



Research Paper

Reducing CO₂ emissions in the copper smelting process by using high-temperature solar heat: Tecno-economic assessment

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ARTICLE INFO

Keywords:

Solar mining
Copper smelting process
Industrial heat process
CSP_{th} Central Tower technology

ABSTRACT

The work explores the idea of using high-temperature solar heat in the copper smelting process; a Hybrid Central Tower system is analyzed to supply the high-temperature air for this process. The methodology was built based on the equilibrium of the smelting reactions; therefore, this analysis only account for the reactions' energy demand. Two process schemes (process with/without using high-temperature air) and five off-gas scenarios were evaluated. Using Hybrid Central Tower systems with 13 h of Thermal Energy Storage leads to significant reductions in the annual equivalent energy consumption of the reactions (up to 22.61 %) and in the CO₂ emissions of the smelting process (up to 61.4 %). The scheme that doesn't use high-temperature air is the lower-cost option; however, with a 15 % reduction in the capital expenditure and using a discount rate of 5 %, the scheme that uses Hybrid Central Tower systems with 13 h of Thermal Energy Storage shows the similar present value costs. If a carbon price of 25 USD/tCO₂e is included, the latter scheme represents the lower-cost option and the most cost-effective solution to avoid CO₂ emissions.

1. Introduction

Copper is an important metal for the global development. Owing its chemical, thermal, electrical, and mechanical properties, copper is widely used for electrical and electronic equipment, construction, infrastructure, industrial processes, and transport [1]. To fulfill the world's copper demand, copper production by mining has been growing from 15.9 million tons in 2010 to an estimated 20 million tons in 2020 [2]; this represents a growth rate of nearly 3 % per year. However, as much as copper is needed for a wide range of applications, copper has its downsides: producing copper leaves a significant footprint on the environment in the form of atmospheric emissions, and both solid and waterborne wastes [3,4].

Copper is produced by two main routes: the pyrometallurgical and the hydrometallurgical route [5]. The pyrometallurgical route accounts for about 80 % of the primary copper production [6]. Norgate et al. [7] calculated with a Life Cycle Assessment (cradle to gate) that every kilogram of refined copper (kg-Cu) requires around 33 MJ and generates about 3.3 kg-CO₂ if processed by the pyrometallurgical route. Using this

data for a rough estimation, in 2020, the pyrometallurgical route was accountable for about 52.8 million tons of CO₂ emissions. However, CO₂ emissions are related to energy consumption [8] and the energy consumption is highly influenced by the ore grade [4], which is decreasing progressively. Lower ore grades demand more energy for the mining and beneficiation processes. For example: in Chile, the energy demand of the copper mining industry grew by 63 % from 2001 to 2012, whereas the copper production increased just 15 % [9].

In order to sustain the growth rate of copper production while part of the environmental damage is avoided, copper production requires a large-scale decarbonization. In this sense, some studies propose to use solar energy to address the energy requirements of this industry. One of the main and potential topics is the substitution of electricity from the grid (or changing the current generation mix) by using either Photovoltaic (PV) systems or Concentrating Solar Power (CSP) systems [10–12]. Another common topic is the use of low-temperature solar heat for processes such as leaching, froth flotation, electrowinning, and electrorefining [9,13–15]. In other level of development, the use of solar fuels has been mentioned for processes that require fuel consumption

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<https://doi.org/10.1016/j.applthermaleng.2023.120270>

Received 16 October 2022; Received in revised form 17 January 2023; Accepted 17 February 2023

Available online 24 February 2023

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on-site [16]; also, at an innovative level, direct solar irradiation has been studied for new processes of copper production [17,18]. As it can be seen, there are already some feasible alternatives for the use of solar energy in this industry; however, there are other options that have not been studied, such as using high-temperature solar heat for the high-temperature processes.

At the current commercial state, the CSP Central Tower technology produces high-temperature heat and can be scaled in the order of megawatts. Besides, this technology provides a high-reliable energy supply if combined with Fuel-Based systems: this combination is known as CSP Hybrid systems [19]. It should be noted that “CSP” refers to electric power generation; for this work, the term “CSP_{th}” was introduced to refer to Concentrating Solar Thermal Power. Nowadays, just few works evaluate the use of a CSP_{th} Hybrid Central Tower system (CSP_{th} Hybrid-CT system) for industrial process heat; for example, Schröders and Allelein [20] studied this technology for the ammonia production process. However, no work has analyzed the use of this technology for copper production.

In this sense, this work explores the effects of using high-temperature solar heat in the copper smelting process. The work proposes to use a CSP_{th} Hybrid-CT system to produce the high-temperature solar heat. The entire analysis is based on the equilibrium of the chemical transformations of the reactants. Several process scenarios were analyzed: for each scenario, a CSP_{th} Hybrid-CT system was designed and evaluated. The CSP_{th} Hybrid-CT systems were designed using two solar multiples, 1 and 2.5; for the solar multiple of 2.5, a Thermal Energy Storage system was integrated in the analysis. The paper also presents an estimation of the avoided CO₂ emissions and an economic analysis. Section 2 gives a short description of the copper smelting process, Section 3 describes the methodology, Section 4 presents results and discussions, and Section 5 summarizes the main conclusions of this work.

2. The copper smelting processes

Copper is mainly presented in the form of copper sulfide minerals, such as chalcopyrite (CuFeS₂), chalcocite (Cu₂S) and bornite (Cu₅FeS₄). In the book Extractive Metallurgy of Copper, Schlesinger et al. [5] describe the two routes for processing copper minerals; the best option to treat sulfide minerals is the pyrometallurgical route (Fig. 1). Because the ore grade in copper minerals goes from 0.5 % for open-pit mines to 2 % for underground mines, the ore passes through comminution and beneficiation processes to produce copper concentrates, which contain between 20 % and 30 % of copper. The concentrates are dried to eliminate humidity; in some cases, a roasting process is carried out to eliminate impurities. Copper concentrates are sent to the smelting process, which produces matte, slag, and off-gas. The converting process transforms the matte into copper blister, which then is converted into copper anodes in a thermal refining process. These anodes are electro-refined to produce high-purity copper cathodes (99.99 % Cu).

The smelting, converting, and thermal refining processes operate at temperatures around 1,250 °C. Although smelting and converting involves exothermic reactions, a significant amount of fuel is combusted in these processes [22,23]. Fuel consumption depends on the furnace technology, which is diverse; Moskalyk and Alfantazi [24] provide a review of the smelting technologies. Particularly, the reverberatory and flash-smelting furnaces account for about 25 % and 50 % of the world's copper smelting capacity, respectively [25].

The smelting process is a complex sequence of concatenated chemical reactions [26]. However, the process can be illustrated with a general simplification [27]; Fig. 2 shows the control volume and the mass flows involve in the flash-smelting process. The input flows are copper concentrates, fossil fuel, air, industrial oxygen, silica flux, and recovery dust. The chemical reactions produce matte, slag, and off-gas; matte and slag are separated in the settler shaft, while the off-gas is

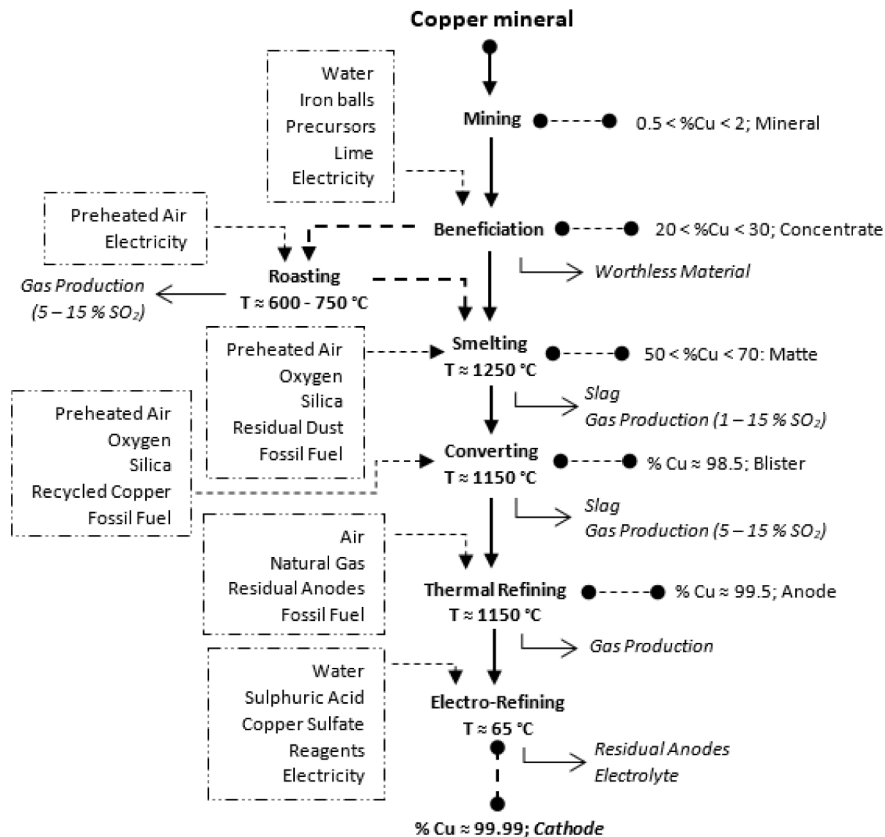


Fig. 1. Pyrometallurgical route for copper production. Information sources: [5,21].

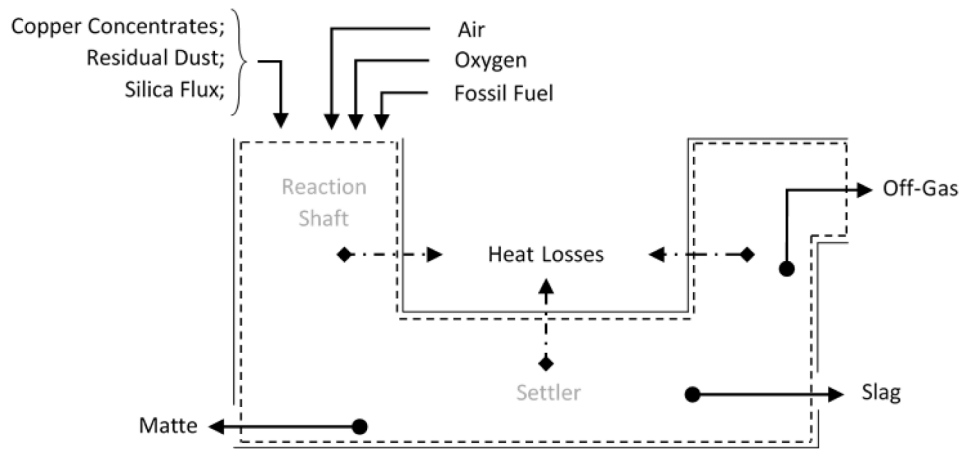


Fig. 2. Flash smelting process.

extracted by the off-gas taker. The smelting process is exothermic because of the sulfur oxidation; this heat is used by the reactions. However, fossil fuel is combusted for four purposes: to complement the energy requirements, to raise the process temperature, to avoid cold spots, and for temperature control. Energy leaves the furnace through the products and part of the energy is lost through the furnace walls.

One goal during the smelting process is to maintain the composition of the products; this goal might be affected by a variation in the feed material [28]. Usually, the control of the process involves models that combine input parameters and feedback data, such as the products' quality. An important quality parameter is the copper grade in matte; this parameter is obtained after testing matte samples. Given the delay between the continuous process and the feedback data, variations in input parameters might complicate the furnace operation. In this sense, some authors have proposed alternatives to predict and control the smelting process [29–34].

However, a classical methodology to model the chemical reactions of the smelting process is the mass and energy balance. This methodology does not consider the reactions' kinetics and fluid dynamics, but it is of high relevance because it provides the thermodynamic equilibrium of the smelting process. The mass and energy balance is a useful tool to simulate the smelting process [27]. The results can be used to compare with industrial data and to find improvement opportunities [35].

3. Methodology

One important input for the smelting process is air (Fig. 2). Air introduces oxygen that is used for the combustion of hydrocarbons and sulfur. The nitrogen in the air does not react; however, it consumes energy from the reaction to increase its temperature. Preheating the air avoids the cooling effect of nitrogen and provides energy for the chemical reactions; in consequence, the smelting process requires less industrial oxygen and less fossil fuel.

In this sense, the paper proposes to use a CSP_{th} Hybrid-CT system to supply high-temperature air to the smelting process. The methodology in this paper consists of three models: one for the smelting process, one for the CSP_{th} Hybrid-CT system, and one for the economic evaluation. The input rate of preheated air and its temperature were obtained from the equilibrium of the chemical reactions; therefore, the smelting process was solved using a steady-state mass and energy balance. For the CSP_{th} Hybrid-CT system, the CSP_{th} Central Tower was designed and evaluated using SolarPILOT and an energy balance was performed to estimate the energy required from the backup system. Data and results were analyzed and processed using Wolfram Mathematica. The geographic site chosen for the analysis corresponds to the Region of Antofagasta, Chile; this site has a high solar resource (annual DNI 3,454

kWh/m²) [36]; besides, Chile is the biggest producer of copper concentrates [37].

3.1. Definition of the CSP_{th} Hybrid-CT system

The most practical way of preheating air with the CSP_{th} Central Tower technology is to use air as a heat transfer fluid. If air acts as a heat transfer fluid, the CSP_{th} Central Tower technology can preheat it at temperatures up to 800 °C [38–40]. However, this scheme presents one significant drawback for the purpose of this work: there isn't a commercial Thermal Energy Storage (TES) system for air preheating. Nowadays, the commercial technology of CSP_{th} Central Tower with TES system uses molten salt as a heat transfer fluid. A typical molten salt called "solar salt" is a blend composed of sodium nitrate (60 %) and potassium nitrate (40 %), this salt can operate at temperatures up to 574 °C [41]; however, a single nitrate component can operate at a temperature around 600 °C, whereas carbonate-based salts or chloride-based salts can operate at around 650 °C [42]. In this sense, this work proposes to use a heat exchanger to transfer heat from a hot molten salt to the air.

Fig. 3 shows a general scheme for the CSP_{th} Hybrid-CT system. The figure shows the plant configuration and the major components of the system. The heliostat field reflects the solar irradiation towards the receiver device. The receiver absorbs irradiation and transforms it into thermal energy. Then, molten salt removes heat from the receiver and goes to the TES system. High-temperature air is produced by using a heat exchanger between molten salt and air. A backup system (auxiliary boiler) operates if there isn't enough energy from the solar source; as explained further in the text, the backup system could heat the cold molten salt and send it to the hot tank. Finally, the high-temperature air is sent to the flash smelting furnace.

General assumptions for the CSP_{th} Hybrid-CT system:

- For this work, just the major components of the CSP_{th} Hybrid system were considered.
- The system's performance was evaluated throughout the year, using time steps of 1 h.
- The system was considered to operate in steady-state at each time step.
- The solar energy production was weighted with an annual degradation factor of 0.2 % [43].
- Pressure drops were neglected.
- The electrical parasitics of the CSP_{th} Central Tower, which usually accounts for about 10 % of the electricity output in power generating systems [44], were not considered.
- The backup system was considered to operate with natural gas.
- The system's lifespan was considered to be 30 years.

