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Research Paper

Waste heat recovery of the glass melting furnace via non-linear process optimization

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ABSTRACT

The European glass industry faces strict greenhouse gas (GHG) emission reduction targets, necessitating enhanced energy efficiency in glass melting processes. Energy efficiency can be enhanced by, e.g., waste heat recovery. This study presents a mathematical optimization model incorporating waste heat recovery (WHR) through multi-stage configurations in glass furnaces. Current practices primarily utilize single-stage WHR, which still results in significant energy losses, particularly from high-temperature flue gases. Our model incorporates five WHR technologies: oxidizer preheating, fuel preheating, batch and cullet preheating, heat-to-power conversion, and integration into a carbon capture process. Our model optimizes both total annualized cost (TAC) and GHG emissions of configurations of WHR technologies for the glass melting furnace in a multi-objective optimization. Our results demonstrate that implementing multi-stage WHR can substantially lower both TAC and GHG emissions: A two-stage WHR configuration with air preheating and carbon capture reduces TAC by 31.4% and GHG emissions by 70% compared to using a natural gas-fired glass furnace with air preheating. Furthermore, a sensitivity analysis reveals that while increasing electrification diminishes available waste heat for recovery, optimal multi-stage WHR configurations can still yield significant benefits across different fuel and electrification scenarios. Overall, our research underscores the importance of advanced process modeling and optimization in developing cost-effective strategies for enhancing energy efficiency within the glass industry amidst evolving regulatory landscapes. The findings provide valuable insights for decision-makers aiming to implement economically and environmentally favorable practices in new furnace designs while meeting future emission standards.

1. Introduction

The glass industry must reduce greenhouse gas (GHG) emissions from the glass melting process by 40% until 2030 to comply with European emission targets [1,2]. Current glass furnaces mainly utilize natural gas-air combustion as energy supply for the melting process, leading to high GHG emissions [3]. Waste heat recovery (WHR) is a promising strategy to enhance the energy efficiency, thereby reducing the energy demand and, consequently, energy-related GHG emissions [4,5].

Today's glass industry already utilizes WHR to preheat combustion air in regenerative melting furnaces. Approximately 75% of container glass furnaces and 90% of flat glass furnaces utilize regenerators as WHR method [4]. However, despite the usage of regenerators, about 25–30% of the total energy input is lost due to high-temperature flue gases leaving the melting furnace [3]. Thus, further WHR can help to reduce energy losses associated with high-temperature flue gases [6]. Further WHR typically involves utilizing energy that would otherwise be lost through flue gases to increase the overall energy efficiency of the process.

To decrease the energy losses from high-temperature flue gas, multiple WHR technologies other than regenerators can be implemented within the glass production. However, these other WHR technologies are not sufficiently spread within the glass industry due to site-specific design and uncertain payback times [6]. Combining multiple WHR technologies has rarely been applied in the glass industry [4].

Mokarram et al. [7] analyze the utilization of WHR cycles from a glass furnace. They consider three types of WHR cycles to generate electricity from the thermal energy embedded in the flue gas stream: Organic Rankine cycle, Kalina cycle, and supercritical CO_2 cycle. They

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further analyze the economic potential showing that all assessed WHR cycles can reduce overall process cost while increasing energy efficiency. However, utilizing waste heat internally to preheat process streams are out of scope of their work.

Dolianitis et al. [8] and Karellas et al. [9] model a batch and cullet preheater for WHR. They utilize the waste heat in the flue gas after the regenerator. They show that the energy demand decreases by 12–15% when utilizing batch and cullet preheating compared to the glass melting process without batch and cullet preheating.

Miserocchi et al. [6] analyze the status and improvements of energy efficiency within the glass industry. They focus on options that directly impact the energy demand of the process, e.g., by heat recovery and decreasing structural heat losses. They focus on the variation of process parameters, e.g., cullet ratio, glass exit temperature, and electric boosting ratio to decrease the specific energy demand of the glass production [6].

The presented studies analyze various configurations for WHR. However, none of the studies has systematically developed a mathematical optimization model to optimize WHR. Inayat [10] highlights this gap and emphasizes that mathematical modeling, pinch analysis, and exergy analysis are useful to identify and optimize waste heat losses. The author recommends future studies on industries where WHR technologies do not yet fully exploit the potential for heat recovery. Thus, current literature lacks a mathematical model for optimizing WHR for the glass melting process that considers multi-stage WHR. Such an assessment is crucial for fully exploiting the potential for WHR and reducing both costs and GHG emissions by enhancing the energy efficiency of the glass melting process.

However, incorporating multi-stage WHR is complex, as it requires addressing temperature constraints and their effect on the melting process to fully realize the potential for heat recovery. Due to the process-specific degrees of freedom, mathematical optimization is essential to determine the optimal configuration of multi-stage WHR. Mathematical optimization can maximize the utilization of waste heat and achieve significant energy efficiency gains and GHG emission reductions.

In this study, we present a mathematical optimization model of the glass melting process to determine the optimal configuration of WHR technologies to minimize costs and GHG emissions. We model the glass melting process, incorporating multiple relevant WHR technologies including preheating of process streams (fuel, oxidizer, batch, and cullet), along with heat-to-power conversion and waste heat integration into a carbon capture process to also avoid inherent process-related emissions. Process-related emissions arise due to the melting reaction. We allow for multi-stage heat recovery to maximize the exploitation of waste heat. As a benchmark we use the glass melting process with natural gas combustion with regenerative air preheating as it is found in industry nowadays.

In the following, we first describe technologies that are already utilized for WHR in the glass industry nowadays (Section 2). Section 2.1 shows the modeling of WHR technologies used within our optimization model to determine the optimal configuration for WHR for the glass melting process. The objective functions for the process optimization are presented in Section 2.2, while our case study is described in Section 2.3. Then, we show the optimal configurations of WHR for the glass melting process for both economic and emission targets (Section 3). Finally, we conclude the key findings of our assessment and point out further research options (Section 4).

2. Modeling of waste heat recovery for the glass melting process

Several technologies for waste heat recovery (WHR) are utilized in the glass industry nowadays. In our study, we consider five technologies for WHR: Oxidizer preheating, fuel preheating, batch and cullet preheating, heat-to-power conversion process, and waste heat integration into a carbon capture process. Fig. 1 shows schematically how the various WHR technologies can be integrated into the glass furnace. The figure distinguishes the glass melting furnace as the central source of high-temperature flue gas for the WHR technologies that can utilize this waste heat at different temperature levels. In the schematic, the flue gas

