating furnace as described in section 2.1.2. In addition to the economic analysis of plasma torch system, analysis of other emerging CO_2 mitigation technologies are also carried out which include the post-combustion CO_2 process and hydrogen combustions.

The details of the total estimated CAPEX of the plasma, MEA and hydrogen scenario are presented in Table 14, Table 15 and Table 16 respectively. The plasma scenarios is evaluated based on the process presented in Figure 12, in which CO_2 is used as plasma gas carrier and fully recirculated throughout the process. As shown in Table 14, the estimated CAPEX value for the plasma scenario is around 549.2 MSEK. The main CAPEX component in the case of the plasma scenario is the plasma torch system itself as its price equal to 70% of the total CAPEX. Meanwhile, the main component of the MEA process is the CO_2 capture unit which account for 40% of the total CAPEX. In general, adding the MEA process in the existing furnace costs 52% lower CAPEX than replacing the existing burner with plasma torches. On the other hand, the hydrogen scenario has a significantly lower CAPEX (51.5 MSEK) than other scenarios if the cost of H_2 transmission is not considered in the estimation. Nevertheless, the estimated CAPEX of the hydrogen scenario could potentially reach 508.9 MSEK if the cost of H_2 transmission is included with an assumption of a 50 km transmission line.

Table 14. CAPEX of the plasma torch system installation .

CAPEX parameter	Cost (MSEK)
Electricity grid	48.6
Plasma torch system	384.0
CO_2 filter and compressor	38.8
Project design & management	77.8
Total CAPEX (MSEK)	**549.2**

Table 15. CAPEX of the MEA-based CO_2 capture process installation.

CAPEX parameter	Cost (MSEK)
Pretreatment unit	20.8
CO_2 capture unit	105.4
CO_2 compressor	85.3
Auxiliary	4.5
Project design & management	44.6
Total CAPEX (MSEK)	**260.7**

Table 16. CAPEX of the hydrogen scenario.

CAPEX parameter	Cost (MSEK)	
	With H_2 transmission	Without H_2 transmission
Burner	24.0	24.0
Control system	16.0	16.0
H_2 transmission	363.1	-
Project design & management	81.6	9
Total CAPEX (MSEK)	**508.9**	**51.5**

The total production cost of all scenarios is presented in Table 17. In this table, the value of the production cost does not consider the capital cost of the existing furnace, the fixed O&M of the existing furnace, as well as the cost of labor for the operation of the new installed system. As shown in the table, the production cost of the plasma scenario is approximately 221.3 SEK/t-steel, which is mainly dominated by the cost of electricity. Hence, compared to the existing operation, the installation of new plasma heating system will require additional production cost of 62.6 SEK/t-steel.

Furthermore, the production cost of plasma scenario is cheaper than that of MEA scenario, despite the higher CAPEX of plasma torches. This difference could be more larger if the cost of labor is considered in the OPEX calculation of the new system, as the operation of MEA process arguably would need more labor cost than that of plasma torch operation. The cost of energy in the MEA process is a 41.5 SEK/t-steel higher than that of existing furnace due to the operation of the electric reboiler and the CO_2 compressor (discharge pressure 150 bar). In total, 83.6 SEK/t-steel additional cost is needed in the MEA scenario.

On the other hand, the hydrogen scenario has the highest production cost regardless if the H_2 transmission is considered in the cost calculation which up to 263.1 SEK/t-steel. Nevertheless, the production cost is significantly lower if the H_2 transmission is excluded which is equal to 231.8 SEK/t-steel. This number is about 5% higher than the plasma scenario. This higher cost is due to the high cost of green hydrogen fuel that is currently between 22-28 SEK/kg [13]. Nevertheless, it is predicted that the cost of green hydrogen can potentially be cheaper in the future. IRENA predicted that the cost of hydrogen can be as low as 13 SEK/kg in 2030 and 10 SEK/kg in 2050 [13].

Table 17. Total production cost for different technologies excluding cost of labor and capital cost of the existing furnace.