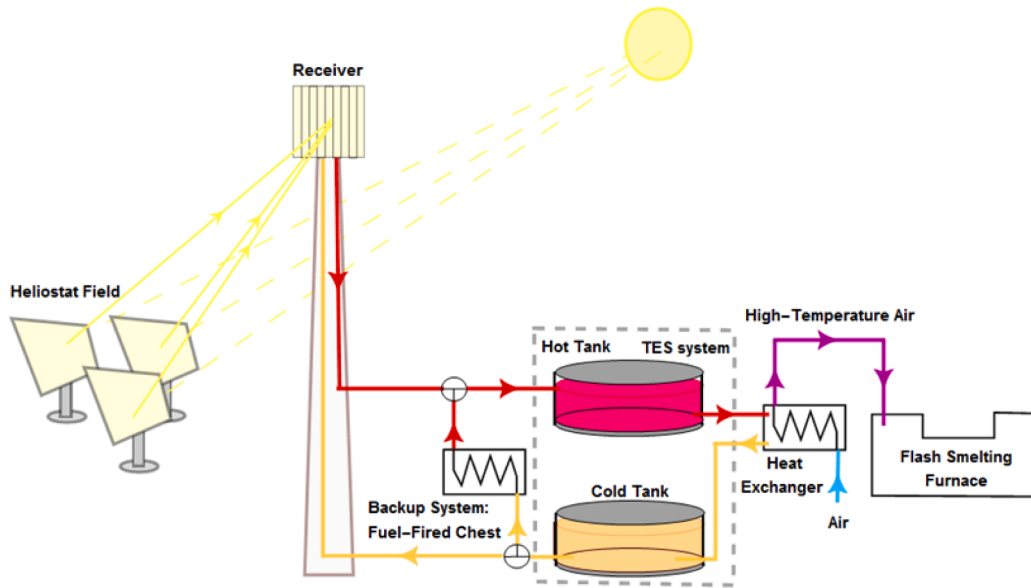
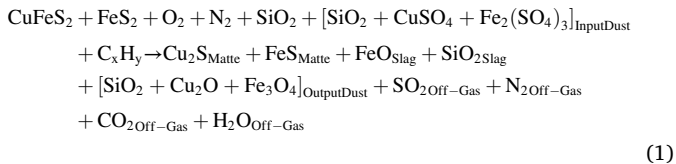


Fig. 3. Scheme of the CPS Hybrid-CT system adapted for the smelting process.

3.2. Smelting process model

The smelting process was modeled using steady-state mass and energy balances. The mass balance equations were built based on every element entering and leaving the flash furnace, whereas the energy balance equation was built based on the first law of thermodynamics. This set of equations were solved using linear algebra. Finally, a parametric analysis was conducted for the solutions, and the amount of energy for air preheating was obtained. The molar weights and enthalpies used in this model were obtained from the FactSage-Education software.

For this work, the copper concentrate was considered to be chalcopryrite (CuFeS_2) and pyrite (FeS_2). Two sources of oxygen were considered: industrial oxygen and air; air also introduces nitrogen to the process. Natural gas was selected as fossil fuel. The analysis also considered recovery dust. The off-gas carries dust in the form of Cu_2O , Fe_3O_4 , and SiO_2 ; this dust contains a significant amount of copper. After cooling the off-gas, the dust is recovered and sent to the furnace in the form of CuSO_4 , $\text{Fe}_2(\text{SO}_4)_3$, and SiO_2 . Using a method similar to that used by Davenport and Partelpoeg [27], the following unbalanced stoichiometric equation condenses the smelting process studied in this paper.



Two kind of mass balance equations were used to define the smelting process: equations for single elements and complementary equations. Equation (2) describes the general form of the mass balance equations for single elements.

$$M_{E_i} = \left| \sum_{j=1}^n \beta_{E_i}^{C_j} * m_{C_j} \right|_{\text{Reactants}} = \left| \sum_{j=1}^n \beta_{E_i}^{C_j} * m_{C_j} \right|_{\text{Products}} \quad (2)$$

M_{E_i} : Mass of element “i” (elements: Cu, Fe, S, O, N, SiO_2 , C, H).

C_{j_i} : Compound “j” (Reactants: CuFeS_2 , FeS_2 , O_2 , N_2 , SiO_2 , $\text{Dust}_{\text{input}}$, C_xH_y ; Products: Cu_2S , FeS , FeO , SiO_2 , $\text{Dust}_{\text{output}}$, SO_2 , N_2 , CO_2 , and H_2O).

$\beta_{E_i}^{C_j}$: Concentration of element “i” in compound “j”.

m_{C_j} : mass of compound “j”.

SiO_2 is an inert chemical specie in the smelting reaction [35]; therefore, it was treated as it were a single element.

Eight balance equations and sixteen variables were generated using equation (2). These mass balance equations were complemented with other seven equations. Equation (3) specifies the slag composition. Equation (4) specifies the matte grade, but it introduces a new variable which is defined with equation (5). Equations (6) and (7) specify the rate of input and output dust. Since the fossil fuel (natural gas) contains a significant amount of nitrogen, other two variables and two equations were included, equations (9) and (10).

$$m_{\text{SiO}_2\text{Slag}} = m_{\text{FeO}} * \left(\frac{m_{\text{SiO}_2}}{m_{\text{FeO}}} \right)_{\text{Slag}} \quad (3)$$

$$0 = \beta_{\text{Cu}}^{\text{Cu}_2\text{S}} * m_{\text{Cu}_2\text{S}} + \beta_{\text{Cu}}^{\text{Matte}} * m_{\text{Matte}} \quad (4)$$

$$m_{\text{Matte}} = m_{\text{Cu}_2\text{S}} + m_{\text{FeS}} \quad (5)$$

$$m_{\text{InputDust}} = d^* (m_{\text{SO}_2} + m_{\text{N}_2} + m_{\text{CO}_2} + m_{\text{H}_2\text{O}}) \quad (6)$$

$$m_{\text{OutputDust}} = 0.5 * m_{\text{InputDust}} \quad (7)$$

$$m_{\text{Input N}_2\text{Fuel}} = \beta_{\text{N}_2}^{\text{Fuel}} * m_{\text{Fuel}} \quad (8)$$

$$m_{\text{Output N}_2\text{Fuel}} = m_{\text{Input N}_2\text{Fuel}} \quad (9)$$

d: rate between the mass of input dust and the mass of off-gas.

The energy that enters and leaves the flash furnace was calculated based on the compounds’ enthalpy, energy inputs, and energy losses. The chemical transformations that take place in the furnace’s reaction shaft are carried out at constant pressure with no other work than the work performed by the volume change against pressure. Under these conditions, the net heat exchange during the reactions is an exact differential, independent of the path or the transformation steps. This heat can be calculated using the compounds’ enthalpy (Hess’s Law). Because the enthalpy is a thermodynamic property, the net heat exchange depends only on the nature and condition of the initial reactants and final products.

For the energy balance equation, the energy inputs must be equal to the energy outputs. A new variable was added to the energy inputs, the energy for air preheating “ E_{AP} ”; also, the variable energy losses “ E_L ” was added to the energy outputs. The energy losses correspond to the conductive, convective, and radiative thermal losses in the flash furnace.

$$\left| \sum_{j=1}^n (\Delta H_f^0)_{V_j} \cdot m_{V_j} \right|_{\text{Reactants}} + E_{AP} = \left| \sum_{j=1}^n (\Delta H_f^0)_{V_j} \cdot m_{V_j} \right|_{\text{Products}} + E_L \quad (10)$$

ΔH_f^0 : enthalpy of formation per unit of mass of variable j .

m_{V_j} : mass of variable j .

The enthalpy of the fossil fuel (natural gas) was calculated from its composition and the enthalpies of its compounds.

This set of mass and energy balance equations is a linear system of 16 equations with 21 variables. In order to solve the system, a numerical value has to be specified for the variables m_{CuFeS_2} , m_{FeS_2} , m_{Fuel} , E_{AP} , and E_L . The system was solved for a fixed rate and composition of copper concentrates (m_{CuFeS_2} , m_{FeS_2}) and for a fixed rate of energy losses (E_L); on the other hand, the system was evaluated for several increments of both fuel consumption (m_{Fuel}) and energy for air preheating (E_{AP}). For every solution, the mass of industrial oxygen “ m_{IO} ” was calculated.

$$m_{\text{IO}} = m_{\text{O}_2} - \left(\frac{0.23}{0.77} \right) m_{\text{N}_2} \quad (11)$$

Every solution provides information on the smelting process: industrial oxygen consumption, fuel consumption, energy for air preheating, mass of air, mass and composition of the off-gas. These parameters were plotted in 2-D space and were characterized using linear equations (see Appendix A). The general form of equation (12) defines all the parameters as function of two of them: the energy for air preheating and the industrial oxygen consumption.

$$P(E_{AP}, O_I) = a_P(E_{AP}) + b_P O_I = (a_{1P} + a_{2P} E_{AP}) + b_P O_I \quad (12)$$

P : Parameter: off-gas, total energy consumption, mass of air, sulfur dioxide, carbon dioxide, and steam.

a_P and b_P : coefficients of the linear equations.

O_I : industrial oxygen consumption.

For the copper smelting process, the off-gas production is a key parameter because of two reasons: 1) the off-gas handling systems impose a technical limit in the rate of smelting, and 2) the off-gas production establishes a correlation between industrial oxygen consumption, fuel consumption, and energy for air preheating. Considering these reasons, the off-gas parameter was used to establish five off-gas scenarios (see Appendix B) where theoretical baseline cases that doesn't use high-temperature air are compared to theoretical scenarios that use high-temperature air. Appendix B also shows the procedure to calculate the thermal power required for air preheating, which is further used to generate the layouts of the CSP_{th} Hybrid Central Tower systems.

In order to evaluate the benefits of replacing fuel or industrial oxygen by high-temperature air, the mass of these inputs was converted to equivalent energy.

The general assumptions that were considered for the smelting process model are the following:

- Copper concentrates' composition: 80 % chalcopirite (CuFeS_2) and 20 % pyrite (FeS_2).¹
- Input dust's composition: 40 % CuSO_4 , 50 % $\text{Fe}_2(\text{SO}_4)_3$, and 10 % SiO_2 .¹
- Output dust's composition: 40 % Cu_2O , 40 % Fe_3O_4 , and 20 % SiO_2 .¹
- Rate of smelting: 50 ton of copper concentrates per hour.²
- Matte grade: 60 %.
- Off-gas scenarios: 1328, 1528, 1728, 1928, and 2128 kg/ton of copper concentrates.³
- Furnacés energy loss: 25,000 MJ/hour.
- Energy equivalent of 1 kg of industrial oxygen: 4.38 MJ.⁴
- Gross heat of combustion of natural gas: 51.04 MJ/kg.⁵

¹ Data from Davenport and Partelpoeg [27] was used for the input and output dust compositions.

² This value corresponds to a large-size smelting installation that can process about 500,000 tons of copper concentrates per year.

³ Appendix B.

⁴ The thermal energy equivalent of 1 kg of industrial oxygen was calculated assuming an electric consumption of 0.574 kWh per normal m^3 of oxygen [45] and a thermal to electric efficiency of 0.33 [46].

⁵ The gross heat of combustion of the natural gas was calculated for a gas composition (percentage by volume) of 85 % methane, 6 % Ethane, 4 % Propane, and 5 % Nitrogen.

3.3. Layout of the CSP_{th} Central Tower and energy balance of the CSP_{th} Hybrid-CT system

The CSP_{th} Central Tower was designed using SolarPILOT. This software provides layout, characterization, parametric simulation, and optimization capabilities [47]. Two layouts for each scenario were generated to evaluate the effect of the solar multiple. The solar multiple (S.M.) is the ratio between the energy delivered by the system when it operates at design conditions and the nominal energy demand.

The CSP_{th} Central Tower layouts were generated for the noon of the spring equinox (March 20) and a value of 950 W/m² was selected for the design DNI. The general procedure to generate every layout was as follow:

1. Selection of a design thermal power.¹
2. Generation of a coarse layout.
3. Optimization of the solar field based on the system's performance.

¹ For each off-gas scenario, the energy for air preheating “ E_x ” was weighted by the thermal losses of the CSP_{th} Hybrid-CT system to calculate the design thermal power. The thermal losses are described forwards in this section.

The energy balance of the Thermal Energy Storage system was calculated using equation (13).

$$\left(\frac{d\text{TES}}{dt} \right)_i = \left(h_{\text{in}} \frac{dm_{\text{in}}}{dt} \right)_i - \left(h_{\text{out}} \frac{dm_{\text{out}}}{dt} \right)_i - \left(\frac{dQ_{\text{loss}}}{dt} \right)_i \quad (13)$$

Kolb [48] estimates a thermal energy loss of 1 MW_{th} for a TES system of 5,000 MWh; this represents an hourly loss of 0.02 %. For this work, the hourly energy loss of the TES system was assumed to be the same, 0.02 % of the stored energy.

$$\left(\frac{dQ_{\text{loss}}}{dt} \right)_i = 0.0002 \text{ TES}_{i-1} \quad (14)$$

Equations (15) to (18) were used to calculate the charging and discharging process of the TES system.

$$E_{\text{GrossX}} = (E_{\text{APx}} / \eta_{\text{HE}}) \quad (15)$$

$$\left(h_{\text{in}} \frac{dm_{\text{in}}}{dt} \right)_i = \begin{cases} E_{\text{Solar}_i} & ; \text{TES}_{i-1} + E_{\text{Solar}_i} - E_{\text{GrossX}} \leq S_U \\ S_U - (\text{TES}_{i-1} - E_{\text{GrossX}}) & ; \text{TES}_{i-1} + E_{\text{Solar}_i} - E_{\text{GrossX}} > S_U \end{cases} \quad (16)$$

$$\left(h_{\text{out}} \frac{dm_{\text{out}}}{dt} \right)_i = \begin{cases} 0; & \text{TES}_{i-1} + \left(h_{\text{in}} \frac{dm_{\text{in}}}{dt} \right)_i \leq S_L \\ E_{\text{TES-Air}_i}; & \text{TES}_{i-1} + \left(h_{\text{in}} \frac{dm_{\text{in}}}{dt} \right)_i > S_L \end{cases} \quad (17)$$

$$E_{\text{TES-Air}_i} = \begin{cases} E_{\text{GrossX}} & ; \text{TES}_{i-1} + \left(h_{\text{in}} \frac{dm_{\text{in}}}{dt} \right)_i - E_{\text{GrossX}} \geq S_L \\ \text{TES}_{i-1} + \left(h_{\text{in}} \frac{dm_{\text{in}}}{dt} \right)_i - S_L & ; \text{TES}_{i-1} + \left(h_{\text{in}} \frac{dm_{\text{in}}}{dt} \right)_i - E_{\text{GrossX}} < S_L \end{cases} \quad (18)$$

E_{APx} : energy that the smelting process demand for air preheating.

E_{GrossX} : energy that the CSP Central Tower must supply.

η_{HE} : efficiency of the heat exchanger between molten salt and air.

S_U and S_L : upper and lower charging limits of the TES system.

Table 1

Reference data for the calculation of Capital Expenditure.

Equipment	Reference Cost (year)	References
Solar Field Tower	130 – 217 \$USD/m ² 3,170,000 e ^{0.0113H} (2010)	[19,54–58,59–60] [53]
Receiver	97,020,000 USD; Size: 1,571 m ² (2010)	[53]
Storage	14–33 \$USD/kWh _{th}	[55–57,59–61]
Heat exchanger molten salt- air (steam generation system)	29,000,000 USD; Size: 260 MW _{th} (2011)	[56]
Backup system (fuel-based boiler)	4,200,000 USD; Size: 26.6 MW _{th} (2015)	[63]
Indirect Cost	15–17 (% of D.C.)	[55,59,61]

Table 2

Reference data for the calculation of annual costs.

	Reference value	References	Values used in this work
O&M (% of CAPEX)	1–2.5 %	[19,56,65–67,68–70]	2 %
Insurance (% of CAPEX)	0.5–1 %	[19,55,56,62,63,65–68,70]	0.5 %

There isn't a work that reports the study of a heat exchanger between molten salt and air. In the absence of data, the efficiency of such heat exchanger was assumed similar to the efficiency of a steam coil air heater, though they might show a different behavior. The energy efficiency of steam coil air heaters has been reported to be up to 98 % [49]; however, with a conservative approximation, the paper assumes a value of 90 % for the heat exchanger.