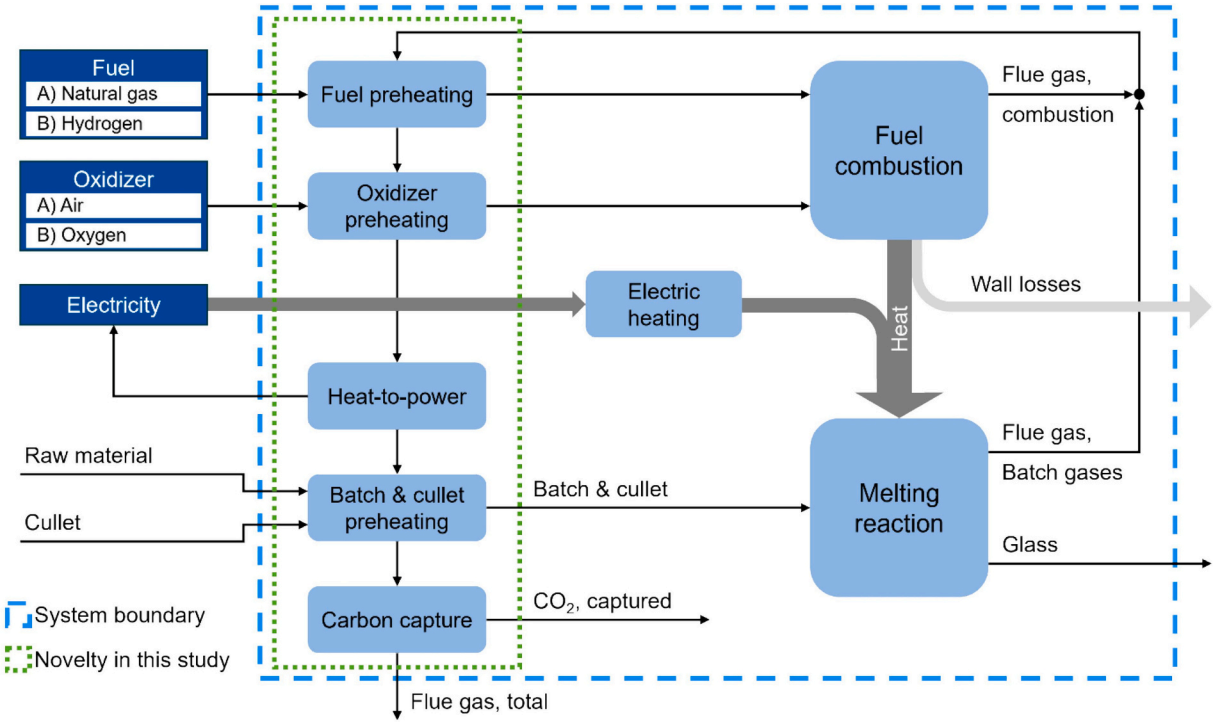


Fig. 1. Schematic overview of the glass melting furnace integrating waste heat recovery (WHR) technologies. The model of the glass melting furnace includes the melting reaction, electric heating, fuel combustion, and wall losses. The WHR technologies include fuel preheating, oxidizer preheating, heat-to-power, batch and cullet preheating, and a carbon capture process. Adapted from [11].

released from the furnace can be directed to the various WHR technologies. Depending on the selected WHR configuration, these technologies can be arranged sequentially such that the flue gas is cooled stepwise while its residual heat is recovered in multiple stages.

Currently, most combustion processes are still carried out with air, whereby the flue gas heat is used for heat recovery by means of recuperators or regenerators to preheat the combustion air [12–14]. Additional preheating of the fuel is not used when air is used as an oxidizer, as fuel preheating is not economically viable in this case. Preheating of fuel can become economically viable when considering oxyfuel combustion [4].

The preheating of batch and cullet is associated with high investment costs and large space requirements. To date, batch and cullet have mainly been preheated with flue gases from the combustion of fossil fuels, but there are initial pilot projects that implement preheating with flue gases from oxyfuel combustion [14]. Preheating increases the temperature of the batch when entering the glass melting process, which reduces the specific heat requirement of the glass melting process.

The most used heat-to-power process is the steam Rankine cycle (SRC) which is commonly used in thermal power plants [15,16]. Thus, we focus our study on modeling a SRC to utilize waste heat. In the SRC, the waste heat in the flue gas is used to produce steam which is then used in a turbine to produce electricity. As the minimal flue gas temperature for an economically viable operation of an SRC is around 400 °C [17], the glass industry with a flue gas temperature of up to 1600 °C is a viable option for the integration of an SRC. We assume a fixed efficiency of 37% for the heat-to-power conversion which represents an upper bound of efficiencies for SRCs. Thus, we assess the maximal potential of utilizing a heat-to-power process for WHR in glass melting.

Further, the waste heat can be utilized in a carbon capture process that is used to capture direct CO_2 emissions from the flue gas. The heat demand of the carbon capture process arises from the heat required for the desorption process of the capturing solvent, here monoethanolamine. The heat is provided by steam that is produced at 2.5 bar from waste heat of the flue gas [18]. We assume that the heat demand of steam production for the carbon capture process can be supplied by either fuel combustion, electric heating, or WHR from the flue gas of the glass melting process. Utilizing waste heat within the carbon capture process avoids indirect greenhouse gas emissions from the energy demand of the carbon capture process. Further information of the WHR technologies is described in the supplementary information (SI).

We model the glass melting furnace and the WHR technologies using energy and mass balances. The energy and mass balances incorporate specific enthalpies depending on the temperature. Using specific enthalpies allows to calculate the enthalpy difference between the in- and outgoing energy flows. We choose an ambient temperature of 25 °C and a pressure of 1 bar as the reference point for all non-preheated mass and energy flows.

The thermodynamic model utilized for calculating the energy requirements of the melting reaction is based on energy and mass balances [25]. The thermodynamic model uses the standard enthalpy of formation of educts and products of the melting reaction. The enthalpy-temperature relationships are based on tables of material properties and applied to process-scale heat integration rather than detailed reaction kinetics or phase-equilibrium modeling of the glass melt. To decrease computational effort, the thermochemical material properties, e.g., enthalpies in the energy balances, are linearly interpolated. The material properties are derived from literature [19–24]. The resolution of the interpolation is chosen to 100 °C due to the available accuracy of material properties.

The educts of the melting reaction are assumed as solid raw materials and cullet. The maximal preheating temperature of batch and cullet is limited to 600 °C to ensure that no CO_2 decomposition reaction occurs when preheating batch and cullet. This maximal temperature is lower than the first decomposition temperature in glass melting. The product of the melting reaction is assumed as liquid glass and gaseous batch gases. Therefore, we consider the enthalpy of phase change together with the standard enthalpy of formation. Higher resolution of material properties may be beneficial for detailed equipment design and transient process analyses and can be accounted in future studies.

Further, a minimal temperature gap between the process streams utilized for waste heat recovery must be fulfilled. To guarantee the temperature gap, we apply a pinch analysis within the optimization. To reliably maintain the minimum temperature gap regardless of the resolution of the material properties, a method of conservatively linearizing the material properties is proposed. This method conservatively estimates the temperatures of the process streams by underestimating the actual temperatures of the hot streams and overestimating those of the cold streams. In addition to the minimum temperature difference, this over- and underestimation also results in an additional temperature difference that ensures compliance with the pinch temperature (see Fig. 2).

We model the heat transfer from the hot towards the cold stream via counterflow heat exchangers rather than parallel flow heat exchangers as the heat exchange is more efficient [26]. We assume heat exchange without losses and calculate the transferred heat with an energy balance according to Eq. (2-1):

$$H_{\mathrm{hot}}\left(T_{\mathrm{hot,in}}\right) - H_{\mathrm{hot}}\left(T_{\mathrm{hot,out}}\right) = H_{\mathrm{cold}}\left(T_{\mathrm{cold,out}}\right) - H_{\mathrm{cold}}\left(T_{\mathrm{cold,in}}\right) \tag{2-1}$$

H describes the enthalpies of the hot and cold streams at the respective input and output temperatures T. The index *hot* corresponds to the hot streams while *cold* corresponds to the cold streams. Further, the indices *in* and *out* denote the input or output of the heat exchange. The heat transfer is modeled within our model for the glass melting process, which is based on our existing model of the glass melting process [11]. The previous model does not consider temperatures of the process streams for heat exchange. Further, the previous model only considers a single-stage WHR from the flue gas. We extend the existing model to consider temperatures of process streams as well as multiple WHR levels. For the previous model, refer to [11]. The relevant adaptions to the previous model can be found in the SI. In the following, we describe the modeling of the flue gas and how the waste heat incorporated in the flue gas can be utilized in multi-stage WHR to derive optimal configurations of WHR (Section 2.1). Then, we show the modeling of the objective functions used for the optimization of the WHR of the glass melting furnace (Section 2.2). Finally, we present the case study in Section 2.3.