Cost (SEK/t-steel)	**Existing furnace**	**New installed process**			
		Plasma	**MEA**	**Hydrogen** (with H_2 transmission)	**Hydrogen** (without H_2 transmission)
CAPEX (levelized)	-	35.4	16.8	31.2	3.2
OPEX					
Electrical power	-	179.0[a]	41.5	-	-
Fuels	158.3	-	158.3	231.1[b]	231.1[c]
Other O&M	0.4	6.9	23.6	0.7	0.7
Total OPEX	158.8	185.9	223.7	231.8	231.8
Total production cost (SEK/t-steel)	**158.8**	**221.3**	**235.5**	**263.1**	**231.8**
Additional cost to the reference furnace (SEK/t-steel)	**-**	**62.6**	**83.6**	**104.3**	**76.2**

[a]plasma torch efficiency = 90%
[b]hydrogen and oxygen

Table 18. The CO_2 emission and CO_2 avoidance cost.

Parameters	**Plasma**	**MEA**	**Hydrogen** (with H_2 transmission)	**Hydrogen** (without H_2 transmission)
CO_2 emitted (kg-CO_2/ton-steel)	-	8.3	-	-
CO_2 captured (kg-CO_2/ton-steel)	-	74.6	-	-
CO_2 avoided (kg-CO_2/ton-steel)	82.9	74.6	82.9	82.9
CO_2 avoidance cost (SEK/t-CO_2)	**760.6**	**1120.6**	**1258.0**	**919.4**

Table 18 presents the CO_2 emission and CO_2 avoidance cost. As shown in the table, at the best scenario (i.e., highest plasma torch efficiency and specific plasma gas enthalpy), the plasma scenario has a lower CO_2 avoidance cost than the MEA and hydrogen scenario. For instance, the cost is equal to 760.6 SEK/t-CO_2. These values are at least 47% and 21% lower than that of MEA and hydrogen scenario, respectively.

3.2.2 Sensitivity analysis

3.2.2.1 Effect of the plasma torch efficiency

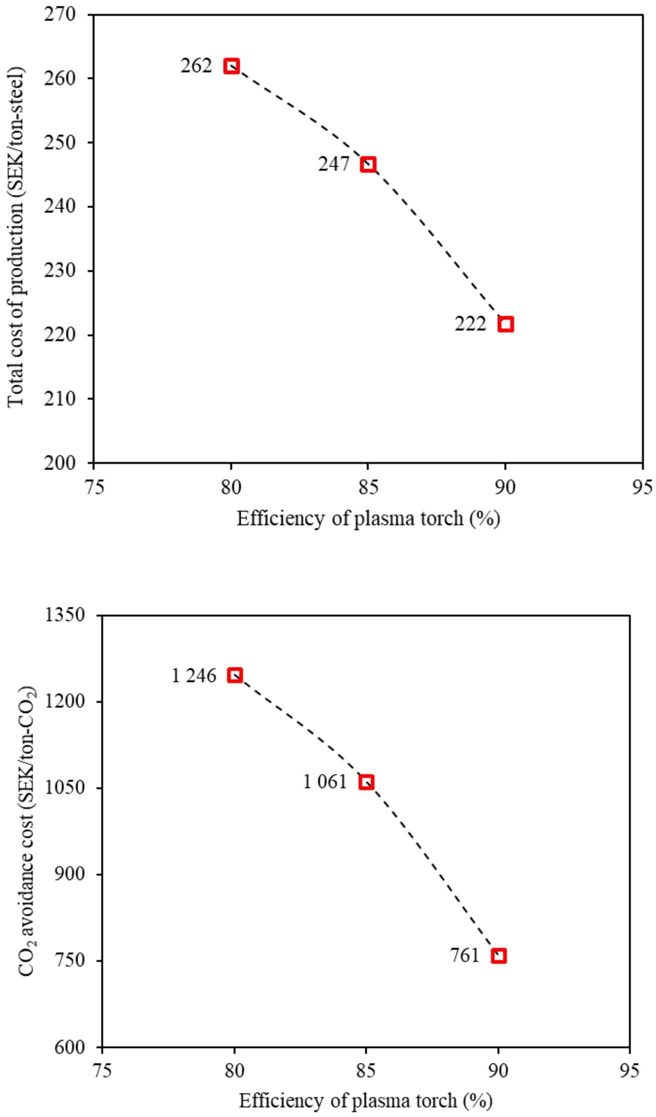


Figure 22. The effect of the plasma torch efficiency on the total production cost and CO_2 avoidance cost.