The fuel consumption for the backup system was calculated using equations (19) and (20).

$$FC_i = \begin{cases} E_x/\eta_B; & \left(h_{out} \frac{dm_{out}}{dt}\right)_i = 0 \\ E_{F-Air_i}; & \left(h_{out} \frac{dm_{out}}{dt}\right)_i > 0 \end{cases} \quad (19)$$

$$E_{F-Air_i} = \begin{cases} 0 & ; \left(h_{out} \frac{dm_{out}}{dt}\right)_i = E_{Grossx} \\ \left(E_x - \eta_{HE} \left(h_{out} \frac{dm_{out}}{dt}\right)_i\right) / \eta_B & ; \left(h_{out} \frac{dm_{out}}{dt}\right)_i < E_{Grossx} \end{cases} \quad (20)$$

η_B : efficiency of the backup system.

Commercial fuel-based boilers for heating molten salt have not been found. However, the project Solar Two [50] is a precedent that this can be possible; in that project, both molten salt and the hot tank of the TES system were heated using a propane-fired chest and flue gases. As an approximation, the paper assumes a similar system for the backup system, with an efficiency similar to a medium-level of efficiency boiler for steam production (71 %) [51].

3.4. Economic evaluation

Two alternatives were analyzed in this work: carrying out the reactions without using high-temperature air and carrying out the reactions using high-temperature air. For the second alternative, air is preheated using a CSP_{th} Hybrid-CT system. The two alternatives aim to obtain the same products; however, the only measure of difference between the two alternatives is the equivalent energy consumption of the reactions, which can be expressed in terms of costs. For this reason, the economic evaluation can only indicate which is the most cost-effective solution.

In this context, the Present Value is the most suitable measure to evaluate and compare the economic viability of these two alternatives.

The Present Value indicates the equivalent value at time 0 of a set of cash flows. This measure is easy to use because of the sign convention for cash flows: positive cash flows represent revenues, while negative cash flows represent costs. The Present Value was calculated using equation (21). Since all cash flows are costs, the Present Value is negative; therefore, the most cost-effective solution is the one that shows the minor absolute value.

$$PV_{costs} = CAPEX + \sum_{n=1}^N \frac{Costs_n}{(1+r)^n} \quad (21)$$

CAPEX: capital expenditure.

Costs_n: annual costs incurred at year “n”.

r: discount rate.

N: system's lifespan.

The capital expenditure for the CSP_{th} Hybrid-CT systems was calculated considering direct and indirect costs (equation (22)). The direct costs include the costs of the main components of the CSP_{th} Hybrid-CT system (equation (23)), while the indirect costs include the owner's costs, planning and contracting costs, engineering and construction management, and contingency costs [52].

$$CAPEX = DC + IC \quad (22)$$

$$DC = (HF_C + T_C + R_C + TES_C + HE_C + B_C) \quad (23)$$

HF_C: heliostats field cost.

T_C: tower cost.

R_C: receiver cost.

TES_C: thermal energy storage system cost.

HE_C: heat exchanger cost.

B_C: backup system cost.

Table 1 shows the reference data that was used to calculate the CAPEX of the CSP_{th} Hybrid-CT systems. The heliostat field cost was calculated by multiplying the heliostat field area by a solar field price; the most recent reference in Table 1 was used, 145 \$USD/m² (2020). The TES system cost was calculated by multiplying the TES capacity by 24 \$USD/kW_{th} (2020). The tower cost was calculated with an exponential function, equation (24). There isn't prior data about the cost of a heat exchanger that works with molten salt and air; therefore, the cost of this equipment was assumed similar to a steam generation system (SGS). The same situation occurs with the backup system; the cost of this system was assumed similar to a fuel-based boiler. The receiver cost, the steam generation system cost, and the Fuel-Based boiler cost were calculated using a capacity function. Finally, the indirect costs were assumed to be 15 % of the direct costs.

$$T \text{ cost} = C_R e^{s \cdot H} \quad (24)$$

$$C_x = C_R (I_{2019}/I_R) (S_x/S_R)^s \quad (25)$$

C_x: estimated cost of the equipment of size “S_x

C_R: estimated cost of the equipment of size “S_R

H: tower's height.

s: scaling exponent.

The scaling exponents were 0.0113 for the tower, 0.7 for the receiver, and 0.8 for both the steam generation system and the Fuel-Based boiler [53]. The reference costs in Table 1 were actualized for equation (25). The actualizations were carried out using the Chemical Engineering Plant Cost Index 2019 (CEPCI 2019), equation (26).

$$C_R = C(I_{2019}/I_R) \quad (26)$$

C: reference cost at year of reference.

I₂₀₁₉: Index CEPCI- 2019.

I_R: Index CEPCI- year of reference.

Table 2 shows reference data for the calculation of the annual costs; they comprise three concepts: operation and maintenance expenses “O&M”, insurance, and annual expenses due to the equivalent energy

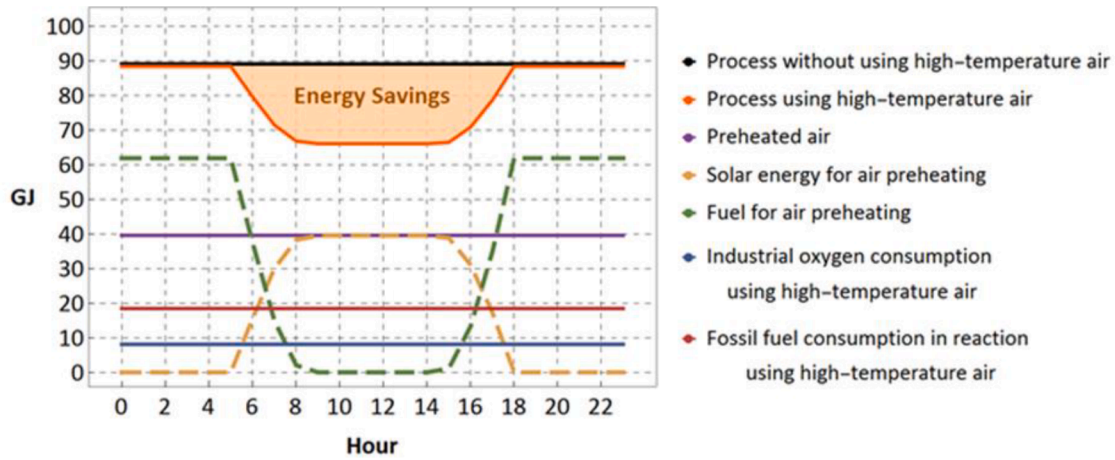


Fig. 4. Energy consumption of the chemical reactions and operation of the CSP Hybrid-CT system. Off-gas scenario: 1,728 kg/ton of concentrates. Evaluation day of the CSP Hybrid-CT system: 355.

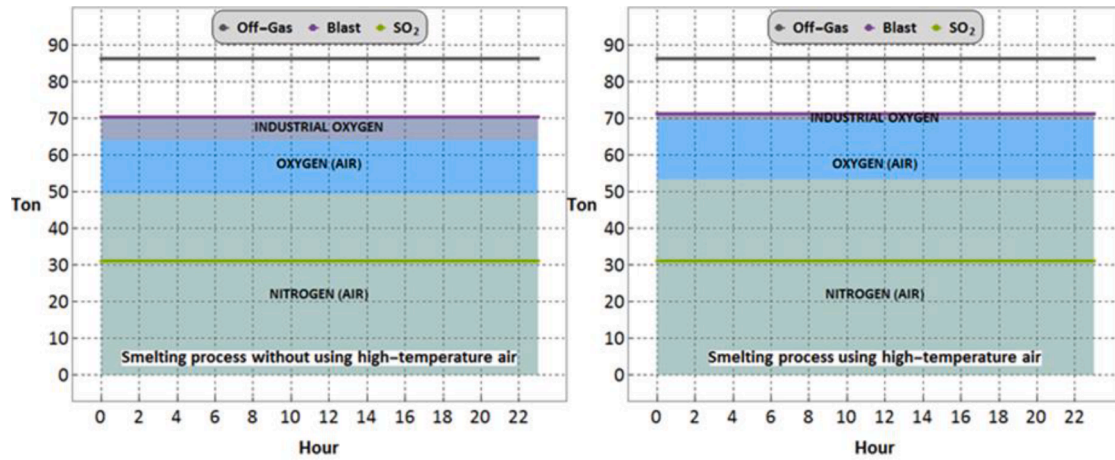


Fig. 5. Off-gas production and mass of blast. Off-gas scenario: 1,728 kg/ton of concentrates.

consumption “ AE_{EEC} ”. The value “ AE_{EEC} ” was calculated by multiplying a reference fuel price by the annual equivalent energy consumption “ EEC ” that does not come from the solar source. The value “ EEC ” was calculated with equation (27).

$$EEC = OI_{EE} + FFR_{EE} + FFP_{EE} \quad (27)$$

OI_{EE} : annual equivalent energy consumption due to industrial oxygen.

FFR_{EE} : annual equivalent energy consumption due to fossil fuel in reactions.

FFP_{EE} : annual equivalent energy consumption due to fossil fuel for air preheating.

For the theoretical baseline cases (no air preheating), the annual costs consist just in the value of “ AE_{EEC} ”. For this work, the natural gas price was chosen as the reference fuel price. The natural gas price was assumed to be 7 USD/MMBTU, which was the price of U.S. LNG exports to Chile in 2021 [64].

The Present Value was calculated with the annual costs at constant value. Finally, a real rate of 8 % was used to discount the annual costs.

4. Results and discussions

This section presents the results that were obtained using the methodology of Section 3. First, the section shows the results corresponding to one off-gas scenario to describe the implementation of the

CSP_{th} Hybrid-CT system. Then, the section presents the annual energy consumption for the five off-gas scenarios; the analysis includes the results for CSP_{th} Hybrid systems designed with solar multiples of 1 and 2.5. Finally, the section shows the CO₂ emissions for all the cases and the results of the economic evaluation.

Fig. 4 shows the equivalent energy consumption of the chemical reactions and the operation of the CSP_{th} Hybrid-CT system; the results correspond to the off-gas scenario of 1,728 kg of off-gas per ton of copper concentrates, and the performance of the CSP_{th} Hybrid-CT system corresponds to December 21. As mentioned before, the copper smelting rate was set in 50 tons of concentrates per hour; therefore, the energy values of Fig. 4 corresponds to this smelting rate. The equivalent energy consumption of the reactions without using high-temperature air is 89.2 GJ per hour (black line): 69.5 % of this energy corresponds to the fuel consumption in reactions and 30.5 % corresponds to the industrial oxygen consumption. For a process that uses high-temperature air, the equivalent energy that the reactions consume corresponds to a steady stream of industrial oxygen (8.1 GJ – blue line), a steady stream of fossil fuel (18.45 GJ – red line), and a steady stream of preheated air (39.6 GJ – purple line). However, the actual energy consumption for air preheating depends on the performance of the CSP_{th} Hybrid-CT system. Air is preheated with fossil fuel and solar thermal energy; these sources are complementary: fuel (green line) is consumed when the solar energy (yellow line) is not enough to fulfill the thermal demand for air preheating. Due to the efficiencies of the backup system, every unit of

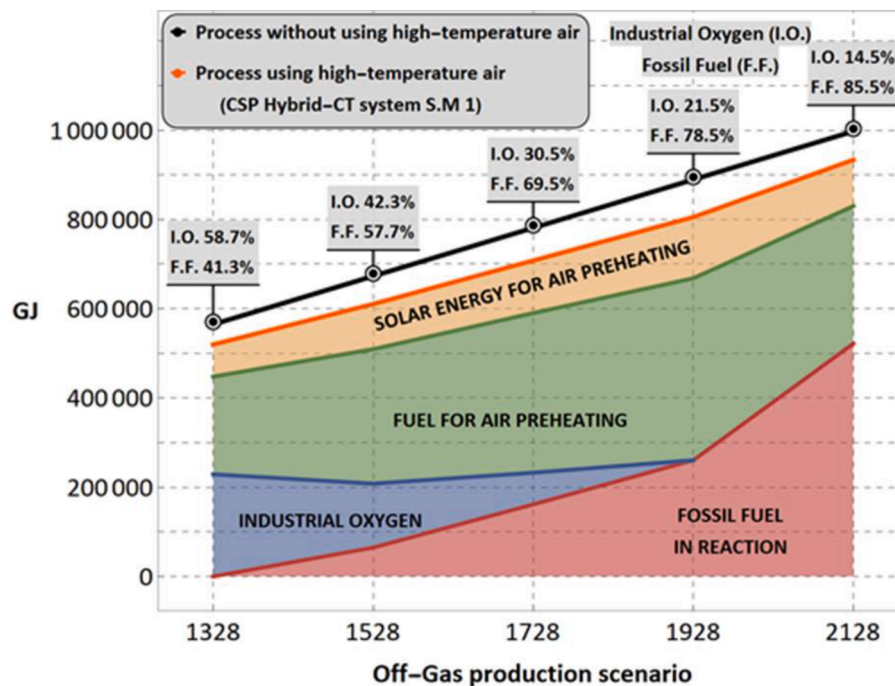


Fig. 6. Annual equivalent energy consumption of the reactions. CSP_{th} Hybrid systems S.M. 1. (First year of operation).

energy for air preheating demands more equivalent energy if this energy comes from the fuel source; this fact is clearly seen from the 00:00 to the 05:00 h and from the 18:00 to the 23:00 h.

As seen in Fig. 4, the equivalent energy consumption of the reactions using high-temperature air (orange line) is lower than the equivalent energy consumption of the reactions in the scheme that doesn't use high-temperature air (black line); the equivalent energy consumption decreases due to an improvement of the reactions. Desulfurization of concentrates requires certain amount of oxygen to get a specific copper content in matte. If the energy demand of the reactions is complemented by burning fossil fuel and not by preheating the air, the oxygen demand increases considerably. This increment in the oxygen supply, either by consuming more air or more industrial oxygen, also increases the equivalent energy consumption of the chemical reactions.

Two possible concerns of using high-temperature air are the burner's performance and the operation of the off-gas handling system, particularly the operation of the acid plant. A change in the velocity and composition of the blast (mass of industrial oxygen + mass of air) can affect the burner's performance, whereas a change in the sulfur dioxide content in the off-gas can diminish the efficiency of the acid plant.

In this sense, Fig. 5 shows the off-gas production and the mass of blast for the two process schemes: the process without air preheating and the process using air preheating. The results in this figure correspond to the same off-gas scenario: 1,728 kg of off-gas per ton of concentrates. As seen in Fig. 5, the off-gas production and the sulfur dioxide content remain constant for the two schemes: 86.4 tons of off-gas per hour and 31.2 tons of SO₂ per hour. The blast rate increases from 70.4 tons per hour (process without air preheating) to 71.3 tons per hour (using air preheating); for these blast rates, the air content is 91.2 % and 97.4 %, respectively. These changes in the rate and composition of the blast are not significant; however, the high-temperature air produces a higher blast volume, which in turn leads to a higher blast velocity. The effect of higher blast velocities on the burner's performance should be further evaluated using fluid dynamic techniques; however, that evaluation is not within the scope of this work. It is worth noting that, in industrial practice, steam or flue gases have been used to preheat air at temperatures up to 300 °C; and, for reverberatory furnaces, air has been preheated to higher temperatures [22].

The annual equivalent energy consumption corresponding to the two process schemes was calculated for this off-gas scenario. For the scheme where the reactions use high-temperature air, the industrial oxygen consumption represents 70,956 GJ in the annual equivalent energy consumption, whereas the fuel consumption in reactions represents 161,622 GJ; the equivalent energy consumption for air preheating was calculated after an annual evaluation of the performance of the CSP_{th} Hybrid-CT system. For this specific off-gas scenario, the CSP_{th} Central Towers' layout was designed with a design thermal power of 12.18 MW. With this layout, the CSP_{th} Hybrid-CT system delivers an annual value of 117,863 GJ of solar energy for air preheating and burns an annual amount of 357,721 GJ of fossil fuel for air preheating. In sum, for the scheme where the reactions use high-temperature air, the reactions consume 708,162 GJ annually. For the scheme where the reactions do not use high-temperature air (theoretical baseline case), the reactions consume 781,392 GJ annually: 30.5 % by industrial oxygen consumption and 69.5 % by burning fossil fuels in the reactions. These results indicate a reduction of 9.37 % in the annual equivalent energy consumption if the reactions are carried out using high-temperature air; for this case, the air is preheated to an approximate temperature of 550 °C.

