Integrated steel plants challenges during transition to green steel – a holistic quantitative evaluation of CO_2 reduction potentials using digital twins in m.simtop

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Production of steel via the well-established fossil-based integrated route involves numerous operation facilities and energy intensive process steps. To reach high-quality steel products at a competitive price requires a wide range of raw materials as well as in-process recycles and systems integration. To meet the increased demands for CO_2 emission reduction, many options ranging from state-of-the-art plant modifications up to the switch to fully new production processes are available. However, finding the optimum transition path for an existing integrated operation site is challenging due to the significant amount of boundary conditions to be considered.

During the last decades process simulation has gained ground in the metallurgic industries, aiding decision-makers in strategic planning. In this elaboration, selected options for CO_2 emission reduction will be applied in a case study starting from a base case of an integrated steel plant facility. Cases will cover the implementation of various waste heat recovery and recycle steps across the production chain up to the substitution of core processes as eg. blast furnace replacements. Results in terms of CO_2 reduction, material streams as well as gas network changes and energy demand are given quantitatively.

KEYWORDS: DECARBONIZATION – GREEN STEEL – DIGITAL TWIN – CO2 REDUCTION – HYDROGEN – M.SIMTOP – WASTE HEAT RECOVERY – DRI – SMELTER – PROCESS SIMULATION

INTRODUCTION: GREEN STEEL – A STEPWISE TRANSITION

The steel industry is a core supplier for infrastructure, mobility, mechanical engineering and numerous industries, thus essential for our societies daily life. However, it is also one of the largest industrial sources of carbon dioxide (CO_2) emissions, contributing significantly to global climate change (1). As environmental concerns intensify and regulatory pressures increase, the imperative for steel producers to reduce carbon emissions has never been more critical. While European steelmakers are setting benchmarks with their ambitious commitments to significantly reduce CO_2 emissions by 2030 and reach carbon neutrality by 2050 (2), approximately 90 percent of the global steel industry have also declared carbon-neutral targets (3).

The decarburization of the iron and steel industry will be a gradual process lasting several decades. An optimization of the blast furnace-basic oxygen furnace (BF-BOF)

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route, which currently accounts for ~70% of global crude steel production (4), and increased scrap usage are logical first steps.

However, scrap availability is limited and to reach carbon-neutral targets, optimization of the coal-based BF-BOF route alone will not be sufficient. A switch of large capacities to more sustainable steel production, such as the direct reduction-electric arc furnace (DR-EAF) route is required. While natural gas (NG)-based direct reduction, emits the least CO_2 among available ironmaking technologies, innovative processes like MIDREX Flex™ also enable transition between NG and hydrogen (H_2) as fuel without major equipment change, further lowering emissions (5). Facing a multitude of technical options, strategic planning is crucial to navigate and achieve sustainability goals while maintaining competitiveness. Process simulation has emerged as a powerful tool in this context, enabling steel plants to optimize operations, enhance efficiency and reduce environmental impact. By simulating production routes and creating digital twins of steel plants, simulation technology allows for the analysis and prediction of performance under various scenarios, facilitating informed decision-making.

This paper explores a step-by-step strategy for decarbonizing an integrated steel plant in a comprehensive case study using Primetals m.simtop simulation platform. It covers optimization measures like waste gas recycling and injection of blast furnace gas in the sinter plant, utilizing hot briquetted iron (HBI) in the blast furnace and additional waste heat recovery options as well as major changes like replacement of a BF by a DR plant and an electric smelting unit. The case study results include the various impacts on emissions, material streams, gas network changes and energy demand. The goal is to demonstrate that with strategic planning and investment, the steel industry can achieve significant reductions in CO_2 emissions by a stepwise approach, aligning with global efforts to combat climate change and promote a greener future.

M.SIMTOP: AN ADVANCED METALLURGICAL MODEL LIBRARY

Over recent years, Primetals Technologies Austria, combined modeling expertise, operational knowledge, process and equipment know-how to develop the comprehensive metallurgical model library m.simtop (6,7) with partners voestalpine and TU Wien. Its flexible, equation-oriented flow sheeting environment covers a wide range of metallurgical processes and auxiliary units, enabling it to perform feed-forward and -backward calculations as well as complex optimization routines. m.simtop can be used to simulate individual equipment as well as complete steel plants and production routes from ore to steel. Applications of m.simtop are (7):

- Assessment of CO_2 and other emissions, process and production route optimization
- Strategic operation planning including calculation of consumption and production figures
- Conceptual operation and investment planning, trace material investigations

CASE STUDY: BENCHMARK BASIS AND DIGITAL TWINS

To achieve a most representative and realistic impression with this case study, the operation of a European integrated steel plant was chosen as basis. Respective raw materials, the plant set ups and partly operation data are available to the authors and will serve as a benchmark to demonstrate the applicability of m.simtop in the calculation of CO_2 emissions and conceptual operation and investment planning. Thus, a digital twin of the integrated steel plant from ore to crude steel liquid phase (BOF) was set up and selected sub plants operation data compared with m.simtop models results. Subsequently selected operational and plant changes were applied to digital twins in the case study and ensuring highest flexibility for evaluations. Figure 1 gives an overview on the integrated steel plant set up implemented as digital twin in m.simtop.