2.1. Modeling waste heat recovery of the flue gas

As part of the process optimization of the glass furnace, we consider

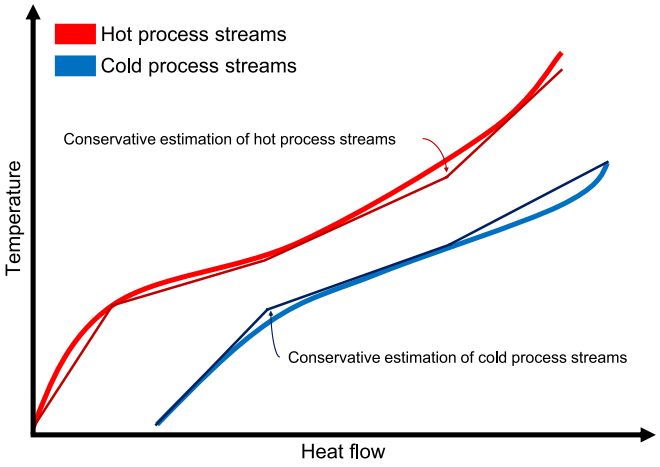


Fig. 2. Schematic diagram for conservatively estimating the enthalpy-temperature curves of hot and cold process streams.

multi-stage WHR with five WHR technologies (see Fig. 1): fuel preheating (*F*), oxidizer preheating (*O*), batch and cullet preheating (*bcp*), heat-to-power (*htp*), and carbon capture (*cc*). We consider $L = \{1, 2, \ldots, L_{\max}\}$ levels of WHR with the possibility of air mixing before each level. Fig. 3 shows schematically the modeling of $L_{\max}$ levels of WHR incorporating air mixing on each level. In our study we consider $L_{\max} = 5$ possible levels of WHR. The flue gas flow is modeled as the hot stream in the heat exchanger of each WHR technology (cf Eq. (2-1)). Conceptually, each WHR level represents one possible heat recovery step in which the flue gas transfers heat to exactly one selected sink. After each step, the flue gas leaves the respective unit at a lower temperature and may either enter the next WHR stage directly or be mixed with ambient air if this is required to satisfy downstream process constraints. This stage-wise representation allows the model to determine not only which WHR technologies should be selected, but also in which sequence they should be arranged along the cooling path of the flue gas.

2.1.1. Waste heat recovery

The decision which WHR processes are used in which order is modeled with a *LxT*-dimensional decision variable matrix σ_{WHR} where T is the set of possible WHR technologies. The matrix entries $\sigma_{\text{WHR},l,t}$ are 1 if a WHR technology t is utilized on a level l and 0 if technology t is not used. We allow for one WHR technology per level l (Eq. (2-2)). Further, each technology can only be utilized once (Eq. (2-3)):

$$\sum_{t} \sigma_{\text{WHR},l,t} \leq 1, \forall l \in L \tag{2-2}$$

$$\sum_{l} \sigma_{\text{WHR},l,t} \leq 1, \forall t \in T \tag{2-3}$$

Further, the number of WHR technologies N_{WHR} can be constrained:

$$\sum_{t}\sum_{l} \sigma_{\text{WHR},l,t} \leq N_{\text{WHR}}, \forall l \in L \wedge \forall t \in T \tag{2-4}$$

To ensure a feasible configuration of WHR technologies, the levels of WHR must be utilized consecutively. If a WHR technology is used at level $l+1$, there must be a technology used on level l:

$$\sum_{t} \sigma_{\text{WHR},l,t} \geq \sum_{t} \sigma_{\text{WHR},l+1,t}, \forall t \in T \wedge \forall l \in L \backslash L_{\max} \tag{2-5}$$

2.1.2. Air mixing

Additionally, air mixing can be required, as the flue gas from the glass melting furnace must undergo purification before being released into the environment. The purification requires the flue gas to be cooled to a lower temperature [14].

The flue gas is cooled by mixing with air, which both increases the mass flow of the flue gas and reduces the exergy it contains due to the reduced temperature level. The energy quantity of the gas mixture remains constant, although the temperature level of the flue gas decreases. Thus, the air mixing change influences the enthalpy-temperature dependency and thus the heat transfer behavior of the flue gas. Further, air mixing is utilized to model the influence of parasitic air. In our model, air mixing is possible before each level of WHR.

Mixing air to the flue gas on a specific level l of WHR is described by the binary decision variable vector σ_{air}. Each entry of the vector $\sigma_{\text{air},l}$ is 1 if air is mixed to the flue gas on a specific level and 0 if no air mixing is considered. Thus, the vector σ_{air} is described by

$$\sigma_{\text{air},l} \in \{0, 1\}, \forall l \in L. \tag{2-6}$$

We assume the mixed air as an ideal gas mixture consisting of nitrogen and oxygen. The mass flow $\dot{m}_{\text{air},l}$ for each level l is also considered as a variable. The mass flow of mixed air is constrained by a minimal air flow $\dot{m}_{\text{air,min}}$ and a maximal air flow $\dot{m}_{\text{air,max}}$.

$$\dot{m}_{\text{air},l} \geq \sigma_{\text{air},l} \cdot \dot{m}_{\text{air,min}} \tag{2-7}$$

$$0 \leq \sum_{l} \dot{m}_{\text{air},l} \leq \dot{m}_{\text{air,max}} \tag{2-8}$$

As mixing of air influences the temperature of the flue gas, the temperature of the flue gas is modeled in more detail. We assume the flue gas temperature $T_{\text{flue gas}}$ after fuel combustion and melting reaction as constant. All further flue gas temperatures are considered as variables since the temperatures are influenced by WHR and air mixing. The flue gas temperatures are modeled as a $L_{\max}$x2 matrix T_{G} describing the flue gas temperature on each level l of WHR. The columns describe the input temperature $T_{\text{G,in}}$ and output temperature $T_{\text{G,out}}$ of the flue gas, while the rows of the matrix describe the level l of the WHR.

The input temperature $T_{\text{G,in},l}$ of level l is dependent on the output temperature of the previous level and the mass flow of air mixing flow $\dot{m}_{\text{air},l}$. The air mass stream is mixed at ambient temperature T_{u} leading to a decrease of the temperature of the flue gas stream on WHR level l. Simultaneously, the mixed air for level l of WHR is heated to $T_{\text{G,in},l}$. If air mixing is not considered on level l, the input temperature $T_{\text{G,in},l}$ is equal to the output temperature $T_{\text{G,out},l-1}$ of the previous level of WHR $l-1$. For the first level of WHR, we consider the input temperature as the flue gas temperature after the fuel combustion and melting reaction $T_{\text{flue gas}}$. The energy balance for the level l of WHR and air mixing is described by:

$$\dot{H}_{\text{flue gas}}\left(T_{\text{G,out},l-1}\right) + \sigma_{\text{air},l} \cdot \dot{H}_{\text{air}}(T_{\text{u}}) = \dot{H}_{\text{flue gas}}\left(T_{\text{G,in},l}\right) + \sigma_{\text{air},l} \cdot \dot{H}_{\text{air}}\left(T_{\text{G,in},l}\right) \tag{2-9}$$