The same analysis was carried out for the other four off-gas scenarios. Fig. 6 shows the annual equivalent energy consumption for the five off-gas scenarios. The CSP_{th} Hybrid-CT systems were designed with solar multiples of 1, and the results correspond to the first year of operation of the system. The chemical reactions require less energy at lower values of off-gas production; this is related to the industrial oxygen consumption. When the reactions depend on ambient-temperature air to obtain most of the oxygen supply, the fossil fuel must deliver enough energy for the reactions and enough energy to increase the nitrogen's temperature. When the reactions are carried out with ambient-temperature air, increasing the industrial oxygen content in the blast reduces the air demand, the nitrogen income, the need for burning fossil fuel, the blast rate, and, in consequence, the off-gas production. Given these correlations, the scenarios with high off-gas production rates require low or no industrial oxygen consumption and demand more energy. If the reactions use high-temperature air, there is a reduction in the annual equivalent energy consumption; the cause of this reduction was already explained using Fig. 4. These reductions represent 7.97 %, 9.37 %, 10.7 %, and 12.1 %, respectively.

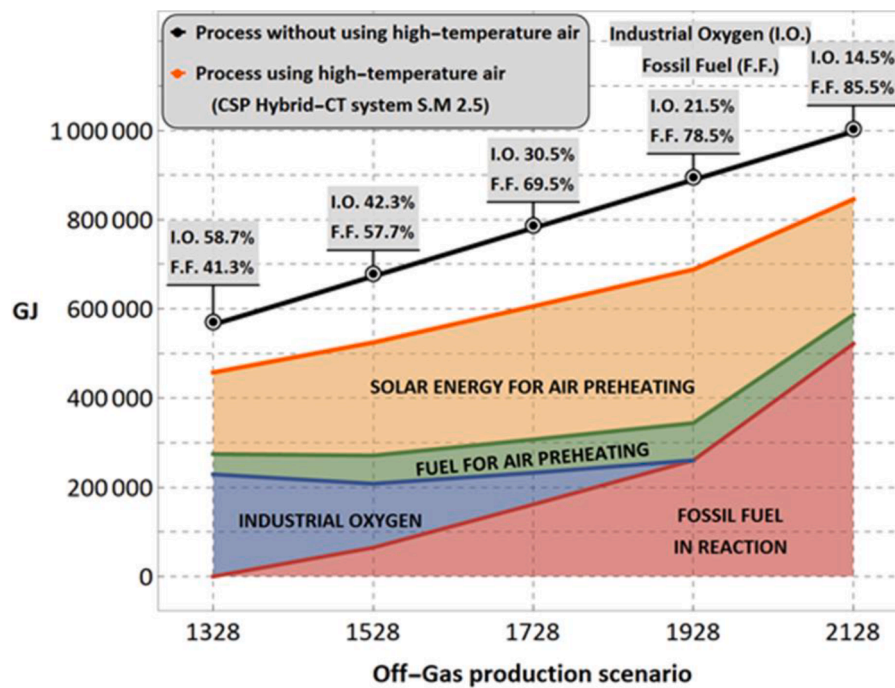


Fig. 7. Annual equivalent energy consumption of the reactions. CSPth Hybrid systems S.M. 2.5 with 13 h of thermal energy storage. (First year of operation).

9.28 %, 9.37 %, 9.44 %, and 6.4 % of the annual equivalent energy consumption for the off-gas scenarios of 1328, 1528, 1728, 1928, and 2128 kg/ton of concentrates, respectively.

These results indicate that using high-temperature air results in a significant advantage regarding the reactions' energy consumption. However, for CSPth Hybrid-CT systems designed with solar multiples of 1, burning fossil fuel is the main source (75 %) of the equivalent energy consumption for air preheating. In order to increase the solar energy contribution (solar fraction), the CSPth Hybrid-CT systems were designed with solar multiples of 2.5; the increment in the solar multiple also requires the inclusion of a thermal energy storage (TES) system. After an economic analysis, a TES system of 13 h was chosen for these CSPth Hybrid-CT systems.

Fig. 7 shows the annual equivalent energy consumption for the five off-gas scenarios; the results correspond to CSPth Hybrid-CT systems (S.M. 2.5) with 13 h of thermal energy storage for the first year of operation. For these cases, burning fossil fuel represents about 20 % of the equivalent energy for air preheating, while solar energy represents 80 %. This increase in the solar fraction also reduces the annual equivalent energy consumption: as mentioned before, every unit of energy for air preheating demands more equivalent energy if this energy comes from the fuel source. Now, compared with the scheme that doesn't use high-temperature air, the scheme that use high-temperature air shows reductions of 19.03 %, 22.05 %, 22.45 %, 22.61 %, and 15.22 % in the annual equivalent energy consumption for the off-gas scenarios of 1328, 1528, 1728, 1928, and 2128 kg/ton of concentrates, respectively.

The ultimate goal of using a CSPth Hybrid-CT system to deliver high-temperature air to the reactions is to reduce CO₂ emissions. The annual CO₂ emissions were calculated by multiplying the emission factor of the natural gas, 56.1 kg of CO₂/GJ [59], and the annual equivalent energy consumption that does not come from the solar source; this calculation was made for every case and off-gas scenario.

Table 3 shows the annual CO₂ emissions and the annual avoided CO₂ emissions for the two schemes and the five off-gas scenarios; the table presents the results of using the CSPth Hybrid-CT systems designed with the solar multiples of 1 and 2.5 for the first year of operation. Compared with the process that doesn't use high-temperature air, the process that uses it shows a significant reduction in the annual CO₂ emissions. Regarding the off-gas scenario, the reductions of CO₂ emissions vary between 14.5 % and 22 % if using a CSPth Hybrid-CT system designed with a solar multiple of 1, and between 41 % and 61.4 % if using a CSPth Hybrid-CT system designed with a solar multiple of 2.5. This can represent a significant advance towards the decarbonization of the copper smelting process: for example, for the off-gas scenario of 1,928 kg/ton of concentrates with an annual process rate of 438,000 tons of concentrates, the avoided emissions are 28,399 tons of CO₂ if using a CSPth Hybrid-CT system S.M. 2.5 to preheat air.

Using high-temperature air has a positive effect in terms of avoiding CO₂ emissions; moreover, the reduction of CO₂ emissions becomes more significant if the air is primarily preheated with solar energy. Given the way that emissions were calculated, a reduction of CO₂ emissions means a reduction of the annual equivalent energy consumption, which means

Table 3
Annual CO₂ emissions of the schemes. (First year of operation).

Off-Gas Scenario (kg of off-gas/ton of concentrates)		1,328	1,528	1,728	1,928	2,128
		Tons of CO ₂				
Process without using high-temperature air (Alternative 1)	Emissions	30,402	35,682	40,936	46,216	51,471
Alternative 2 - using high-temperature air: CSPth Hybrid-CT system S.M. 1	Emissions	25,125	28,444	32,374	36,015	44,002
	Avoided emissions	5277 (17.3 %)	7238 (20.3 %)	8562 (20.9 %)	10,201 (22 %)	7469 (14.5 %)
Alternative 3 - using high-temperature air: CSPth Hybrid-CT system S.M. 2.5	Emissions	15,404	15,082	16,487	17,817	30,340
	Avoided emissions	14,998 (49.3 %)	20,600 (57.7 %)	24,449 (59.7 %)	28,399 (61.4 %)	21,131 (41 %)

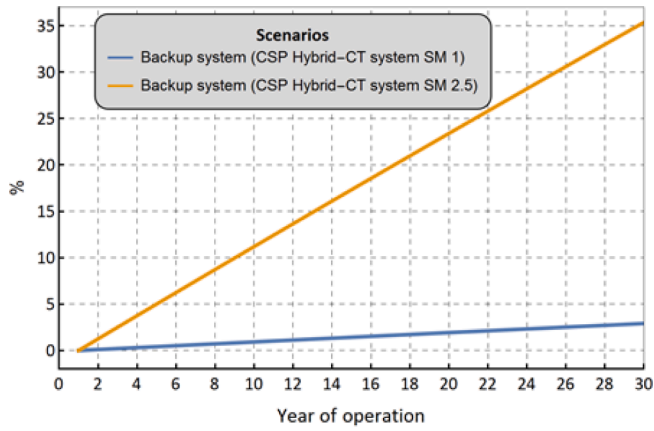


Fig. 8. Annual increase of the fuel requirements in the backup system.

Table 4

Abatement cost of CO₂ emissions.

Off-Gas Scenario (kg of off-gas/ton of concentrates)	1,328	1,528	1,728	1,928	2,128
	USD/Ton of CO ₂				
Alternative 2	88.67	62.1	59.7	47.3	53.1
Alternative 3	34.75	28.8	24.4	20.8	25.6

a reduction in annual expenses. However, installing a CSP_{th} Hybrid-CT system for air preheating represents a significant capital expenditure; therefore, an economic analysis is carried out to evaluate the benefits and the costs of the alternatives. Before the economic evaluation, the performance of the CSP_{th} Hybrid-CT systems was weighted by the annual degradation factor. Fig. 8 shows the increase in the fuel requirements of the backup system due to the annual degradation of the CSP_{th} Central Tower. Since the backup system of the CSP_{th} Hybrid-CT systems SM 1 has a contribution of 75 % in the energy for air preheating, a reduction on the solar share due to the annual degradation has a low relative impact in the fuel consumption for air preheating. On the contrary, for the CSP_{th} Hybrid-CT systems SM 2.5, the same degradation of the CSP_{th} Central Tower and the reduction of the solar share (80 % for this system) has a significant effect on the fuel consumption in relative terms.

Fig. 9 shows the Present Value for all the alternatives and off-gas scenarios. In absolute values, the present value of the costs tends to

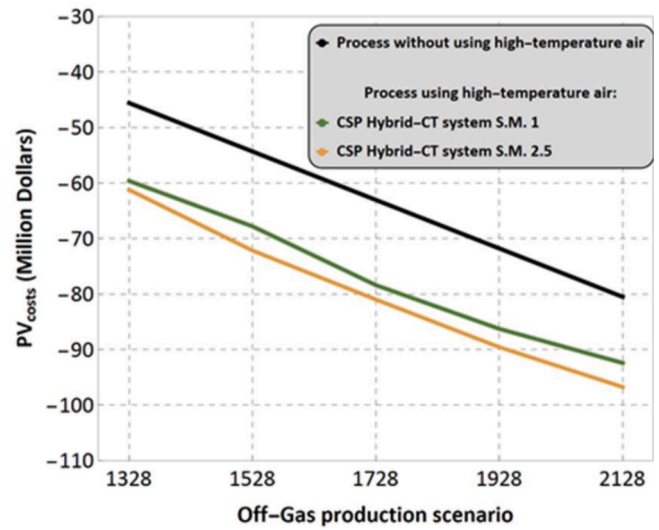


Fig. 9. Present value of the costs associated with the reactions' energy consumption.

increase for large off-gas scenarios. Alternative 1 represents the lower-cost option for every off-gas scenario; however, this alternative does not lead to a reduction in CO₂ emissions. Between alternatives 2 and 3, alternative 2 shows a slightly lower-cost option to reduce CO₂ emissions; however, alternative 3 shows reductions about three times larger than the alternative 2.

If the main goal is to reduce CO₂ emissions, the abatement cost is a better measure to compare alternatives 2 and 3. The abatement cost is defined as the estimated cost of avoiding a ton of CO₂ emissions. To calculate the abatement cost, the difference of Present Value (ΔPV_{costs}) between the alternative 2 (or 3) and the alternative 1 was weighted by the total avoided emissions of the alternative 2 (or 3); the total avoided emissions corresponds to 30 years (lifespan of the CSP_{th} Hybrid-CT systems) of annual avoided emissions considering the annual degradation of the system. Table 4 presents the abatement costs for the alternatives 2 and 3. The alternative 3 shows lower abatement costs; in other words, the alternative 3 reduces CO₂ emissions at lower costs.

The value " ΔPV_{costs} " depends on three main parameters: capital expenditure, discount rate, and O&M costs. Fig. 10 shows a sensitivity analysis for the value " ΔPV_{costs} " of alternatives 2 and 3; the results correspond to a reference off-gas scenario (1,728 kg /ton of

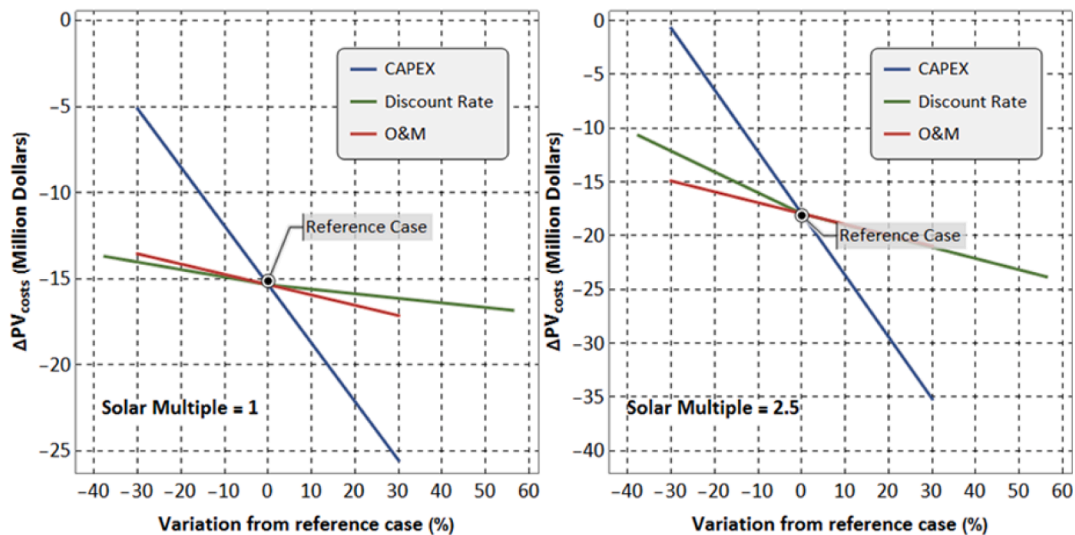


Fig. 10. Sensitivity analysis for the value " ΔPV_{costs} ".

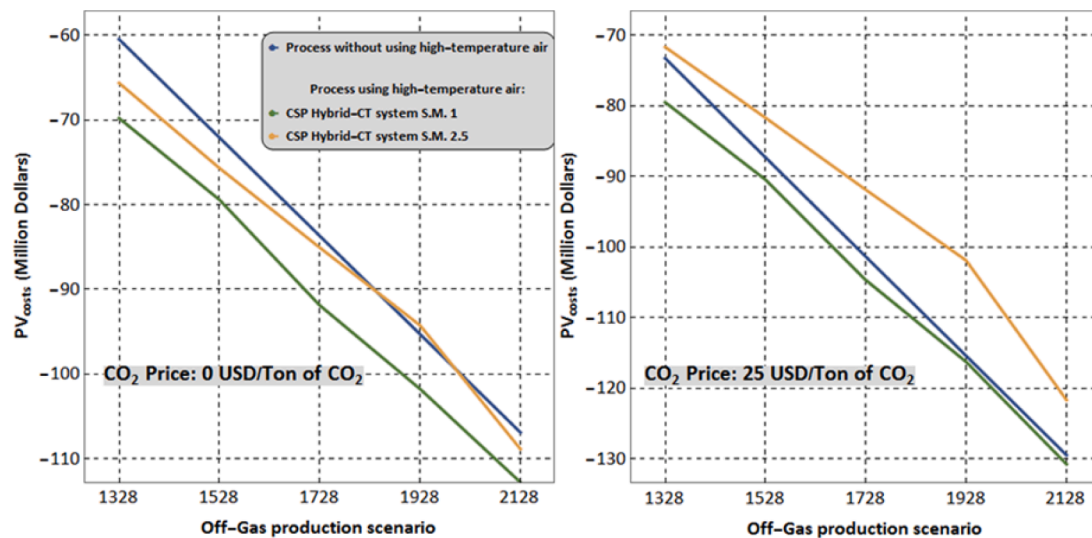


Fig. 11. Present value of the costs associated with the reactions' energy consumption. Calculation with a CAPEX reduction of 15 % and a discount rate of 5 %.

concentrates). A change of $\pm 30\%$ in the capital expenditure was used to evaluate the effect of this parameter. Two scenarios were used for the discount rate: a scenario with government guarantees on low-carbon technology investment (5 %), and a scenario of risk aversion toward low-carbon technology investment (12.5 %) [71]. Finally, a change of $\pm 30\%$ was applied to the O&M costs.