Operation of the integrated steel plant is typical for central Europe: a wide mixture of raw materials is charged to the sinter and coking plant, including a significant amount of recycle streams. Blast furnace operation is based on a majority of sinter with additionally including pellets, lump ore and PCI injection apart from coke as a fuel. Detailed operation data was available for sinter plant and blast furnace and used for model validation. Quality of operation data is key to achieve later robust and professional results from digital twins. The operation data was investigated in a standardized procedure on plausibility and conservation of mass balance. From experience in checking mass balance it is known, that operation data is always affected by uncertainties and incomplete figures, demanding pragmatic procedures in later modelling steps of combining operation data, technological knowledge and other sources of information such as literature. Figure 2 combines resulting comparisons of selected process parameters for sinter plant and blast furnace. Available operation data contained a significant amount of deviations in the conservation of mass, such as iron, carbon, calcium and magnesia elements for sinter plant as well as carbon, nitrogen and iron elements for the blast furnace, which result in figure 2 shown deviations. Due to closed mass balances in m.simtop incorrect or missing process values can easily be highlighted. As Figure 2 right hand side shows, for closing the mass balance at the blast furnace in m.simtop a significantly lower lump ore rate would apply, which shows that somewhere in the real plant material handling of ferrous burden materials most likely improvements are required.

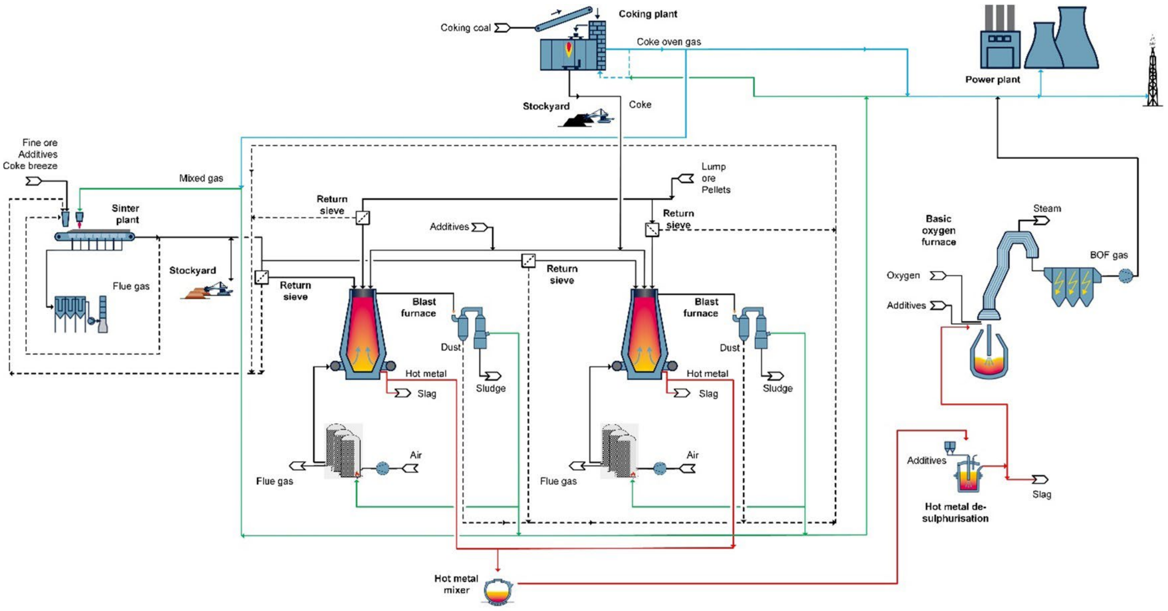

Fig.1 - Depiction of the integrated steel plant setup and implementation in m.simtop.

As no official CO_2 production figures of the various sub plants of the integrated steel plant were available to the authors, the available flue gas measurements CO_2 contents indicated respective CO_2 emissions.