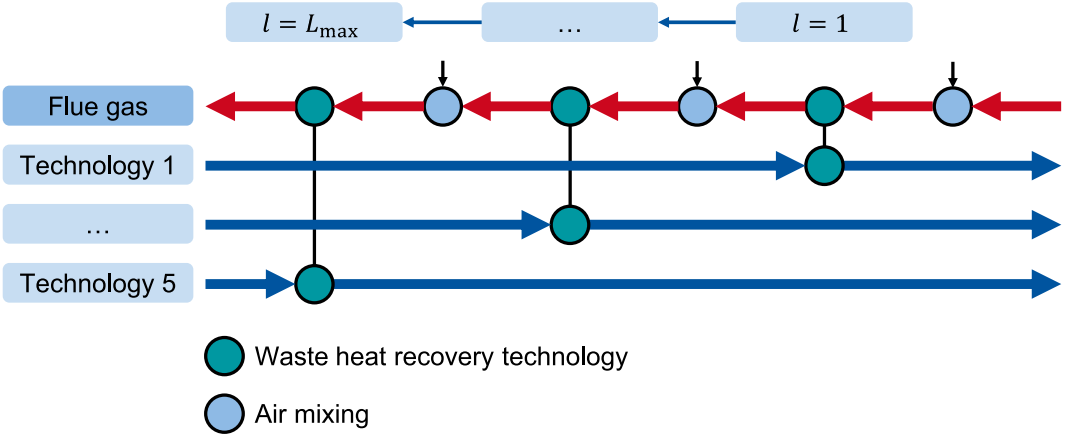


Fig. 3. Schematic modeling of $L_{\max}$ levels of waste heat recovery (WHR) incorporating air mixing on each level of WHR. The flue gas is modeled as the hot stream (red) for heat integration, while the process stream from the WHR technologies is modeled as the cold stream (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The heat of the flue gas $\dot{Q}_l$ that is utilized on a specific WHR level l can be determined with the binary matrix σ_{WHR} and the enthalpies of the flue gas from combustion $\Delta\dot{H}_{\text{flue gas,combustion},l}$, batch gases $\Delta\dot{H}_{\text{flue gas,batch},l}$, and mixed air $\Delta\dot{H}_{\text{air},l}$:

$$\dot{Q}_l = \sum_t \left(\sigma_{\mathrm{WHR},l,t}\right)\cdot\left(\Delta\dot{H}_{\text{air},l} + \Delta\dot{H}_{\text{flue gas,combustion},l} + \Delta\dot{H}_{\text{flue gas,batch},l}\right) \quad (2\text{-}10)$$

The enthalpies $\Delta\dot{H}_{\text{flue gas,combustion},l}$, $\Delta\dot{H}_{\text{flue gas,batch},l}$, and $\Delta\dot{H}_{\text{air},l}$ are dependent on the input and output temperatures $T_{\mathrm{G,in},l}$ and $T_{\mathrm{G,out},l}$ of the WHR level l. We assume a minimal heat that needs to be utilized within a technology $\dot{Q}_{\mathrm{WHR,min}}$. The heat that is integrated in a WHR technology $\dot{Q}_t$ is coupled to the heat from the flue gas $\dot{Q}_l$. For the heat transfer we assume an ideal heat transfer without losses:

$$\dot{Q}_t = \sum_l \left(\sigma_{\mathrm{WHR},l,t}\cdot\dot{Q}_l\right) \quad (2\text{-}11)$$

Further, we restrict the input temperature of the flue gas $T_{\mathrm{G,in},l}$ for specific WHR technologies according to technology specific temperatures $T_{\mathrm{G,max},t}$ reported in literature:

$$T_{\mathrm{G,in},l} = \sum_t \left(\sigma_{\mathrm{WHR},l,t}\cdot T_{\mathrm{G,max},t}\right) \quad (2\text{-}12)$$

The minimal output temperature of the flue gas $T_{\mathrm{G,out},l}$ is constrained by a minimal temperature of 200 °C to account for acid dew point limitations from acids within the flue gas. Constraining the minimal flue gas temperature therefore avoids the risk of corrosion. As this study focuses on analyzing optimal configurations of WHR technologies for glass melting, we neglect requirements of flue gas purification systems such as electrostatic precipitators and bag filters. The potential for waste heat recovery in industrial application is therefore expected to be reduced due to additional flue gas purification systems. Future engineering studies should account for these purification systems.

The heat transferred from the flue gas to the WHR technologies is used to preheat process streams, generate electricity, or waste heat integration into a carbon capture process. The modeling of the specific WHR technologies including temperature constraints is described in more detail in the SI.

The heat integration requires the consideration of pinch analysis to guarantee minimal temperature gaps ΔT_{min} in the heat exchangers for each WHR technology. For the pinch analysis, we consider the flue gas as the hot stream and the process stream of the WHR technology as the cold stream. According to [27,28], we assume a minimal temperature gap ΔT_{min} of 15 °C. The pinch analysis is applied for each level l of WHR for both the input and output streams of the WHR technology. Thus, the minimal temperature gap is ensured at the entry and exit of each heat exchanger. Further, the model allows for checking the minimal temperature gap at further points in between input and exit of the heat exchangers. The points are determined using a predefined step width.

2.2. Objective functions of the process optimization

The objective functions of process optimization include both economic and environmental aspects. Economic evaluation is crucial for industrial decisions with the primary goal of minimizing operational (OPEX) and capital expenditures (CAPEX). Thus, we optimize the total annualized costs (TAC) to consider both CAPEX and OPEX in the objective function:

$$\mathrm{TAC} = \alpha\cdot\mathrm{CAPEX} + \mathrm{OPEX} \quad (2\text{-}13)$$

The CAPEX is annualized with the annuity factor α. The CAPEX considers the investment cost of all WHR technologies based on the amount of recovered heat within the technology. The specific investment cost of each waste heat utilization technology is described in more detail in the SI. The OPEX considers the relevant cost factors including the prices of fuel c_{fuel}, oxygen c_{O2}, electricity c_{el} and CO_2 certificates c_{CO2}, based on price forecasts for 2030 [29,30]. In addition, a selling price for self-produced electricity $c_{\mathrm{el,export}}$ is introduced as 80% of the electricity cost c_{el}. The OPEX are then derived according to:

$$\mathrm{OPEX} = c_{\mathrm{fuel}}\cdot\dot{m}_{\mathrm{fuel,tot}} + c_{\mathrm{O2}}\cdot\dot{m}_{\mathrm{O2,tot}} + c_{\mathrm{el}}\cdot P_{\mathrm{el,import}} + c_{\mathrm{el,export}}\cdot P_{\mathrm{el,export}} + c_{\mathrm{CO2}}\cdot\dot{m}_{\mathrm{CO2,flue\ gas}} \quad (2\text{-}14)$$

$\dot{m}_{\mathrm{fuel,tot}}$ summarizes the fuel requirement for the combustion and the heat requirement of a fuel-operated carbon capture system. The oxygen demand $\dot{m}_{\mathrm{O2,tot}}$ includes the oxygen demand of the combustion reaction when oxyfuel combustion is considered. The electricity requirements for the processes within our system boundary are also modeled. The electricity demand $P_{\mathrm{el,total}}$ consists of the demand for electric heating of the melting process $P_{\mathrm{el.heating}}$, the energy generated by heat-to-power $P_{\mathrm{htp,el}}$ and the electricity demand for an electrically operated carbon capture system $P_{\mathrm{cc,el}}$:

$$P_{\mathrm{el,total}} = P_{\mathrm{el.heating}} - P_{\mathrm{htp,el}} + P_{\mathrm{cc,el}} \quad (2\text{-}15)$$

We assume that the generated electricity is fully utilized, thus avoiding electricity cost. If more electricity is generated than required within the system limits, the net electricity $P_{\mathrm{el,export}}$ is sold. Otherwise, $P_{\mathrm{el,export}}$ is 0.