For alternative 2, the " ΔPV_{costs} " is -15.34 Million USD at the reference off-gas scenario. A 30 % reduction in CAPEX takes this value to -5.13 million USD (change of $+10.21$ Million USD), while a 30 % increase of this parameter takes the " ΔPV_{costs} " to -25.55 Million USD (change of -10.21 Million USD). The discount rate of 5 % produces a change of $+1.64$ Million USD in the " ΔPV_{costs} ", while the risk-aversion rate (12.5 %) produces a change of -1.49 Million USD. The " ΔPV_{costs} " is less sensitive to changes in O&M costs; a $\pm 30\%$ in this parameter changes the " ΔPV_{costs} " in ± 1.79 Million USD. Larger solar multiples extend the effect of these parameters. For example: for alternative 3, the " ΔPV_{costs} " is -17.94 Million USD at the reference off-gas scenario; a 30 % reduction in CAPEX lowers the " ΔPV_{costs} " to -0.72 Million USD, which is a change of $+17.22$ Million USD. This value contrast with the change of $+10.21$ Million USD of alternative 2.

Two ideas should be addressed: 1) there is still a significant opportunity to reduce the capital expenditure for the CSP_{th} Central Tower technology [72], and 2) the growing concern about climate change is leading governments, multilateral development banks, and capital funds to stimulate investment in low-carbon technologies through lower costs of capital (discount rates). In this sense, the Present Value for the three alternatives was calculated using a 15 % reduction in the capital expenditure and a discount rate of 5 %. Additionally, a carbon price was taken into consideration to calculate the Present Value.

Carbon pricing creates a financial incentive that drives technological innovation and investment in clean energy. Carbon prices are introduced through taxes on fossil fuels or by putting a price on GHG emissions; additionally, emissions are regulated using two kinds of carbon market systems: Emission Trading Systems (ETS) and Baseline-and-Credit mechanisms [73]. Today, 21.5 % of the global GHG emissions are covered by carbon pricing instruments [74]. However, most carbon prices remain below the range needed to help meet the limit of 1.5 °C [75]. The High-Level Commission on Carbon Prices suggests that a carbon price consistent with the Paris Agreement's goal should be at least 40–80 USD/tCO₂e by 2020 and 50–100 USD/tCO₂e by 2030 [76]. To address the risk of a surge in the price of GHG emissions, several companies use a voluntary carbon price. In 2020, the median carbon price disclosed by companies was 25 USD/tCO₂e [77]. In this context,

the Present Value for the three alternatives was calculated using a carbon price of 25 USD/tCO₂e.

Fig. 11 shows the Present Value for the three alternatives and the five off-gas scenarios; these calculations consider a 15 % reduction in capital expenditure and a discount rate of 5 %; the results correspond to a carbon price of 0 and 25 USD/tCO₂e. For a carbon price of 0 USD/tCO₂e, the Present Value for alternatives 1 and 3 is almost similar; this means, the costs associated with the equivalent energy consumption of the reactions is similar for alternatives 1 and 3; therefore, it is possible to avoid a significant amount of CO₂ emissions without increasing costs. For a carbon price of 25 USD/tCO₂e, alternative 3 represents the lower-cost alternative to carry out the reactions and the most cost-effective solution to avoid CO₂ emissions.

5. Conclusions

This study explores the idea of using high-temperature solar heat in the copper smelting process. For this purpose, the paper proposes to use a CSP_{th} Hybrid Central Tower system to supply high-temperature air to the process. The methodology of this work was built based on the equilibrium of the chemical reactions; therefore, the analysis and solutions only account for the energy demand of the reactions. To compare different process schemes (one that doesn't use high-temperature air, and one that does), the methodology ensures the same composition of the main products; also, the industrial oxygen consumption and the fossil fuel consumption were transformed into equivalent energy consumption. Several scenarios were evaluated with this methodology.

The CSP_{th} Hybrid Central Tower systems are a reliable source of high-temperature air; therefore, the reactions can be carried out without fluctuations in the airflow. One significant advantage of using high-temperature air is that it reduces the equivalent energy consumption of the reactions; this also leads to a reduction of CO₂ emissions.

Depending on the off-gas scenario, the use of CSP_{th} Hybrid-CT systems designed with a solar multiple of 1 (Alternative 2) can result in reductions between 6.4 % and 9.44 % in the annual equivalent energy consumption and between 14.5 % and 22 % in the CO₂ emissions; on the other hand, the use of CSP_{th} Hybrid-CT systems designed with a solar multiple of 2.5 and 13 h of thermal energy storage (Alternative 3) can result in reductions between 15.22 % and 22.61 % in the annual equivalent energy consumption and between 41 % and 61.4 % in the CO₂ emissions.

Regarding the economic analysis, the process that doesn't use high-temperature air is the lower-cost scheme to carry out the chemical

reactions; however, this alternative does not lead to a reduction in CO₂ emissions. Although alternative 2 represent a lower-cost option than alternative 3, the latter results in lower abatement costs; this means, alternative 3 reduces CO₂ emissions at a lower cost. Using a 15 % reduction in the capital expenditure and a discount rate of 5 %, the Present Value of the costs associated to alternatives 1 and 3 is almost similar; therefore, it is possible to avoid a significant amount of CO₂ emissions without increasing costs. Additionally, if a carbon price of 25 USD/tCO₂e is included in the analysis, alternative 3 represents the lower-cost alternative to carry out the reactions and the most cost-effective solution to avoid CO₂ emissions.

The main drawback of using high-temperature air is that it produces high blast (industrial oxygen + air) velocities in the reaction shaft; this could affect the burners' performance. However, it has been reported the use of air at temperatures of 300 °C for flash furnaces and higher temperatures for reverberatory furnaces. In this sense, the effect of high-temperature air and high blast velocities on the burners' performance should be further evaluated using fluid dynamic techniques. As said before, this analysis only accounts for the equivalent energy consumption of the reactions; therefore, this work does not consider the energy that is used to keep a uniform temperature along the furnace or to avoid

cold spots.

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.

Data availability

Data will be made available on request.

Acknowledgments

This work was carried out at the Institute of Renewable Energies of the National Autonomous University of Mexico. Irving Cruz-Robles thanks CONACYT for the postgraduate scholarship. Claudio A. Estrada thanks DGAPA-UNAM for the PAPIIT scholarship for a sabbatical stay at the University of Arizona and Jorge M. Islas thanks DGAPA-UNAM for the PAPIIT scholarship for a sabbatical stay at CIEMAT-Spain.

Appendix A. Solutions of the smelting model: Parametric plots

See Figs. A1–A6.

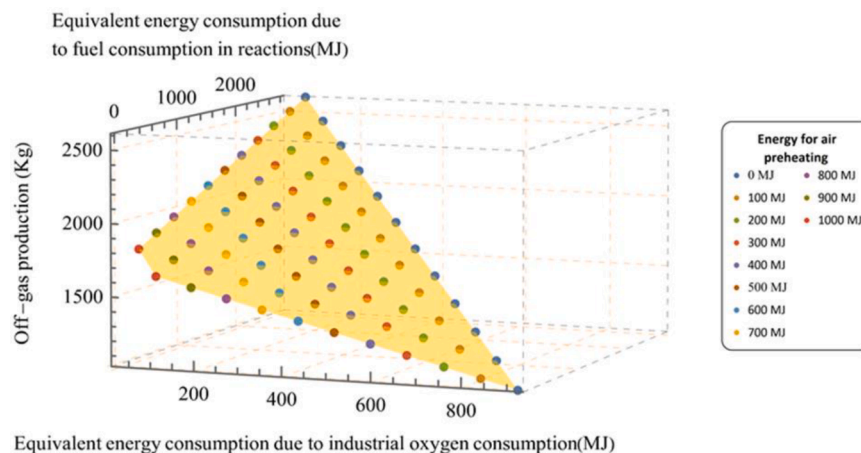


Fig. A1. Correlation between the off-gas production, industrial oxygen consumption, fuel consumption in reactions, and energy for air preheating: 3D Plot.

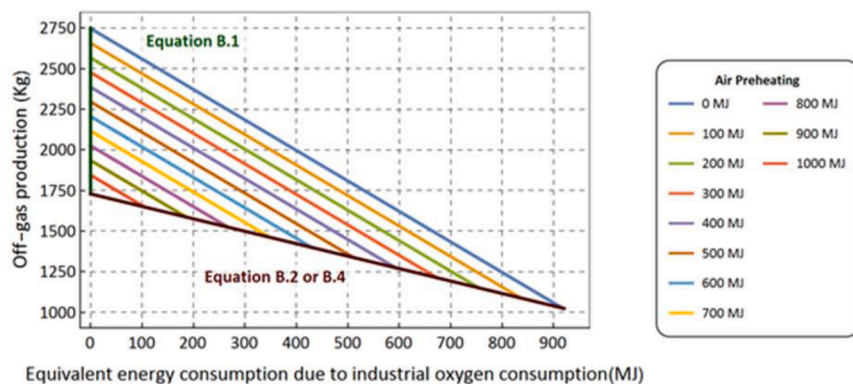


Fig. A2. Correlation between the off-gas production, industrial oxygen consumption, and energy for air preheating. (Equations (B.1) and (B.2) will be explained in Appendix B.).

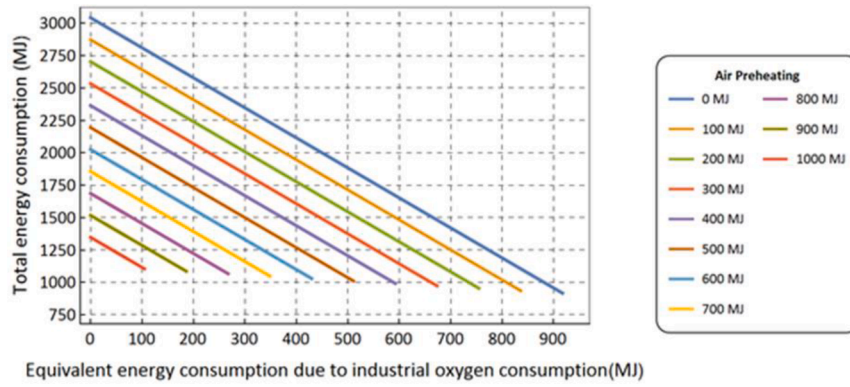


Fig. A3. Correlation between the total energy consumption, industrial oxygen consumption, and energy for air preheating.

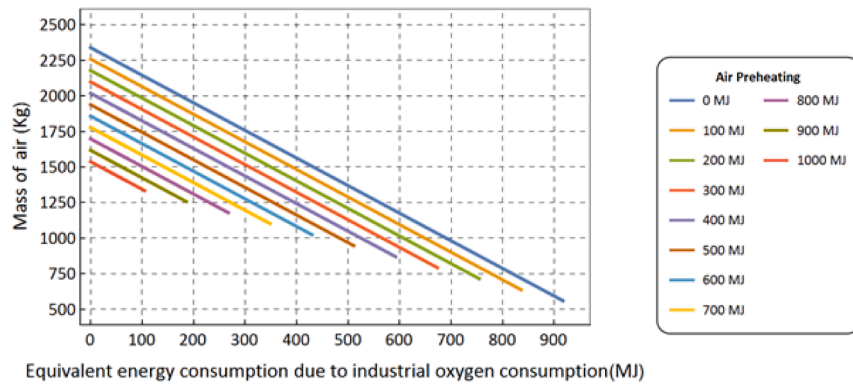


Fig. A4. Correlation between the total energy consumption, industrial oxygen consumption, and energy for air preheating.

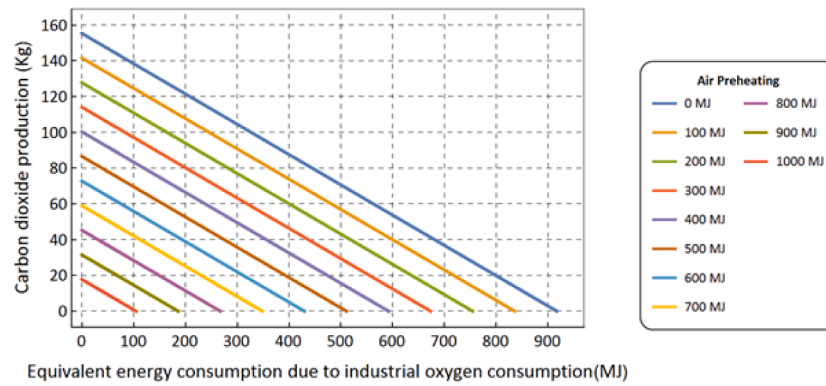


Fig. A5. Correlation between the carbon dioxide production (in reactions), industrial oxygen consumption, and energy for air preheating.

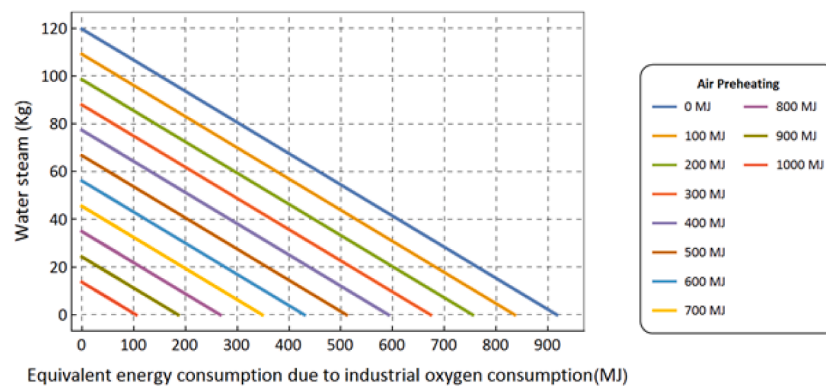


Fig. A6. Correlation between the water steam production (in reactions), industrial oxygen consumption, and energy for air preheating.