Figure 22 presents the relationship between the plasma torch efficiency and the total production cost, as well as the CO_2 avoidance cost. It can be seen in the figure that the efficiency of the plasma torch significantly affects the production cost. Specifically, a decrease in the efficiency from 90 to 80% cause an increase in the production cost by almost 18%. This significant increase is caused by the different in the cost of electricity, which accounts for at least 80% of the production cost as explained previously.

Furthermore, the effect of the plasma torch efficiency is more pronounced in the case of CO_2 avoidance cost. As shown in the figure, a decrease in the efficiency from 90 to 80% would increase the CO_2 avoidance cost up to 63%, as it increase from 761 to 1246 SEK/t-CO_2.

3.2.2.2 Effect of the cost parameters

Figure 23 shows the sensitivity analysis of production cost for plasma scenario. As discussed before, the electrical energy consumption and price are the major parameter that influence the total cost in the plasma scenario, which is also demonstrated in Figure 23. As shown in the figure, variations in the electric price within the -/+25% range can shift the production cost by 20%. At the lower case of electric price (0.375 SEK/kWh), the production cost decreases from 222 to 177 SEK/t-steel. This reduction in the cost of electricity can significantly reduce the CO_2 avoidance cost by more than 60% as it decreases from 552 to only 221 SEK/t-CO_2 as shown in Figure 24. Correspondingly, a raise in the electric price would significantly increase the CO_2 avoidance cost.

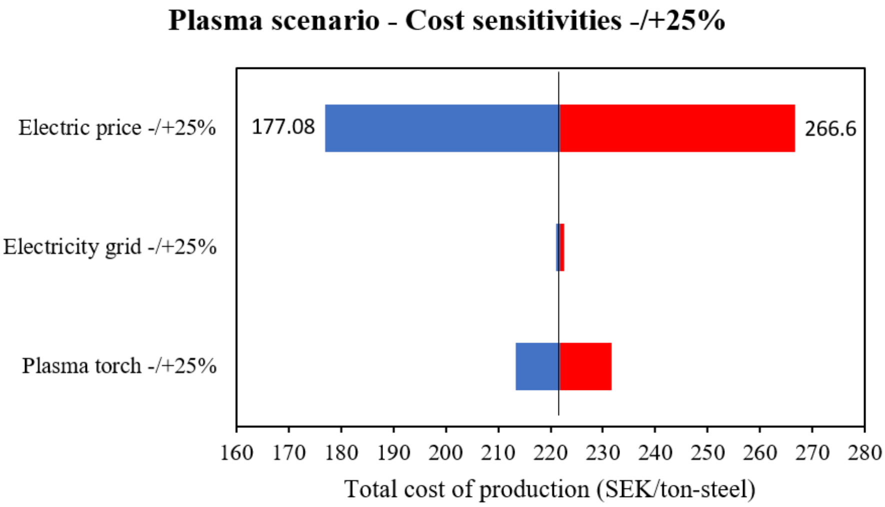


Figure 23. Sensitivity analysis of total production cost for plasma scenario.

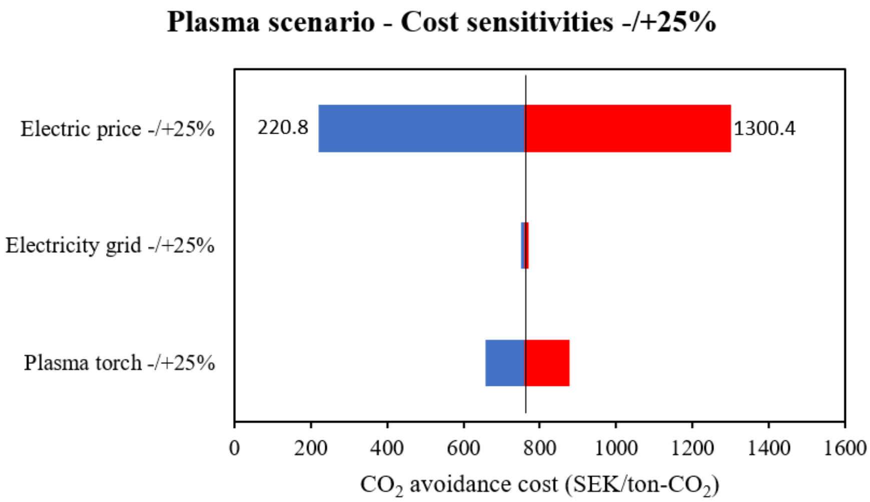


Figure 24. Sensitivity analysis of CO_2 avoidance cost for plasma scenario.