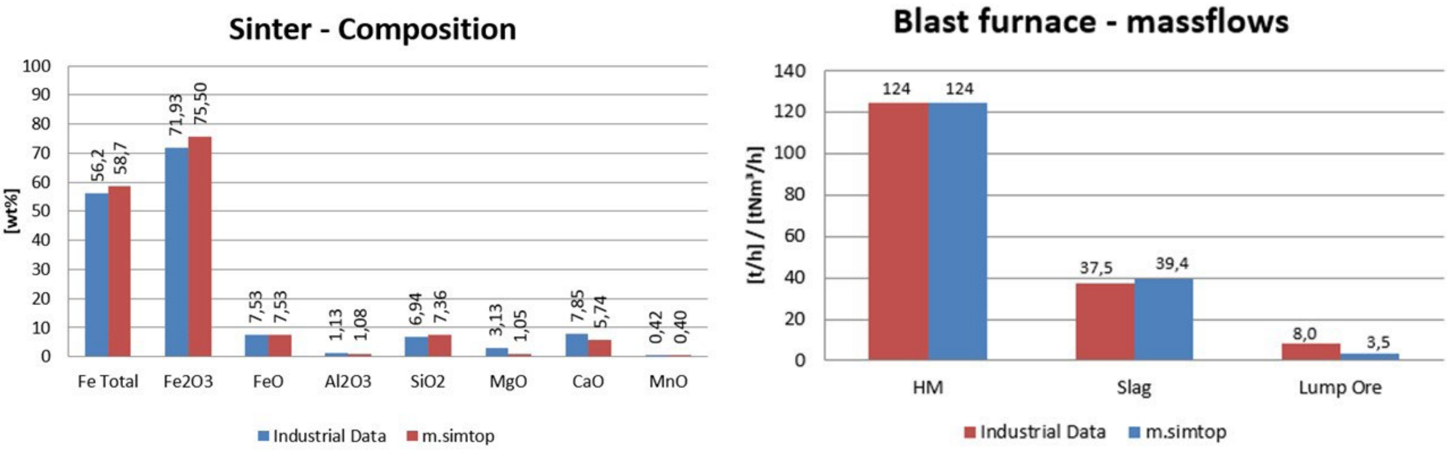

Fig.2 - Comparison of selected process figures and simulation results in m.simtop.
Left: sinter analysis, right: selected mass flows at blast furnace.

Based on this operation data the total CO_2 generated for crude steel production was obtained in m.simtop (scope 1 only) and was found to be in good accordance to values from literature (9). From this starting point subsequently step wise emission reductions and investigations on resulting effects were derived in a case study.

CASE STUDY – DEFINITIONS AND RESULTS

Considering that decarbonization of steel industry will follow a step-by-step approach, different possible steps for CO_2 reduction were investigated. In the first step of the case study focus was laid to a selection of currently available and proven in use operation practices and technologies for reduction of CO_2 emissions focusing on the sinter and blast furnace facilities. To reach a finally significant reduction of CO_2 emissions for a long-term prospect profound structural changes were applied and incorporated as digital twins. This embraces the substitution of one blast furnace by a direct reduction (DR) plant along with a smelter while still maintaining the BOF shop. For final minimization of CO_2 emissions a process route consisting of two DR plants with respective melt shops was applied. In detail the following cases were investigated:

- Case 1: Waste gas recycling at sinter plant (WGR)
- Case 2: WGR and blast furnace gas injection to recirculation gas at sinter plant (BFGI)
- Case 3: WGR + BFGI and charging of HBI to blast furnaces (HBIC)
- Case 4: WGR + BFGI + HBIC and waste heat recovery at hot blast stoves (HB-WHR)
- Case 5: substitution of one blast furnace by a natural gas-based (NG) DR plant and smelter unit
- Case 6: switch of the DR plant from natural gas to hydrogen (H_2) operation
- Case 7: only two DR plants with hydrogen operation including smelter with BOF shop

During the case study numerous frame conditions were held, in the following the most important are described:

- All simulations were done in m.simtop, thus full comparability of the cases is ensured
- A constant production of 2,5 Mtpa crude steel production for all cases was applied
- Focus was laid to scope 1 CO_2 emissions
- For cases 1 to 4 a reduction in sinter and coke demand results, it was assumed that the respective production will be reduced accordingly – resulting in a reduction of coke oven gas (COG production) as well as of CO_2 emissions
- For cases 5 and 6, in the remaining sinter and blast furnace facilities applied measures from cases 1 – 4 were kept active
- For the DR plant was assumed, that a flexible switch from natural gas to hydrogen operation is possible
- Residual gases from coke ovens, blast furnace and BOF were converted in a power plant model to generate a figure for CO_2 emissions of residual gases and to depict conversion to electric energy

The applied changes gradually cause severe changes in the single plant operations, by-products as well as in the interconnected gas network, power generation and usage of recycle materials. Due to the high amount of data made available by the case study and the limited frame of this publication, only selected core figures such as overall CO_2 emissions, total amount of residual gas as well as electric energy output are discussed in detail (see Figure 3).