Appendix B. Selection of the off-gas scenarios and calculation of the energy for air preheating and air temperature

The off-gas parameter was used to calculate the maximum energy for air preheating that the process allows “MaxE_{AP}”. The off-gas reaches its maximum value when the industrial oxygen consumption is zero and the fuel consumption is at its maximum value, and it decreases as more industrial oxygen or energy for air preheating is used (see Figs. A1 and A2). Equations (B.1) and (B.2) were used to calculate the maximum and minimum off-gas production as function of the energy for air preheating (Fig. B1). The value “MaxE_{AP}” was obtained by making the difference between the maximum and minimum off-gas production equal to zero, equation (B.3).

$$\text{MaxG}_1(E_{AP}) = a_{\text{MaxG}_1} + b_{\text{MaxG}_1} E_{AP} \quad (\text{B.1})$$

$$\text{MinG}_1(E_{AP}) = a_{\text{MinG}_1} + b_{\text{MinG}_1} E_{AP} \quad (\text{B.2})$$

$$\Delta G(E_{AP}) = a_{\Delta G} + b_{\Delta G} E_{AP} \quad (\text{B.3})$$

The off-gas value was calculated for “MaxE_{AP}”; this value was used for the criteria of equation (16). Several scenarios of off-gas “G_x” were selected within the range of the solutions; therefore, it was necessary to calculate the maximum allowable energy for air preheating “E_{APx}” for each scenario. Equations (B.4) and (B.5) were used for this purpose.

$$\text{MinG}_2(O_I) = a_{\text{MinG}_2} + b_{\text{MinG}_2} O_I \quad (\text{B.4})$$

$$E_{APx} = \begin{cases} (G_x - (a_{I_G} + b_G(G_x - a_{\text{MinG}_2})/b_{\text{MinG}_2}))/a_{2G} & ; G_x < G(\text{MaxE}_{AP}) \\ (G_x - a_{I_G})/a_{2G} & ; G_x \geq G(\text{MaxE}_{AP}) \end{cases} \quad (\text{B.5})$$

However, the value “E_{APx}” should be limited bearing in mind the maximum temperature that a commercial CSP Central Tower with TES system can provide; this temperature is about 574 °C. In this sense, a maximum air temperature of 550 °C was chosen for this work. For this temperature was necessary to establish a maximum rate of heating per kilogram of air. In order to simplify calculations, the mass composition of air was considered to be 77 % nitrogen-23 % oxygen. The enthalpy change of the air against its temperature was approached using a linear function; data from the FactSage-Education software was used to do these calculations (Fig. B2).

The maximum rate of heat “MaxE_{550°C}” was estimated to be 0.565 MJ per kilogram of air. For each off-gas scenario “G_x”, the smelting model was solved using several increments in the energy for air preheating; then, the industrial oxygen consumption and the mass of air were calculated using equations (B.6) and (B.7). With this data, a linear equation was defined for the correlation between the rate of heat per kilogram of air and the energy for air preheating, equation (B.8). Finally, equation (B.8) was solved for “E_{AP}” by making “Q_{Airx}” equal to “MaxE_{550°C}”, equation (B.9). In Fig. B3, the

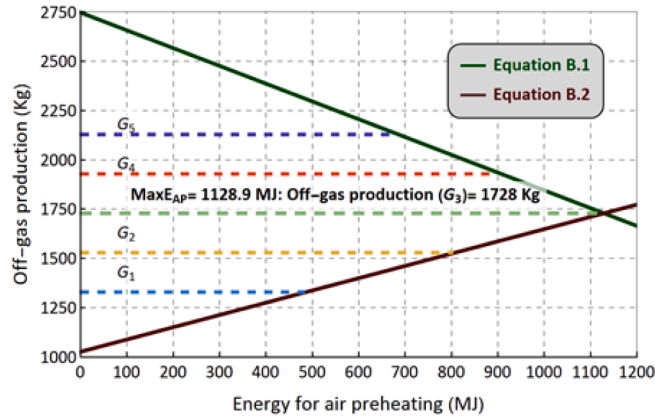


Fig. B1. Off-gas production scenarios.

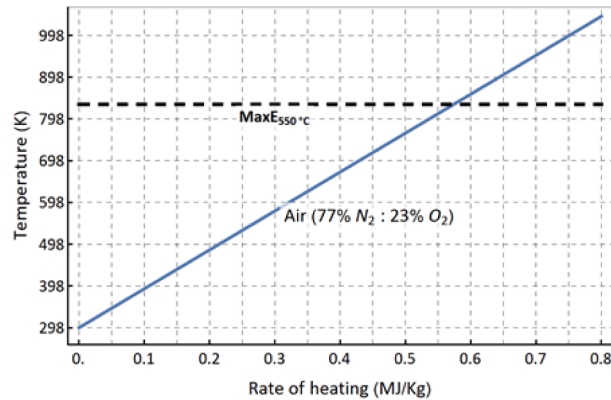


Fig. B2. Air temperature against the rate of heating.

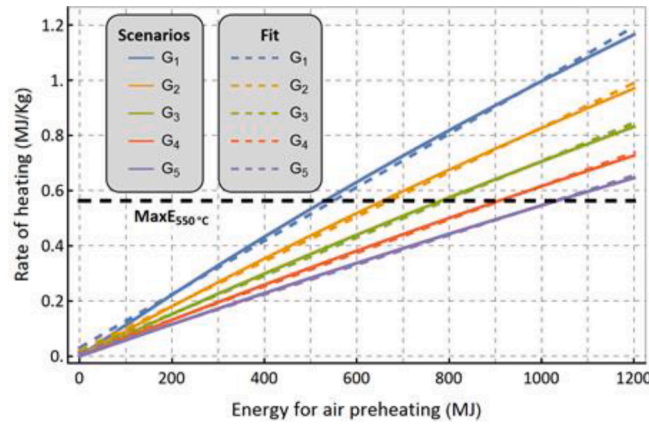


Fig. B3. Correlation of the energy for air preheating and the rate of heating.

Table B1

Layout's design thermal power and air temperatures for the five off-gas scenarios.

Off-Gas Scenario (kg of off-gas/ton of concentrates)	1,328	1,528	1,728	1,928	2,128
Required Thermal Power (MW)	6.73	9.32	10.99	12.61	9.53
Design thermal power (MW) (After weighting by efficiencies of the system)	7.46	10.33	12.18	13.97	10.56
Approximate air temperature (°C)	507	550	550	550	382

intersection between the line “MaxE_{550°C}” and each fit shows the value of “E_{APX;550°C}” for each off-gas scenario.

$$O_{IX}(G_X, E_{AP}) = (G_X - a_{O_{IX}}(E_{AP})) / b_{O_{IX}} \quad (B.6)$$

$$m_{Air_X}(O_{IX}, E_{AP}) = a_{Air_X}(E_{AP}) + b_{Air_X} O_{IX} \quad (B.7)$$

$$\frac{E_{AP}}{m_{Air_X}}(E_{AP}) = Q_{Air_X}(E_{AP}) = a_{Q_X} + b_{Q_X} E_{AP} \quad (B.8)$$

$$E_{AP_X; 550^\circ C} = (MaxE_{550^\circ C} - a_{Q_X}) / b_{Q_X} \quad (B.9)$$

Equation (B.5) specifies the maximum allowable energy for air preheating according to the set of mass and energy balance equations, whereas equation (B.9) specifies the maximum attainable energy for air preheating considering the process' air requirement and the temperature boundary of the CSP Central Tower and TES system. The energy for air preheating should not be superior to “E_{APX}” nor “E_{APX;550°C}” therefore, for each off-gas scenario, the energy for air preheating “E_x” was selected according to the criteria of equation (B.10).

$$E_x = \begin{cases} E_{AP_X} & ; E_{AP_X} < E_{AP_X; 550^\circ C} \\ E_{AP_X; 550^\circ C} & ; E_{AP_X} \geq E_{AP_X; 550^\circ C} \end{cases} \quad (B.10)$$

For each off-gas scenario, Table B1 indicates the required thermal power to preheat air, the design thermal power of the CSP_{th} Central Tower (calculated by weighting the required thermal power with both the efficiency of the heat exchanger molten salt-air and the thermal losses of the TES system), and the approximate air temperature after preheating (calculated using the linear function of Fig. B2). In all cases, the approximate air temperature is not superior to 550 °C, given the restriction imposed in Section 3.2.

Appendix C. Evaluation of the CSP_{th} Central Tower Layout: Solar energy production

The energy that the receiver delivers to the heat transfer fluid was calculated using the following procedure (steps 1–4):

1. The optical efficiency of the solar field was evaluated at 144 sun positions (Fig. C1).
2. For every hour of the year between the sunrise and the sunset, the efficiency value was taken from the nearest sun's position that was evaluated in step 1 (Fig. C2).
3. For every hour before sunrise and after sunset, the solar field's efficiency was fixed at zero.
4. The energy that the heat transfer fluid absorbs was calculated with equation (C.1).

$$E_{Solar_i} = \eta_{SF_i} DNI_i A_{SF} - Q_{R-loss} \quad (C.1)$$

i: hour of the year.

A_{SF}: solar field's area.

DNI_i: Direct Normal Irradiation at hour i.

η_{SF_i}: solar field's efficiency at hour i.

Q_{R-Loss}: receiver's heat loss.

The DNI hourly data was obtained from the Solar Exploratory of the Ministry of Energy of Chile [78]. The value Q_{R-Loss} was assumed constant at 30

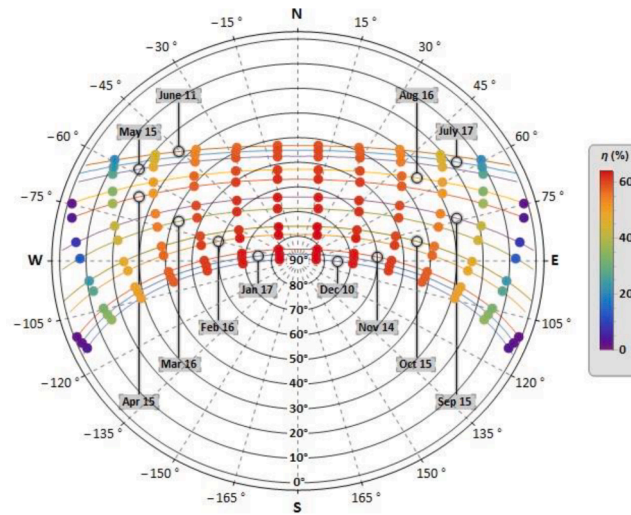


Fig. C1. Efficiency of the CSP_{th} Central Tower layout at 144 evaluated sun positions. Design thermal power 12.18 kW_{th} Solar Multiple 1).

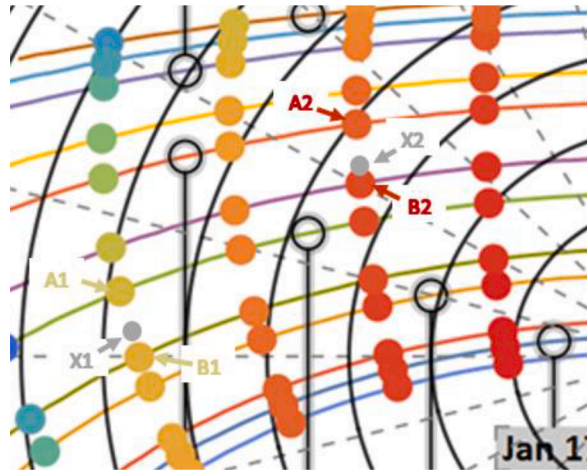


Fig. C2. Assignment of efficiency for non-evaluated sun positions. (X1 = B1, and X2 = B2).

kW/m². This assumption was based on the receiver's performance of the Solar Two project [79]. The thermal losses (radiative, convective, and conductive combined) of the Solar Two's receiver were measured and calculated as function of the wind speed; with a molten salt outlet temperature of 550 °C, the results indicated thermal losses between 2.7 MW and 3 MW for the receiver of 99 m² operating under wind speeds between 5 mph and 20 mph. This indicates a combined thermal loss between 27.27 kW/m² and 30.3 kW/m².

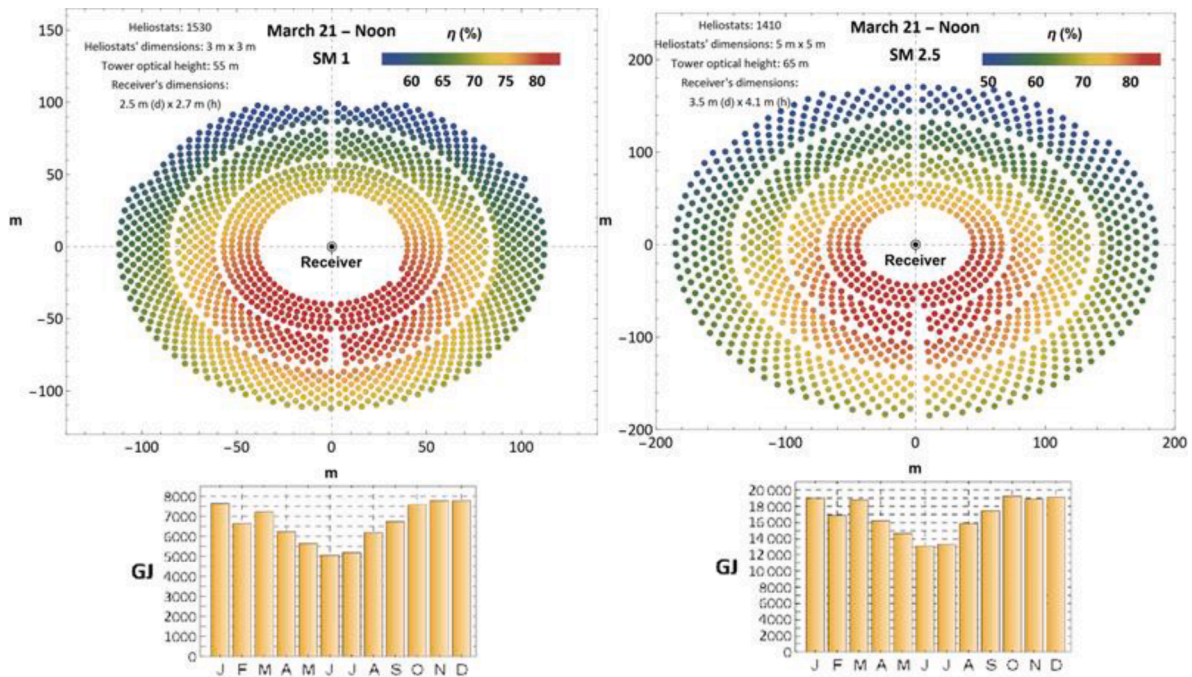
Since Q_{R-Loss} was assumed constant, " E_{Solar} " can be negative for low DNI values and low solar fields efficiencies; in those cases, " E_{Solar} " was changed by zero.

Appendix D. Capital expenditure for the CSP_{th} Hybrid Central Tower systems and performance of the CSP_{th} Central Tower layouts

See Table D1 and Figs. D1–D5.

Table D1Cost of the CSP_{th} Hybrid Central Tower systems.

Systems:	7.46 kW _{th}	10.33 kW _{th}	12.18 kW _{th}	13.97 kW _{th}	10.56 kW _{th}
	Solar Multiple 1				
Heliostats field (\$USD)	1,936,750	2,716,230	3,166,310	3,645,650	2,747,740
Receiver (\$USD)	5,255,060	5,830,400	6,576,630	7,035,180	6,129,460
Tower (\$USD)	5,901,650	5,577,450	6,607,670	6,244,690	5,577,450
Backup system (\$USD)	2,504,520	3,249,480	3,707,250	4,137,060	3,307,240
Heat exchanger (\$USD)	2,053,580	2,664,410	3,039,760	3,392,180	2,711,770
Subtotal (\$USD)	17,651,560	20,037,970	23,097,620	24,454,760	20,473,660
Indirect costs (\$USD)	2,647,734	3,005,696	3,464,643	3,668,214	3,071,049
Total (\$USD)	20,299,294	23,043,666	26,562,263	28,122,974	23,544,709
	Solar Multiple 2.5				
Heliostats field (\$USD)	4,957,910	6,825,460	8,030,550	9,215,390	6,952,050
Receiver (\$USD)	8,909,670	11,491,100	12,546,300	13,452,000	11,862,700
Tower (\$USD)	6,607,670	7,398,160	7,828,190	8,283,220	7,398,160
TES system (\$USD)	2,327,250	3,222,960	3,800,160	4,358,640	3,294,720
Backup system (\$USD)	2,504,520	3,249,480	3,707,250	4,137,060	3,307,240
Heat exchanger (\$USD)	2,053,580	2,664,410	3,039,760	3,392,180	2,711,770
Subtotal (\$USD)	27,360,600	34,851,570	38,952,210	42,838,490	35,526,640
Indirect costs (\$USD)	4,104,090	5,227,736	5,842,832	6,425,774	5,328,996
Total (\$USD)	31,464,690	40,079,306	44,795,042	49,264,264	40,855,636

**Fig. D1.** Configuration of CSP_{th} Central Tower layouts (SM 1 Left; SM 2.5 Right) and energy transferred to the heat transfer fluid (monthly data). Off-gas scenario 1328 kg/ton of con.