3.2.2.3 Effect of the NO_X treatment cost

The process simulation and the economic analysis that are presented in the previous sections are performed by assuming that there is no NO_X formation for the plasma scenario. This is theoretically possible with the use of CO_2 or N_2 as the plasma gas carrier and by preventing air leakage. Nevertheless, depends on the process requirement, the use of plasma torch could still have a potential NO_X formation. For example, when the process requires an excessive exposure of the plasma jet to the outside air.

In the case of plasma heating, the reduction of NO_X can be done through either post-combustion methods or in-situ methods. In the post-combustion method, the Selective Catalytic Reduction (SCR) method is commonly used. The cost of SCR has been reported in the literature. In this section, a typical cost of SCR for an industrial boiler as reported by Sorrels et al. [14] is used to illustrate the potential cost of the SCR in the plasma scenario. According to the report, the cost of the SCR is at least USD 3490/ton-NO_X (cost year of 2016). The cost value includes already both the CAPEX and OPEX elements of the SCR process with plant lifetime of 30 years [14]. The cost is calculated based on a NO_X removal efficiency of 87.5%, with the amount of the NO_X emission in the untreated flue gas equivalent to 150.5 mg/MJ [14]. This NO_X concentration value is comparable with the results of the PLATIS's pilot scale tests in the case of CO_2 and N_2 plasma gases (46–203 mg/MJ-CH_4-eq.). Hence, the cost of the SCR is relevant to the plasma scenario of the PLATIS project.

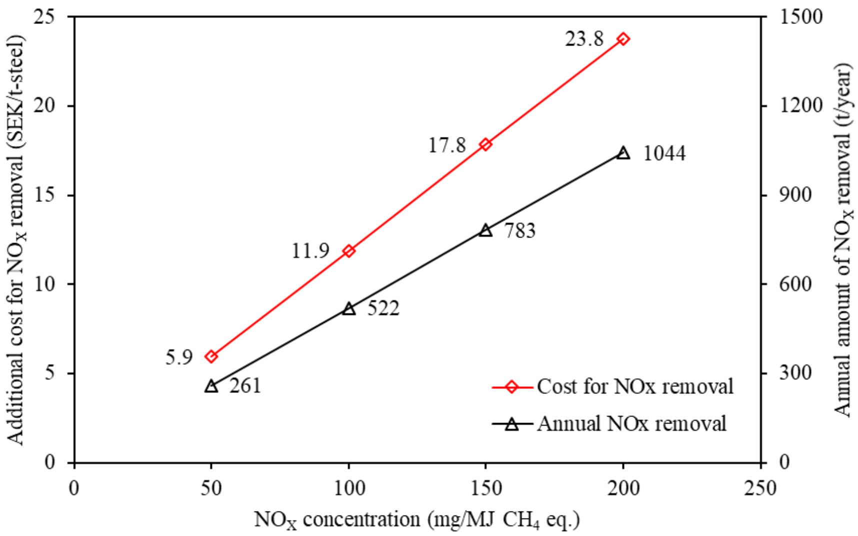


Figure 25. Cost of NO_X removal for different concentrations of NO_X emission (calculated at plasma gas specific enthalpy = 4 kWh/Nm3; torch efficiency = 90%).

Figure 25 shows the additional cost that is required for the NO_X removal at different concentration levels of NO_X emission. As shown in the figure, an additional operating cost of 5.9 SEK/t-steel is needed to eliminate NO_X from a concentration of 50 mg/MJ-CH_4-eq. This cost increase by four time to 23.8 SEK/t-steel if there are 200 mg/MJ-CH_4-eq in the flue gas resulted from plasma heating.

Another possibility of NO_X reduction is the in-situ reduction that can be achieved through the optimization of the plasma torch design and the operating parameters. This potentially may has a lower total cost than the SCR method as it affect mostly the CAPEX. At the same time, OPEX cost for the NO_X reduction can be limited as it does not requires costs for spent materials such as catalyst, as well as the cost of labor.

4 Conclusion

In this report, a technical evaluation and economic analysis of plasma scenarios for the heating furnaces in the steel industries are carried out. From the results obtained in this study, following conclusions can be made.