Furthermore, we consider an environmental objective function to minimize the greenhouse gas (GHG) emissions of the melting process and its energy supply. Thus, the objective function considering GHG emissions is defined as:

$$\mathrm{GHG} = \dot{m}_{\mathrm{CO2,flue\ gas}} + \mathrm{GWP}_{\mathrm{fuel}}\cdot\dot{m}_{\mathrm{fuel,tot}} + \mathrm{GWP}_{\mathrm{O2}}\cdot\dot{m}_{\mathrm{O2,tot}} + \mathrm{GWP}_{\mathrm{el}}\cdot\left(P_{\mathrm{el}} - P_{\mathrm{htp,el}} + P_{\mathrm{cc,el}}\right) \quad (2\text{-}16)$$

The calculation is based on reducing the GHG emissions arising from the direct CO_2 emissions from the melting reaction ($\dot{m}_{\mathrm{CO2,flue\ gas}}$) and further GHG emissions arising from the production and supply of the fuel ($\mathrm{GWP}_{\mathrm{fuel}}$), oxygen ($\mathrm{GWP}_{\mathrm{O2}}$), and electricity ($\mathrm{GWP}_{\mathrm{el}}$). The direct emissions can be reduced by a carbon capture process but result in emissions due to the energy demand of the carbon capture process. Electricity-based emissions can be reduced by the heat-to-power process as it lowers the total electricity demand. In the following, we present the case study that is analyzed with the presented objective functions.

2.3. Case study for optimal waste heat recovery in the glass furnace

As a benchmark, we use the glass melting process with natural gas-air combustion utilizing single-stage WHR to preheat the combustion air. We assume that the flue gas can be cooled to 540 °C by air preheating, as applied in the industry nowadays [31]. Thus, the WHR configuration of the benchmark is fixed within the optimization. As furnace scenarios, we consider different glass melting furnaces with varying fuel, oxidizer and share of electric heating. In the furnace scenarios, each WHR configuration is optimized for a specified number of WHR levels. Table 1 summarizes the considered furnace scenarios.

Low electric heating corresponds to a share of 8% of electric heating as it is implemented in the industry nowadays [32]. High electric heating corresponds to 80% of electric heating which is considered as a potential maximum that can be achieved in the future [33]. In this study, we focus on combustion with air as oxidizer as the potential for WHR is

Table 1
Overview of furnace scenarios regarding considered fuel, oxidizer, and share of electric heating.

Furnace scenario	Fuel	Oxidizer	Electric heating
NG-Air-L	Natural gas	Air	Low (8%)
NG-Air-H	Natural gas	Air	High (80%)
H_2-Air-L	Hydrogen	Air	Low (8%)
H_2-Air-H	Hydrogen	Air	High (80%)

higher than for combustion with oxygen as oxidizer. The higher WHR potential results from the higher mass stream of air combustion from the inert nitrogen. Results of furnaces utilizing oxygen as oxidizer can be found in the SI. Further, the assumptions regarding economic and environmental parameters can be found in the SI.

The presented objective functions are each used individually for process optimization for our case study. Individual evaluation of the objective functions allows a detailed analysis of optimal designs of the glass melting process in which the TAC or GHG emissions are minimized.

3. Assessment of optimal configurations for waste heat utilization in the glass melting process

The goal of our study is to analyze cost- and environmentally optimal configurations of waste heat recovery (WHR) for the glass melting furnace. Thus, we first analyze the total annualized cost (TAC) and greenhouse gas (GHG) emissions of the resulting configurations of WHR.

First, we compare the TAC and GHG emissions of the melting process with natural gas combustion with various numbers of WHR levels, while each configuration is optimized for TAC (Section 3.1). In Section 3.2, we present a contribution analysis of the TAC and GHG emissions of the WHR configurations compared to the benchmark, while the configurations are individually optimized for both TAC and GHG emissions. Then, we extend the assessment by varying the fuel and share of electric heating of the melting process to derive optimal WHR configurations for new innovative melting furnaces (Section 3.3). Further, we discuss the results of our study in Section 3.4.

3.1. Variation of the number of waste heat recovery stages

Fig. 4 shows the TAC of the melting process in furnace scenario NG-Air-L with varying number of WHR levels compared to the benchmark. In the optimization the TAC is used as objective function. The results indicate that a second WHR stage benefits TAC of glass production because it enables the simultaneous reduction of fuel-related operating costs and CO_2 certificate cost through integration of carbon capture. Additional WHR stages beyond the second level provide only marginal further savings, indicating that the economically attractive waste heat potential is already exhausted after the first two recovery stages.

In the benchmark, the TAC accounts to 99.77 €/t_{glass}. The single-stage WHR considers air preheating up to 1164.3 °C while cooling the flue gas to 540 °C. In furnace scenario NG-Air-L, optimizing the WHR of the glass furnace with single-stage WHR with TAC as objective function, reduces the TAC by 4.6% compared to the benchmark to 95.16 €/t_{glass}. The slight cost decrease results from a lower energy demand for the furnace as the combustion air is preheated to a higher temperature of 1275.8 °C while cooling the flue gas to 461.9 °C. The temperatures differ from the benchmark since the temperatures are variables in the optimization and not fixed as in the benchmark. Even though a bigger heat exchanger is required for air preheating, the energy savings offset the higher capital costs. This result shows that even for a conventional single-stage design, optimization of the heat recovery temperature level can slightly improve economic performance compared to current industrial operation. The reduction in TAC remains limited, however, because single-stage air preheating only affects the sensible heat demand of the combustion process and does not address the major cost driver associated with direct CO_2 emissions from melting and combustion.

When utilizing a further level of WHR, the TAC decreases by 31.7% compared to the benchmark to 68.18 €/t_{glass}. The additional WHR level is used to supply heat to a carbon capture process. The carbon capture process is useful as it reduces cost by avoiding cost related to CO_2 certificates. Thus, the potential savings by carbon capture strongly correlate to the CO_2 price. Utilizing more than two WHR levels does not lead to a further cost decrease. Thus, the optimal number of WHR levels for the glass furnace is two with air preheating and carbon capture as technologies. The cost reduction between one and two WHR levels highlights that the economic value of waste heat is not determined solely by the amount of recovered heat, but by the process in which this heat is utilized. Utilizing residual waste heat in the carbon capture system is economically more valuable than other WHR technologies because it substitutes external energy demand in a CO_2 abatement technology and simultaneously reduces certificate costs. This finding emphasizes that multi-stage WHR should be evaluated at the process-system level rather than by considering isolated heat recovery units.