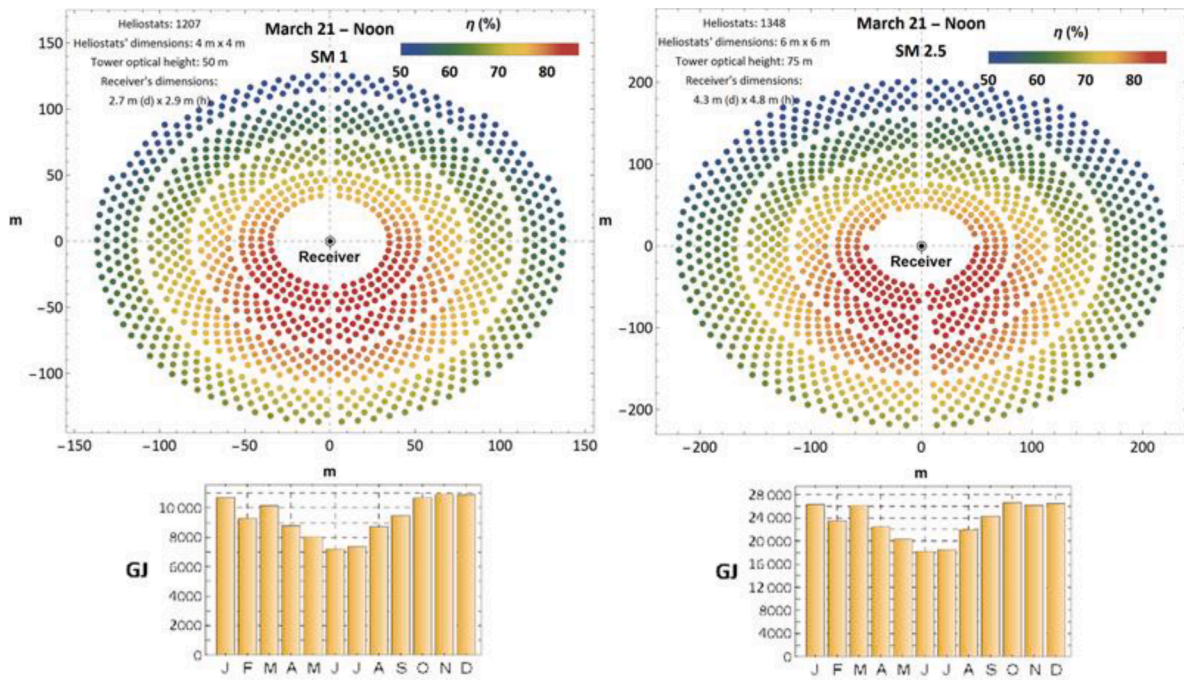


Fig. D2. Configuration of CSP_{th} Central Tower layouts (SM 1 Left; SM 2.5 Right) and energy transferred to the heat transfer fluid (monthly data). Off-gas scenario 1528 kg/ton of con.

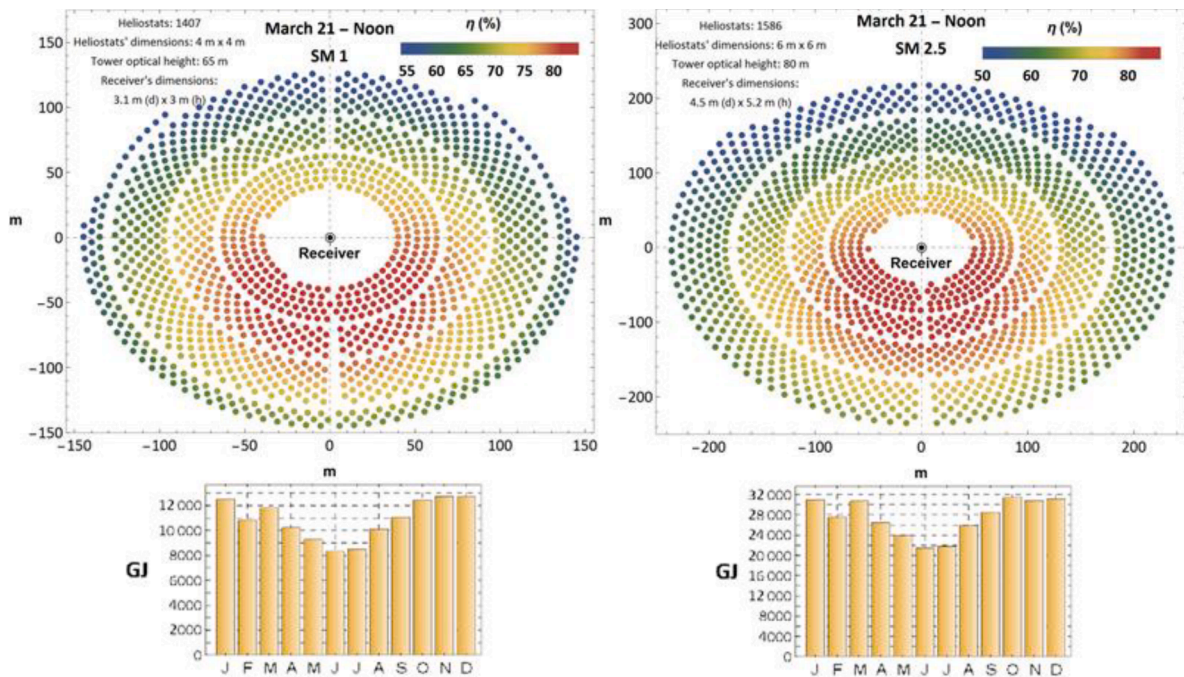


Fig. D3. Configuration of CSP_{th} Central Tower layouts (SM 1 Left; SM 2.5 Right) and energy transferred to the heat transfer fluid (monthly data). Off-gas scenario 1728 kg/ton of con.

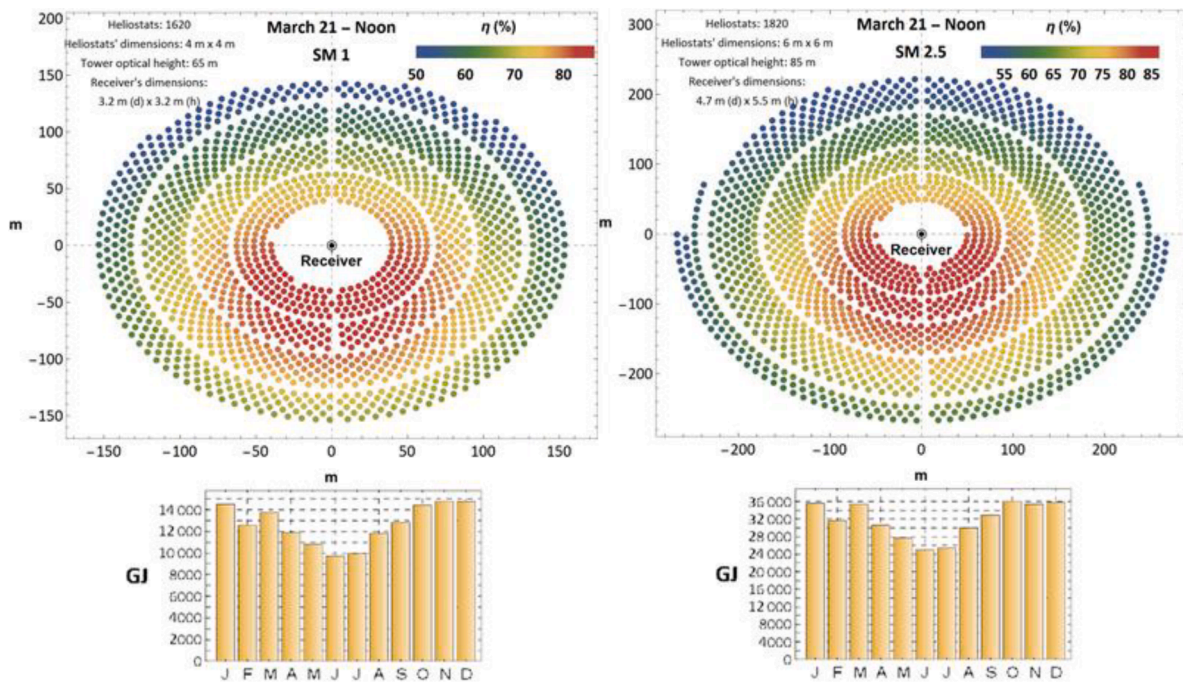


Fig. D4. Configuration of CSP_{th} Central Tower layouts (SM 1 Left; SM 2.5 Right) and energy transferred to the heat transfer fluid (monthly data). Off-gas scenario 1928 kg/ton of con.

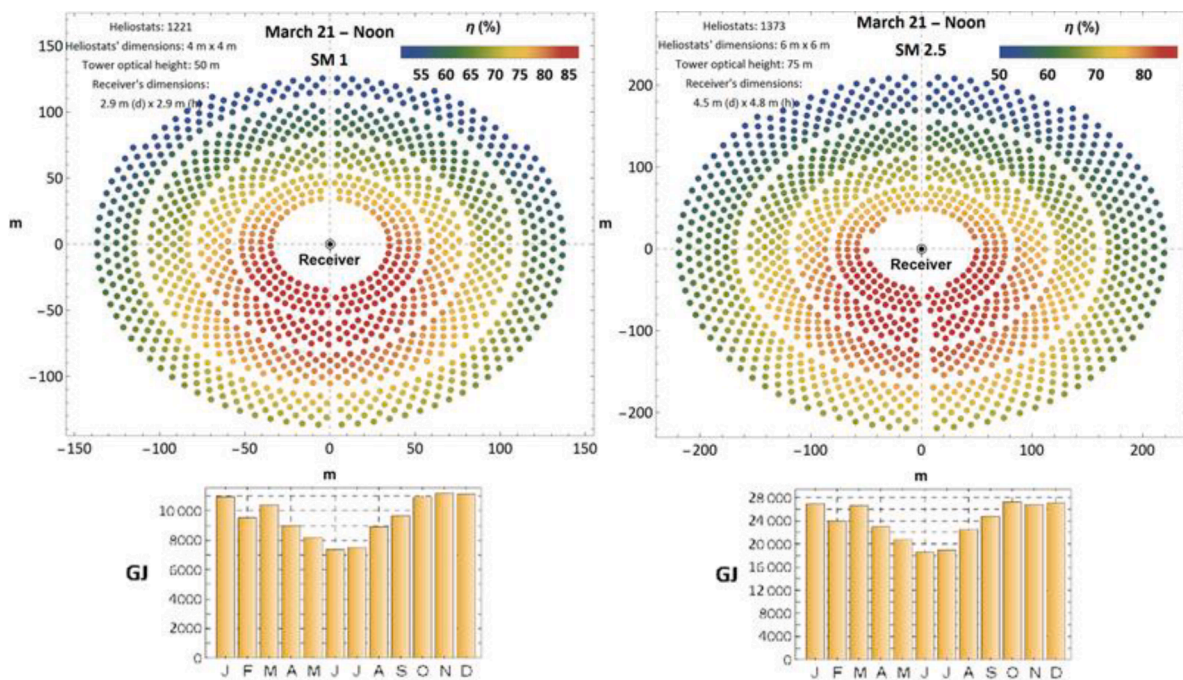


Fig. D5. Configuration of CSP_{th} Central Tower layouts (SM 1 Left; SM 2.5 Right) and energy transferred to the heat transfer fluid (monthly data). Off-gas scenario 2128 kg/ton of con.

References

- [1] International Copper Study Group, The World Copper Factbook 2016, Available Online: https://www.rockstone-research.com/images/PDF/ICSG_CopperFactbook2016.pdf (accessed on January 8, 2023).
- [2] Mineral Commodity Summaries 2022-Copper, Available Online: <https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-copper.pdf> (accessed on January 8, 2023).
- [3] W. Kuckshinrichs, P. Zapp, W.R. Poganietz, CO₂ emissions of global metal-industries: the case of copper, Appl. Energy 84 (7–8) (2007) 842–852, <https://doi.org/10.1016/j.apenergy.2007.01.014>.
- [4] S. Northey, N. Haque, G. Mudd, Using sustainability reporting to assess the environmental footprint of copper mining, J. Clean. Prod. 40 (2012) 118–128, <https://doi.org/10.1016/j.jclepro.2012.09.027>.
- [5] M.E. Schlesinger, M.J. King, K.C. Sole, W.G. Davenport, Extractive Metallurgy of Copper, fifth edition, Elsevier, 2011.
- [6] J. Kulczycka, Ł. Lelek, A. Lewandowska, H. Wirth, J.D. Bergesen, Environmental impacts of energy-efficient pyrometallurgical copper smelting technologies the consequences of technological changes from 2010 to 2050, J. Ind. Ecol. 20(2) (2017), doi: 10.1111/jiec.12369.