- In the case of a continuous reheating furnace with 100% plasma heat, the highest furnace efficiency is obtained when the flue gas is fully recycled as a plasma gas inlet. The injection of a secondary gas into the tuyere will reduce the heat capacity of the plasma gas that enter the furnace; thus, decreasing the efficiency. At the theoretical maximum efficiency of plasma torch, the result from the process simulation shows that the furnace efficiency is slightly higher than that of existing process.

- Compared to the post combustion CO_2 capture process and the hydrogen oxy-combustion, the installation of plasma torches to replace fossil-fuel burners can potentially has a lower total production cost, as well as CO_2 avoidance cost. At the highest value of plasma torch efficiency (90%), the use of plasma torch cause an additional production cost of 62.6 SEK/t-steel. This number corresponds to the CO_2 avoidance cost of 761 SEK/t-CO_2.

- The results of the economic analysis show that the electric power consumption and price are the main major cost elements of the plasma scenario. A -/+ 25% change in the price of electricity will significantly change the total production cost (by 20%) and the CO_2 avoidance cost (by 70%). Correspondingly, the efficiency of the plasma torch is the most crucial operating parameters. It has been shown that a decrease in the plasma torch efficiency from 90 to 80% may increase the CO_2 avoidance and total production cost up to 63% and 18%, respectively.

References

[1] J. Cihlar, A. Villar Lejarreta, A. Wang, F. Melgar, J. Jens, P. Rio, Hydrogen generation in Europe: Overview of costs and key benefits, 2020.

[2] A. Nurdiawati, I.N. Zaini, M. Amin, D. Sasongko, M. Aziz, Microalgae-based coproduction of ammonia and power employing chemical looping process, Chem. Eng. Res. Des. 146 (2019) 311–323.

[3] K.J. Andersson, M. Skov-Skjøth Rasmussen, P.E. Højlund Nielsen, Industrial-scale gas conditioning including Topsoe tar reforming and purification downstream biomass gasifiers: An overview and recent examples, Fuel. 203 (2017) 1026–1030.

[4] M. Ghadamgahi, P. Ölund, T. Ekman, N. Andersson, P. Jönsson, Numerical and experimental study on flameless oxy-fuel combustion in a pilot- scale and a real-size industrial furnace, Appl. Therm. Eng. 141 (2018) 788–797.

[5] M. Ghadamgahi, P. Ölund, N.Å.I. Andersson, P. Jönsson, Numerical study on the effect of lambda value (oxygen/fuel ratio) on temperature distribution and efficiency of a flameless oxyfuel combustion system, Energies. 10 (2017).

[6] J. Törnbom, System analysis for implementing preheated blast furnace gas and oxyfuel combustion in a steel reheating furnace at SSAB EMEA, Oxelösund, Luleå University of Technology, 2015.

[7] T.E. Toolbox, Combustion of Fuels - Carbon Dioxide Emission, (n.d.).

[8] B. Xue, Y. Yu, J. Chen, X. Luo, M. Wang, A comparative study of MEA and DEA for post-combustion CO2 capture with different process configurations, Int. J. Coal Sci. Technol. 4 (2017) 15–24.

[9] K. Li, W. Leigh, P. Feron, H. Yu, M. Tade, Systematic study of aqueous monoethanolamine (MEA)-based CO2 capture process: Techno-economic assessment of the MEA process and its improvements, Appl. Energy. 165 (2016) 648–659.

[10] E.S. Rubin, J.E. Davison, H.J. Herzog, The cost of CO2 capture and storage, Int. J. Greenh. Gas Control. 40 (2015) 378–400.

[11] S. Michailos, O. Emenike, D. Ingham, K.J. Hughes, M. Pourkashanian, Methane production via syngas fermentation within the bio-CCS concept: A techno-economic assessment, Biochem. Eng. J. 150 (2019) 107290.

[12] J. Von Schéele, V. Zilka, R. Eichler, Succesful use of flameless oxyfuel in reheat furnaces and ladle preheating, in: Met. 2011, 2011.

[13] IRENA, Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5 C climate goal, 2020.

[14] J.L. Sorrels, D.D. Randall, K.S. Schaffner, C.R. Fry, Chapter 2 Selective Catalytic Reduction, Econ. Cost Anal. Air Pollut. Regul. (2016).