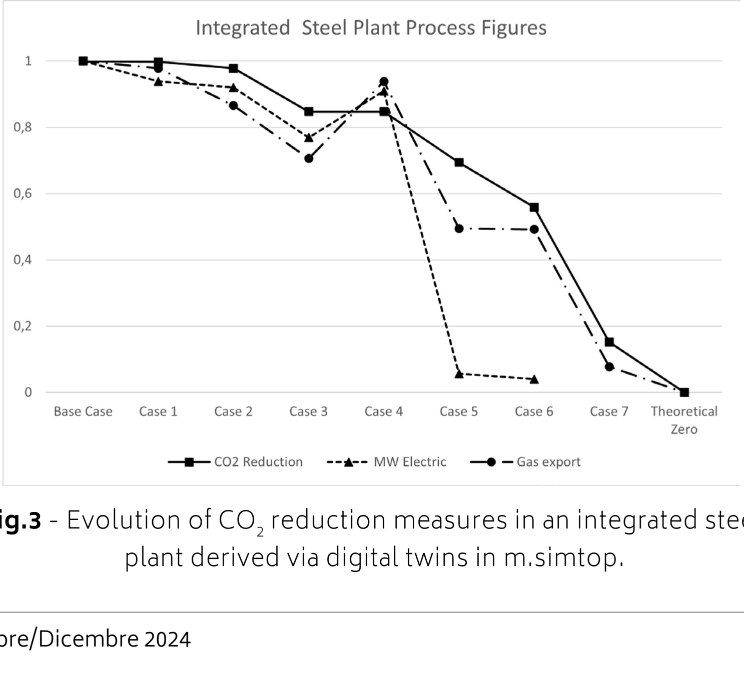

Fig.3 - Evolution of CO_2 reduction measures in an integrated steel plant derived via digital twins in m.simtop.

Initial measures at the sinter plant (case 1 + 2) such as WGR and BFGI (1% of CO in recirculated gas) have only limited effect on the overall figures of CO_2 emissions, residual gases and electricity balance. Additional measures such as application of BFG at the ignition hood and sinter cooler are available, are both already implemented. Case 4 – charging of HBI (200 kg/t hot metal) to the BFs as a well-known practice (8) – shows a significant reduction in the overall CO_2 emission, as it directly results in lower sinter and coke demand which reduces in the frame conditions of this investigation emissions at all involved facilities. Along with this measure, residual gas production and the electrical energy demand also decreases. Implementing HB-WHR again makes more residual gas available, as the consumption at the stoves for heating is cut down – but does not reduce CO_2 emissions as the available BFG is later converted in the power plant. Further measures such as substitute reducing agents injection to the tuyeres, installation of a top gas recovery turbine or even more rigorous technologies such as top gas recycling apart from others could be investigated in the future. With the substitution of one BF with a NG DR plant (case 5) a significant reduction of CO_2 is possible, while having the chance to keep the same raw material basis and BOF shop setup due to the use of a smelter unit. Removing one BF goes along with significant drop of residual gas as well as a drop in electric energy provision – also caused due to the electrical energy demand of the smelter unit. Case 6 again shows a significant reduction in CO_2 emissions with the switch to a H_2 based DR plant. Finally, a radical reduction of CO_2 emissions is reached with the switch to H_2 based DR plants only (case 7). Nevertheless, input of carbon to the process is necessary for operation of the smelter unit, and at least at this stage external supply of electrical energy will be necessary.

CONCLUSIONS

In the scope of this work digital twins were used to investigate CO_2 reduction measures in an integrated steel plant. The basis was given by a central European integrated production site, with step wise application of selected state of the art measures first and finally disruptive changes in the production routes. Based on the available operation data, benchmarking was successfully performed. Beside lowering CO_2 emissions, the CO_2 reduction measures also lead to a decrease in the total amount of residual gases as well as decreased electric power output at the power plant. It can be seen, that measures to reduce CO_2 result directly in a reduced input of carbon, thus lowering the formation of residual gases. By using a smelter unit, the electricity demand is significantly increased and would even require external supply of energy. During this case study it was proven, that process simulation can successfully aid operation controlling and investment planning.

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