- [7] T.E. Norgate, S. Jahanshahi, W.J. Rankin, Assessing the environmental impact of metal production processes, *J. Clean. Prod.* 15 (8–9) (2007) 838–848, <https://doi.org/10.1016/j.jclepro.2006.06.018>.
- [8] S. Alvarado, P. Maldonado, A. Barrios, I. Jaques, Long term energy-related environmental issues of copper production, *Energy* 27 (2) (2002) 183–196, [https://doi.org/10.1016/S0360-5442\(01\)00067-6](https://doi.org/10.1016/S0360-5442(01)00067-6).
- [9] E. Chandra, F. Zaversky, F. Sallaberry, M. Sánchez, Analysis of the energy demand of the Chilean mining industry and its coverage with solar thermal technologies, *Int. J. Sustain. Eng.* 9 (4) (2016) 240–250, <https://doi.org/10.1080/19397038.2016.1148797>.
- [10] S. Moreno-Leiva, et al., Towards solar power supply for copper production in Chile: assessment of global warming potential using a life-cycle approach, *J. Clean. Prod.* 164 (2017) 242–249, <https://doi.org/10.1016/j.jclepro.2017.06.038>.
- [11] J. Hass, et al., Copper mining: 100 % solar electricity by 2030, *Appl. Energy* 262 (2020), <https://doi.org/10.1016/j.apenergy.2020.114506>.
- [12] O. Behar, D. Sbarbaro, L. Moran, Which is the most competitive solar power technology for integration into the existing copper mining plants Photovoltaic (PV), Concentrating Solar Power (CSP), or hybrid PV-CSP, *J. Clean. Prod.* 287 (2021), <https://doi.org/10.1016/j.jclepro.2020.125455>.
- [13] C. Murray, W. Platzer, J. Petersen, Potential for solar thermal energy in the heap bioleaching of chalcopyrite in Chilean copper mining, *Miner. Eng.* 100 (2017) 75–82, <https://doi.org/10.1016/j.mineng.2016.09.022>.
- [14] G. Quiñones, C. Felbol, C. Valenzuela, J.M. Cardemil, R.A. Escobar, Analyzing the potential for solar thermal energy utilization in the Chilean copper mining industry, *Sol. Energy* 197 (2020) 292–310, <https://doi.org/10.1016/j.solener.2020.01.009>.
- [15] O. Behar, et al., The use of solar energy in the copper mining processes_A comprehensive review, *Clean. Eng. Technol.* 4 (2021), <https://doi.org/10.1016/j.clet.2021.100259>.
- [16] T. Eglinton, J. Hinkley, A. Beath, M. Dell'Amico, Potential applications of concentrated solar thermal technologies in the Australian minerals processing and extractive metallurgical industry, *Jom* 65 (12) (2013) 1710–1720, <https://doi.org/10.1007/s11837-013-0707-z>.
- [17] M. Sturzenegger, L. Winkel, C. Guesdon, Solar extraction of copper: on application of concentrated sunlight in extractive metallurgy, *Miner. Process. Extr. Metall.* 115 (1) (2006) 31–40, <https://doi.org/10.1179/174328506X91338>.
- [18] L. Winkel, I. Alxneit, M. Sturzenegger, Thermal decomposition of copper concentrates under concentrated radiation - Mechanistic aspects of the separation of copper from iron sulfide phases, *Int. J. Miner. Process.* 88 (1–2) (2008) 24–30, <https://doi.org/10.1016/j.minpro.2008.04.004>.
- [19] G.J. Nathan, et al., Solar thermal hybrids for combustion power plant : A growing opportunity, *Energy Combust. Sci.* 64 (2018) 4–28, <https://doi.org/10.1016/j.jpecs.2017.08.002>.
- [20] S. Schröders, H. Allelein, Energy economic evaluation of process heat supply by solar tower and high temperature reactor based on the ammonia production process, *Appl. Energy* 212 (2018) 622–639, doi: 10.1016/j.apenergy.2017.12.063.
- [21] T.G. Goonan, Flows of selected materials associated with world copper smelting, 2004, Available Online: <https://pubs.usgs.gov/of/2004/1395/2004-1395.pdf> (accessed on January 8, 2023).
- [22] L.L. Gaines, Energy and materials flows in the copper industry, 1980, Available Online: <https://www.osti.gov/servlets/purl/6540399> (accessed on January 8, 2023).
- [23] I. Najdenov, K.T. Raić, G. Kokeza, Aspects of energy reduction by autogenous copper production in the copper smelting plant Bor, *Energy* 43 (1) (2012) 376–384, <https://doi.org/10.1016/j.energy.2012.04.007>.
- [24] R.R. Moskalik, A.M. Alfantazi, Review of copper pyrometallurgical practice: today and tomorrow, *Miner. Eng.* 16 (10) (2003) 893–919, <https://doi.org/10.1016/j.mineng.2003.08.002>.
- [25] IEA, Tracking Industrial Energy Efficiency and CO₂ Emissions, 2007, Available Online: <https://www.iea.org/reports/tracking-industrial-energy-efficiency-and-co2-emissions> (accessed on January 8, 2023).
- [26] P.I. Guntoro, A. Jokilaakso, P. Taskinen, Copper Matte – Slag reaction sequences and separation processes, *J. Min. Metall.* 54 (3) (2018) 301–311, <https://doi.org/10.2298/JMMB180214021G>.
- [27] W.G. Davenport, E.H. Partelpoeg, *Flash Smelting: Analysis, Control and Optimization*, Pergamon Press, 1987.
- [28] L. Bergh, I. Cornejo, F. Romero, C. Sulzer, Improving copper matte grade control in a concentrate flash furnace, in: IFAC Proceedings Volumes (IFAC-PapersOnline), Vol. 45, no. 23, 2012, pp. 13–18, doi: 10.3182/20120910-3-JP-4023.00035.
- [29] P. Ronan, M. Pritzker, H.M. Budman, Pseudoequilibrium model based estimator of matte grade in a copper smelter, *Ind. Eng. Chem. Res.* 36 (1) (1997) 112–121, <https://doi.org/10.1021/ie960254m>.
- [30] R. Parada, R. Parra, I. Wilkomirsky, Dynamic simulation of a flash furnace, *Can. Metall. Q.* 43 (4) (2004) 561–570, <https://doi.org/10.1179/000844304794409905>.
- [31] V.M. Sanchez-Corrales, J.A. Valera-Gonzalez, P. Flores-Perez, M. Perez-Tello, Mass balance calculations in copper flash smelting by means of genetic algorithms, *Jom* 56 (12) (2004) 29–32, <https://doi.org/10.1007/s11837-004-0231-2>.
- [32] W. Gui, L. Wang, C. Yang, Y. Xie, X. Peng, Intelligent prediction model of matte grade in copper flash smelting process, *Trans. Nonferrous Met. Soc. China (English Ed.)* 17(5) (2017) 1075–1081, doi: 10.1016/S1003-6326(07)60228-3.
- [33] J. Liu, W. Gui, Y. Xie, C. Yang, Dynamic modeling of copper flash smelting process at a Smelter in China, *Appl. Math. Model.* 38(7–8) (2014) 2206–2213, doi: 10.1016/j.apm.2013.10.035.
- [34] Y. Xie, J. Liu, D. Xu, W. Gui, C. Yang, Optimal control strategy of working condition transition for copper flash smelting process, *Control Eng. Pract.* 46 (2016) 66–76, doi: 10.1016/j.conengprac.2015.10.009.
- [35] M. Bacedoni, I. Moreno-Ventas, G. Rios, Copper flash smelting process balance modeling, *Metals* 10 (9) (2020) 1229, <https://doi.org/10.3390/met10091229>.
- [36] World Bank Group, ESMAP, SolarGIS. Global Solar Atlas, Available Online: <https://globalsolaratlas.info/map?c=-23.604131,-69.084278,11&r=-CHL&s=-23.604131,-69.084278&m=site> (accessed on January 8, 2023).
- [37] Mineral Commodity Summaries 2022- Copper. Available Online: <https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-copper.pdf> (accessed on January 8, 2023).
- [38] F.M. Téllez Sufrategui, “Thermal Performance Evaluation of the 200 kWth ‘SolAir’ Volumetric Solar Receiver, 2003”. Available Online: https://inis.iaea.org/collect/on/NCLCollectionStore/_Public/38/115/38115065.pdf (accessed on January 8, 2023).
- [39] European Commission, SolGate, Solar hybrid gas turbine electric power system 2005, Available Online: <https://op.europa.eu/en/publication-detail/-/publication/n/e4f88dd1-74ac-4416-aba0-3868cc8ea5ca> (accessed on January 8, 2023).
- [40] R. Korzynietz, et al., Solugas – comprehensive analysis of the solar hybrid Brayton plant, *Sol. Energy* 135 (2016) 578–589, <https://doi.org/10.1016/j.solener.2016.06.020>.
- [41] C.S. Turchi, M. Boyd, D. Kesseli, P. Kurup, M. Mehos, T. Neises, P. Sharan, M. Wagner, T. Wendelin, CSP systems analysis - final project report, 2019, Available Online: <https://www.nrel.gov/docs/fy19osti/72856.pdf> (accessed on January 8, 2023).
- [42] C.S. Turchi, J. Vidal, M. Bauer, Molten salt power towers operating at 600–650 °C: salt selection and cost benefits, *Sol. Energy* 164 (2019) 38–46, <https://doi.org/10.1016/j.solener.2018.01.063>.
- [43] J. Hernández-Moro, J.M. Martínez-Duart, Analytical model for solar PV and CSP electricity costs Present LCOE values and their future evolution, *Renew. Sustain. Energy Rev.* 20 (2013) 119–132, <https://doi.org/10.1016/j.rser.2012.11.082>.
- [44] S. Craig, G.A. Heat, Molten Salt power tower cost model for the system advisor model (SAM); Technical Report: NREL/TP-5500-57625, National Renewable Energy Laboratory: Golden, CO, USA, 2013.
- [45] Y. Kansha, A. Kishimoto, T. Nakagawa, A. Tsutsumi, A novel cryogenic air separation process based on self-heat recuperation, *Sep. Purif. Technol.* 77 (3) (2011) 389–396, <https://doi.org/10.1016/j.seppur.2011.01.012>.
- [46] U. S. Energy Information Administration, “Electric Power Annual 2017”, Available Online: <http://large.stanford.edu/courses/2018/ph240/walter1/docs/epa-2017.pdf> (accessed on January 8, 2023).
- [47] W. Michael, J.W. Tim, SolarPILOT: a power tower solar field layout and characterization tool, *Sol. Energy* 171 (2018) 185–196, doi: 10.1016/j.solener.2018.06.063.
- [48] G.J. Kolb, An Evaluation of Possible Next-Generation High-Temperature Molten-Salt Power Towers. Sandia National Laboratories, Albuquerque, NM, USA, 2011.
- [49] J. Orovic, V. Mrzljak, I. Poljak, Efficiency and losses analysis of steam air heater from marine steam propulsion plant, *Energies* 11 (11) (2018) 3019, <https://doi.org/10.3390/en11113019>.
- [50] Sandia National Laboratories, An Evaluation of Molten-Salt Power Towers Including Results of the Solar Two Project. Available Online: <https://www.osti.gov/servlets/purl/791898> (accessed on January 8, 2023).
- [51] A. Hasanbeigi, G. Harell, B. Schreck, Energy efficiency potentials in industrial steam systems in China, Development of a steam systems energy efficiency cost curve, 2014, Available Online: https://www.unido.org/sites/default/files/2015-09/EE_Potentials_Steam_Systems_China_0.pdf (accessed on January 8, 2023).
- [52] V. Werner, K. Henry, Large-Scale Solar Thermal Power: Technologies, Costs, and Development; © 2010 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, 2010. ISBN: 978-3-527-40515-2.
- [53] National Renewable Energy Laboratory, System Advisor Model – CSP Cost Data: Turchi C, Heath G., 2013. XLSX Format, Available Online: <https://sam.nrel.gov/concentrating-solar-power/csp-cost-data.html> (accessed on January 8, 2023).
- [54] Sargent & Lundy Consulting Group, Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts; National Renewable Energy Laboratory, Golden, CO, USA, 2003.
- [55] R. Pitz-Paall, J. Dersch, B. Milow, European Concentrated Solar Thermal Road-Mapping, 2005, Available online: <https://cordis.europa.eu/project/id/502578/reporting> (accessed on 3 November 2022).
- [56] G.J. Kolb, C.K. Ho, T.R. Mancini, J.A. Gary, Power Tower Technology Roadmap and Cost Reduction Plan, Sandia National Laboratories, Albuquerque, NM, USA, 2011, doi: 10.2172/1011644.
- [57] J.T. Hinkley, J.A. Hayward, B. Curtin, A. Wonhas, R. Boyd, C. Grima, A. Tadros, R. Hall, K. Naicker, An analysis of the costs and opportunities for concentrating solar power in Australia, *Renew. Energy* 57 (2013) 653–661, <https://doi.org/10.1016/j.renene.2013.02.020>.
- [58] B. Coelho, S. Varga, A. Oliveira, A. Mendes, Optimization of an atmospheric air volumetric central receiver system: impact of solar multiple, storage capacity and control strategy, *Renew. Energy* 63 (2014) 392–401, <https://doi.org/10.1016/j.renene.2013.09.026>.
- [59] F.J. Sorbet, M. Inigo, J. García-barberena, A. Bernardos, Advanced power cycles and configurations for solar towers: Techno-economical optimization of the decoupled solar combined cycle concept, in: Proceedings of the AIP Conference Proceedings, Maharashtra, India, 5–6 July 2018, doi: 10.1063/1.5067073.
- [60] C.S. Turchi, M. Boyd, D. Kesseli, P. Kurup, M. Mehos, T. Neises, P. Sharan, M. Wagner, T. Wendelin, C.S. Turchi, et al., CSP Systems Analysis—Final Project

- Report CSP Systems Analysis—Final Project Report; NREL/TP-5500-72856, National Renewable Energy Laboratory, Golden, CO, USA, 2019.
- [61] M.A. Abaza, W.M. El-Maghlany, M. Hassab, F. Abulfotuh, 10 MW Concentrated Solar Power (CSP) plant operated by 100 % solar energy: Sizing and techno-economic optimization, *Alex. Eng. J.* 59 (2019) 39–47, <https://doi.org/10.1016/j.aej.2019.12.005>.
- [62] K. Hirbodi, M. Enjavi-Arsanjani, M. Yaghoubi, Techno-economic assessment and environmental impact of concentrating solar power plants in Iran, *Renew. Sustain. Energy Rev.* 120 (2019), 109642, <https://doi.org/10.1016/j.rser.2019.109642>.
- [63] Environmental Protection Agency, International Energy Agency, Boiler Replacement Opportunity, Available online: https://www.epa.gov/sites/default/files/2015-07/documents/fact_sheet_chp_as_a_boiler_replacement_opportunity.pdf (accessed on 3 November 2022).
- [64] U.S. Energy Information Administration, U.S. Natural Gas Exports and Re-Exports by Country, Available Online: (https://www.eia.gov/dnav/ng/ng_move_expc_s1_a.htm) (accessed on January 8, 2023).
- [65] P. Viebahn, Y. Lechon, F. Trieb, The potential role of concentrated solar power (CSP) in Africa and Europe—a dynamic assessment of technology development, cost development and life cycle inventories until 2050, *Energy Policy* 39 (2011) 4420–4430, <https://doi.org/10.1016/j.enpol.2010.09.026>.
- [66] J. Hernández-Moro, J. Martínez-Duart, Analytical model for solar PV and CSP electricity costs: present LCOE values and their future evolution, *Renew. Sustain. Energy Rev.* 20 (2013) 119–132, <https://doi.org/10.1016/j.rser.2012.11.082>.
- [67] Z. Zhu, D. Zhang, P. Mischke, X. Zhang, Electricity generation costs of concentrated solar power technologies in China based on operational plants, *Energy* 89 (2015) 65–74, <https://doi.org/10.1016/j.energy.2015.07.034>.
- [68] A.K. Sharma, C. Sharma, S.C. Mullick, T.C. Kandpal, Financial viability of solar industrial process heating and cost of carbon mitigation: a case of dairy industry in India, *Sustain. Energy Technol. Assessments* 27 (2018) 1–8, <https://doi.org/10.1016/j.seta.2018.03.007>.
- [69] X. Zhuang, X. Xu, W. Liu, W. Xu, LCOE analysis of tower concentrating solar power plants using different molten-salts for thermal energy storage in China, *Energies* 12 (2019) 1394, <https://doi.org/10.3390/en12071394>.
- [70] J. Ji, H. Tang, P. Jin, Economic potential to develop concentrating solar power in China: a provincial assessment, *Renew. Sustain. Energy Rev.* 114 (2019), 109279, <https://doi.org/10.1016/j.rser.2019.109279>.
- [71] Carbon Pricing Leadership Coalition, 2017, The carbon prices making low carbon plants competitive, Available online: <https://www.carbonpricingleadership.org/open-for-comments/2017/5/28/the-carbon-prices-making-low-carbon-plants-competitive> (accessed on January 8, 2023).
- [72] G.J. Kolb, C.K. Ho, T.R. Mancini, J.A. Gary, Power Tower Technology Roadmap and Cost Reduction Plan, Sandia National Laboratories, Albuquerque, NM, USA, 2011, doi: 10.2172/1011644.
- [73] Carbon Market Watch, Carbon Markets—The ultimate guide to global offsetting mechanisms, 2020, Available online: <https://carbonmarketwatch.org/publication/s/carbon-markets-101-the-ultimate-guide-to-global-offsetting-mechanisms/> (accessed on January 8, 2023).
- [74] The World Bank, State and Trends of Carbon Pricing 2021, The World Bank, Washington, DC, USA, 2021, doi: 10.1596/978-1-4648-1728-1.
- [75] OECD, Effective Carbon Rates 2018: Pricing Carbon and Emissions Trading, OECD, Paris, France, 2018.
- [76] High-Level Commission on Carbon Prices, 2017, Report of the High-Level Commission on Carbon Prices, World Bank Publications, Washington, DC, 2018, Available online: <https://www.carbonpricingleadership.org/report-of-the-highlevel-commission-on-carbon-prices> (accessed on January 8, 2023).
- [77] Disclosure Insight Action, 2021, Putting a price on carbon: The State of Internal Carbon Pricing by Corporates Globally, Available online: <https://www.cdp.net/en/research/global-reports/putting-a-price-on-carbon> (accessed on January 8, 2023).
- [78] Ministerio de Energía de Chile - Gobierno de Chile, Explorador Solar, Available Online: <https://solar.minenergia.cl/inicio> (accessed on January 8, 2023).
- [79] Sandia National Laboratories, Final Test and Evaluation Results from the Solar Two Project, Available Online: <https://www.osti.gov/biblio/793226> (accessed on January 8, 2023).