As shown, the TAC of the glass production can be reduced by increasing the number of waste heat recovery stages compared to the benchmark. The optimal TAC in scenario NG-Air-L is achieved with two levels of WHR. Introducing more levels of WHR increases the cost slightly due to the additional infrastructure. Further, optimizing the sizing of heat exchangers for air preheating can reduce the overall cost of

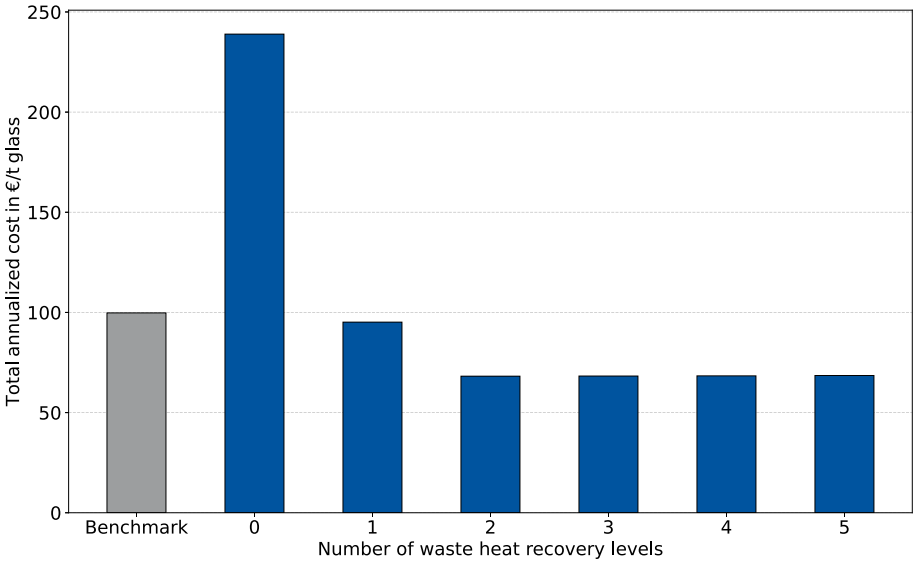


Fig. 4. Total annualized cost (TAC) of the glass furnace in furnace scenario NG-Air-L varying the number of waste heat recovery levels. The TAC is compared to the benchmark of the glass furnace with natural gas combustion preheating of combustion air as single-stage waste heat recovery. The TAC is used as objective function for the optimization.

glass production, highlighting the need for optimization models to design glass furnaces. Despite investment cost of the WHR technologies, the lower operational cost result in an overall cost reduction of the glass production.

3.2. Contribution analysis of the glass melting process with optimized waste heat recovery

The contribution analysis of the TAC is shown in Fig. 5. We compare the benchmark with the TAC- and GHG-optimal glass furnace configurations.

The main cost drivers in the benchmark are the costs for CO_2 certificates and natural gas with a share of 64.4% and 28.3% of the total costs. The high shares result from the cost assumption for 2030 used for our assessment (200 €/t_{CO2}, 28.67 €/MWh_{NG}). All price assumptions are shown in the supplementary information (SI). Utilizing today's cost for CO_2 certificates of 75 €/t_{CO2}, TAC would decrease by approximately 24 €/t_{glass}. Thus, the TAC is sensitive to the assumed utility cost. In the benchmark, only 1.51% of the TAC consist of the investment cost for the oxidizer preheating. This cost structure indicates that the benchmark furnace is dominated by operating expenditures rather than capital-related expenses. Consequently, technologies that reduce direct CO_2 emissions or fuel consumption have a substantially larger leverage on TAC than measures that merely lower electricity demand or shift heat between internal process streams.

The cost for the TAC-optimized glass furnace utilizing single-stage WHR decrease slightly compared to the benchmark. The cost reduction results from the lower energy demand of the glass production which results in less cost for CO_2 certificates, electricity and natural gas. In contrast, the TAC for the GHG-optimized glass furnace with single-stage WHR increase up to 143.7 €/t_{glass}. The integration of the carbon capture process increases the capital expenditures (CAPEX) significantly due to the high investment cost of the carbon capture process. The carbon capture process avoids CO_2 emissions from both melting process and fuel combustion, reducing the cost for CO_2 certificates significantly. Thus, the CO_2 reduction from the carbon capture process outweighs the additional CO_2 emissions from the higher energy demand of the melting process.

When utilizing two stage WHR, the cost decrease significantly for both the TAC- and GHG-optimized process. The TAC mainly decreases by avoiding cost for CO_2 certificates by the carbon capture process and reducing the energy demand with the oxidizer preheating. The carbon capture process reduces the cost for CO_2 certificates by approximately 90% compared to the benchmark. The share of CAPEX increases to approximately 29% in both the TAC-optimized and GHG-optimized furnace with two WHR levels. The resulting TAC is nearly equal for both TAC and GHG emissions as objective function.

We further analyze the GHG emissions of the glass production with optimized WHR configuration compared to the benchmark (see Fig. 6). We analyze the contribution of Scope 1 emissions from the melting reaction and fuel combustion, Scope 2 emissions from the electricity supply, and Scope 3 emissions from the natural gas supply.

In the benchmark, the main driver of GHG emissions are the Scope 1 emissions from the melting process with a share of 83% of the total GHG emissions. The emissions consist of CO_2 emissions from the combustion of natural gas and the melting reaction. The GHG emissions of the TAC-optimized furnace with single-stage WHR decrease slightly compared to the benchmark as more heat is utilized in the WHR leading to a decrease in energy demand. The lower energy demand avoids emissions from the combustion and the natural gas supply.

The emissions of the GHG-optimized furnace with single-stage WHR decrease by 34% compared to the benchmark as a large share of the Scope 1 emissions can be avoided by utilizing a carbon capture process. With the carbon capture process, waste heat is not integrated for preheating the oxidizer. Thus, the overall energy demand of the melting process is higher than for the benchmark. The higher energy demand results in higher Scope 2 and 3 emissions. However, the emission reduction from the carbon capture process outweighs the higher Scope 2 and 3 emissions.

Utilizing two WHR levels can reduce GHG emissions by 70% in both TAC- and GHG-optimized furnace. The main emission reduction results from avoiding Scope 1 emissions from the melting process due to the integration of the carbon capture process as we assume that the captured CO_2 can be permanently stored. The GHG emission reduction would be lower if also the transport and storage of the captured CO_2 were considered. This convergence of the TAC- and GHG optimized furnaces indicates that under the assumed 2030 conditions multi-stage WHR reduces the trade-off between TAC and emissions by enabling an efficient allocation of high-temperature waste heat to both oxidizer preheating and carbon capture.

We show that the utilization of multiple levels of WHR can reduce both TAC and GHG emissions of the glass production for a natural gas-air

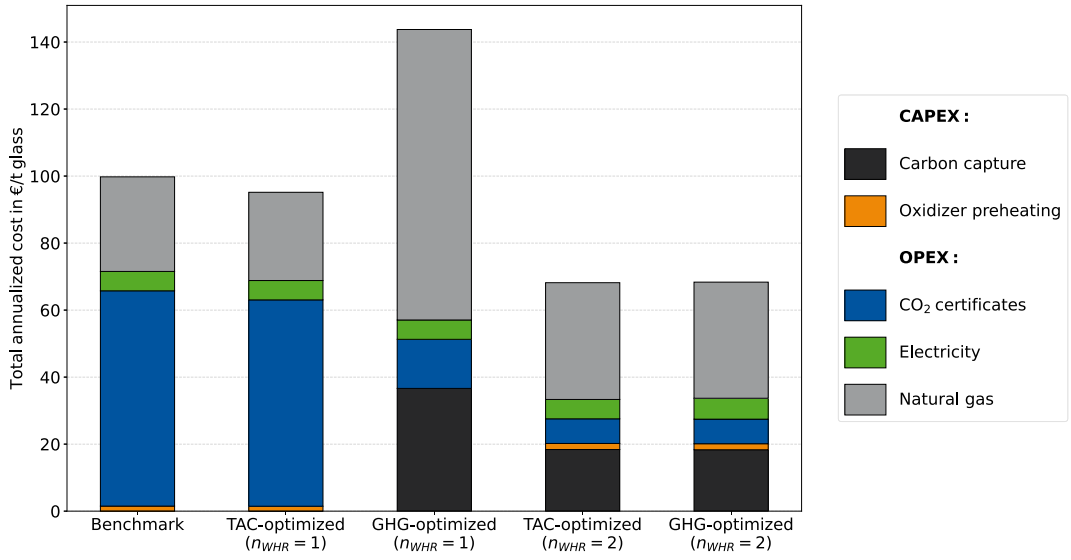


Fig. 5. Contribution analysis of the total annualized cost (TAC) for the glass furnace with optimized waste heat recovery (WHR). The results are compared to the benchmark. n_{WHR} corresponds to the number of WHR stages utilized. The results are shown for the optimization with both TAC and greenhouse gas emissions as objective function.

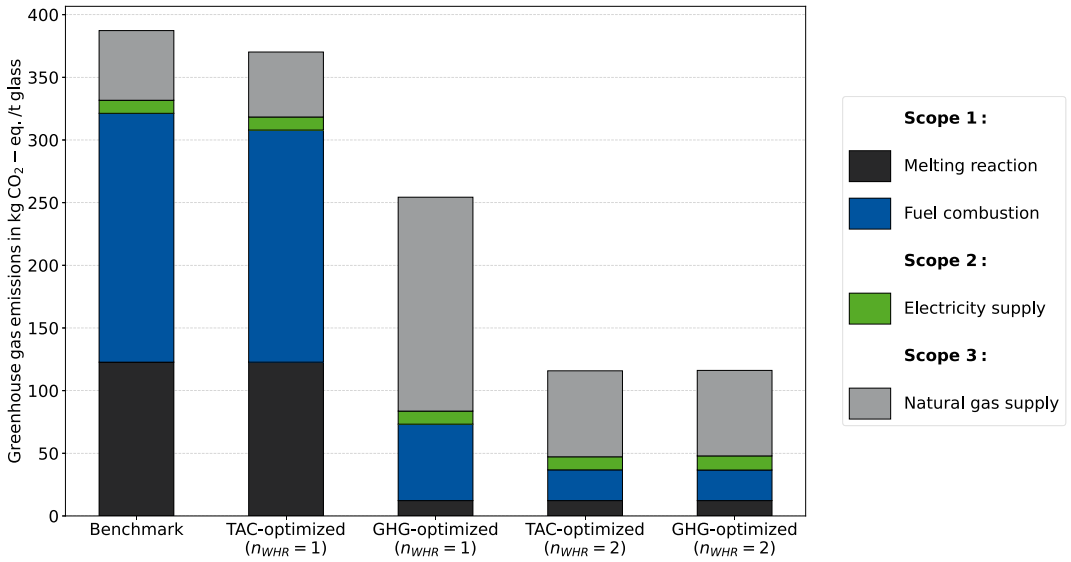


Fig. 6. Contribution analysis of the greenhouse gas (GHG) emissions of the glass furnace with optimized waste heat recovery (WHR). The results are compared to the benchmark. n_{WHR} corresponds to the number of WHR levels utilized. The results are shown for the optimization with both total annualized cost and GHG emissions as objective function.

furnace with a low share of electric heating. As literature further discusses higher shares of electric heating and hydrogen combustion as promising options for new glass furnaces, we analyze which WHR technologies should be utilized for these new furnaces.

3.3. Optimal waste heat recovery for glass furnaces with hydrogen combustion and high electrification

We extend our analysis by varying the fuel and share of electric heating for alternative heat supply in new glass furnaces. The extended analysis can support planners of glass furnaces in designing new glass furnaces. The new glass furnaces are optimized for TAC and GHG emissions by incorporating multi-stage WHR. Fig. 7 shows the TAC and the GHG emissions for all furnace scenarios with varying the number of WHR levels. The comparison across scenarios allows assessment of how robust the identified WHR strategies are under changing furnace concepts and, in particular, whether the role of multi-stage WHR decreases when combustion is partially substituted by electricity or hydrogen.

In all furnace scenarios, the TAC and GHG emissions decrease with the integration of WHR technologies compared to the melting process

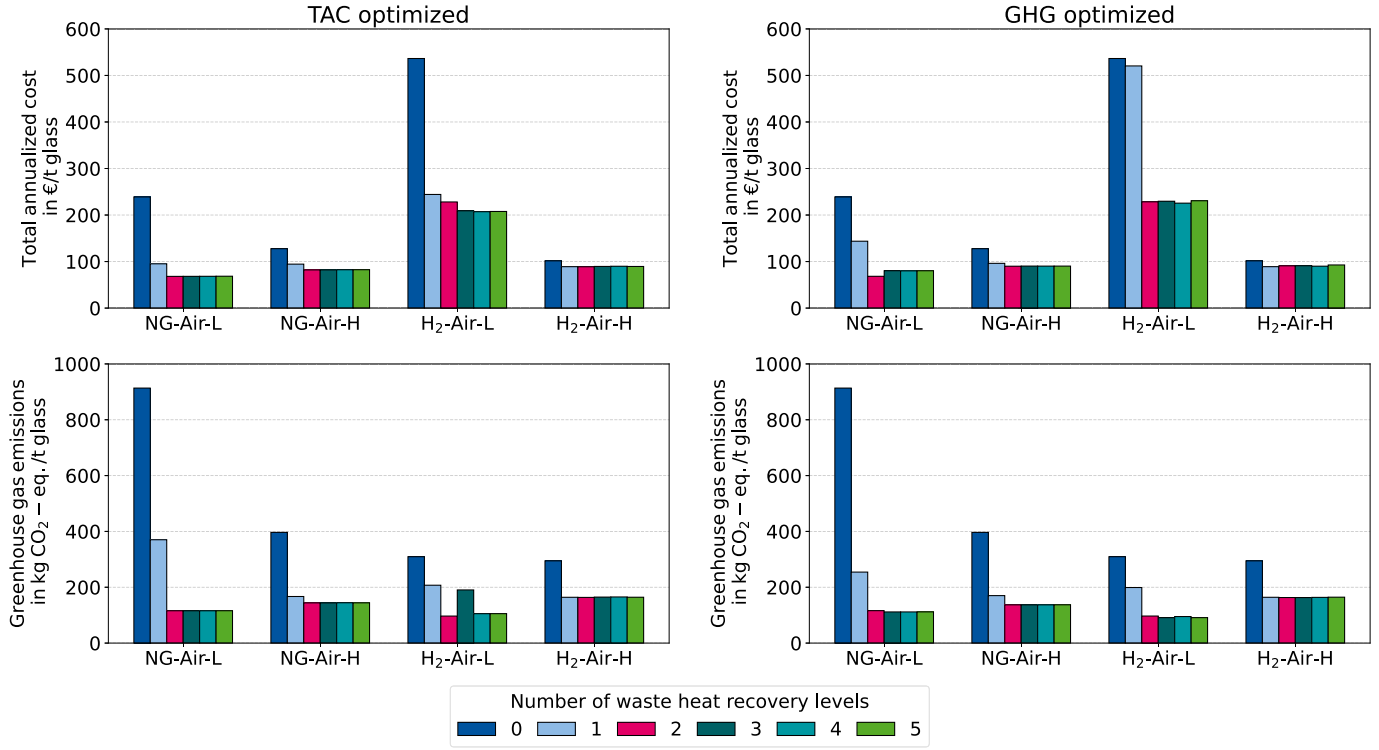


Fig. 7. Total annualized cost (TAC) and greenhouse gas (GHG) of the glass melting furnace with optimized waste heat recovery (WHR) configurations for all furnace scenarios. The number of WHR levels is varied. The furnace scenarios are optimized with both TAC and GHG emissions as objective functions.

without WHR. In all scenarios, the integration of multi-stage WHR reduces the cost and GHG emissions compared to single-stage WHR. In scenarios NG-Air-H and H_2-Air-H, where high shares of electric heating are utilized, the potential of multi-stage WHR to decrease TAC is lower than in the respective scenarios with a low share of electric heating. The lower potential results from a lower amount of available waste heat due to the lower fuel demand. In all assessed scenarios from Table 1, preheating of combustion air and carbon capture are integrated on the first two WHR stages when optimizing TAC as objective function. When utilizing GHG emissions as objective function, oxidizer preheating and carbon capture are favored on the first two WHR stages for furnace scenarios NG-Air-L and H_2-Air-L. However, in furnace scenarios NG-Air-H and H_2-Air-H, preheating batch and cullet is favored instead of oxidizer preheating, because the potential of oxidizer preheating is reduced due to the lower waste heat stream. Thus, the potential for integrating waste heat in batch and cullet preheating is higher than integrating waste heat in oxidizer preheating. The potential for decreasing the GHG emissions of the glass melting furnace is not strongly dependent on the fuel and share of electric heating. This indicates that the qualitative role of the first two WHR stages is robust across the investigated furnace concepts: one stage is mainly used to recover sensible heat and lower furnace energy demand, whereas the second stage enables utilization of residual heat in carbon capture. By contrast, the marginal value of additional stages is scenario-dependent because it is governed by the remaining flue gas heat after these two key functions have been satisfied.

In scenarios H_2-Air-L and H_2-Air-H, the WHR configuration to minimize the TAC requires the integration of four and three stages of WHR, respectively. In scenario H_2-Air-L, fuel preheating and batch and cullet preheating are integrated. In scenario H_2-Air-H, fuel preheating is integrated in the optimal WHR technologies. Even though carbon capture is utilized in all scenarios within the first two stages of WHR, the potential for decreasing the TAC is strongly dependent on the assumed price for CO_2 certificates. Thus, the potential of integrating a carbon capture system into the glass melting furnace requires deeper analysis considering further future price forecasts.

Analyzing the optimal WHR configurations in all scenarios shows similar TAC and GHG emissions of the glass furnace independently of the chosen objective function. The WHR technologies that are utilized in each scenario for each number of WHR are presented in the SI. Further results considering oxygen as oxidizer for the combustion can be found in the SI. Utilizing oxygen as oxidizer results in a lower mass flow in the combustion and the flue gas. The lower mass flow limits the potential for utilizing WHR. The assessment of the optimal WHR configurations shows that the carbon capture process is utilized in all scenarios with oxygen as oxidizer on the first level of WHR. Further, air preheating is not utilized on the first two levels of WHR in all scenarios with oxygen as oxidizer indicating the reduced potential for oxidizer preheating due to the reduced mass flow.

3.4. Discussion

Heat exchanger efficiencies were assumed without losses. Assuming ideal heat transfer overestimates recoverable heat and underestimate TAC and CO_2 emissions. Especially at high heat transfer temperatures heat exchangers are subject to non-ideal effects such as radiation losses, fouling, and finite heat transfer coefficients. Thus, future work can incorporate more detailed heat transfer models. The overall potential for integrating multi-stage WHR is strongly dependent on the efficiency of heat transfer. While our model can derive optimal configurations of waste heat recovery technologies, these optimal configurations should then be used within detailed engineering to determine more realistic energy demands and designs. The present results should therefore be interpreted primarily as identifying thermodynamically and economically promising WHR structures rather than as a detailed equipment design. In particular, the ranking of WHR technologies and the finding that two-stage recovery is highly beneficial are considered more robust than the exact absolute values of TAC and GHG reductions.

Our results rely on assumed future trajectories for fuel, electricity, and CO_2 prices that may deviate under real market conditions. Long-term operational impacts on furnace stability, product quality, and downtime were not modeled but may influence practical feasibility. Thus, sensitivity analysis regarding utility cost should be applied to identify robust WHR configurations for glass furnaces.

Our study assumes a fixed efficiency for the heat-to-power process. However, the actual cycle performance of a heat-to-power process depends on temperature level and quality of recoverable heat from the flue gas. Therefore, future work could incorporate more detailed cycle performance models accounting for varying operating conditions including an efficiency based on temperature levels.

Carbon capture feasibility depends on future regulatory approval, CO_2 storage availability, and infrastructure development. Further, CO_2 transport and storage were neglected. CO_2 transport and storage cause additional cost and emissions.

The presented limitations of our study show that real-world industrial application may require further engineering validation to confirm feasibility.

4. Conclusion

The European glass industry faces significant pressure to reduce greenhouse gas emissions by 40% by 2030, yet most industrial furnaces still rely on natural gas combustion, resulting in high process emissions. While literature highlights enhanced waste heat recovery (WHR) as a key strategy for improving energy efficiency and reducing emissions in glass production, current WHR solutions are limited to mainly single-stage WHR. However, optimizing multi-stage WHR configurations for modern and emerging furnace concepts could lower production costs and emissions. Our study addresses this gap by applying mathematical process modeling and non-linear optimization to optimize total annualized cost (TAC) and greenhouse gas (GHG) emissions of various WHR strategies for glass furnaces. We assess five technologies for waste heat recovery: preheating oxidizer, preheating fuel, preheating batch and cullet, heat-to-power conversion, and heat integration into a carbon capture system. Our model determines the optimal configuration of WHR with the temperatures, mass flows and sizes of WHR technologies as degrees of freedom. A conventional natural gas-air furnace with single-stage combustion-air preheating serves as the benchmark. Increasing the number of WHR stages is analyzed for furnaces with natural gas and hydrogen combustion as well as varying degrees of electrification.

Our model can identify configurations of optimal WHR technologies, which reduce TAC and GHG emissions compared to the current application within the glass industry. In the benchmark scenario which is assumed as a conventional natural gas air furnace, single-stage air preheating results in a TAC of 99.34 €/t_{glass}. *Re*-optimizing in scenario NG-Air-L with single-stage WHR configuration reduces TAC to 94.88 €/t_{glass}, corresponding to a reduction of 4.5%. Introducing a second WHR level decreases TAC further to 68.19 €/t_{glass}, which corresponds to a total reduction of 31.4% relative to the benchmark. At the same time, GHG emissions are reduced by 70% compared to the benchmark configuration. The reduction is mainly achieved by avoiding direct CO_2 emissions from the melting reaction and fuel combustion through the integration of carbon capture, while oxidizer preheating reduces the energy demand of the furnace. The most promising WHR technologies to reduce TAC and GHG emissions are therefore air preheating and carbon capture.

The scenario analysis shows that multi-stage WHR remains beneficial not only for natural gas furnaces, but also for hydrogen-fired and hybrid furnace concepts. In all scenarios, multi-stage WHR reduces TAC and GHG emissions compared to single-stage recovery. However, the economic benefit decreases at high electrification because the lower fuel demand reduces the amount of available waste heat.

Overall, the results demonstrate that the main benefit of multi-stage WHR does not arise solely from recovering a larger amount of heat, but from enabling a more effective allocation of waste heat between furnace efficiency measures and carbon capture. The potential of the optimized glass furnaces should further be assessed within a transitioning energy system with varying utility prices and electricity-related GHG emissions. Such assessments can support decision makers in the glass industry in designing robust low-carbon furnace concepts under future regulatory and market conditions.

Declaration of generative AI and AI-assisted technologies in the writing process

The author(s) used ChatGPT to improve the clarity and readability of this text during the preparation of this work. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publication's content.

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.applthermaleng.2026.132340.

Data availability

Data will be made available on request.

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