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Estimating Material and Energy Demands of a Transition to Hydrogen-Based Steelmaking Using Mathematical Optimization#

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ABSTRACT

One potential alternative for reducing CO_2 emissions from the steel industry involves replacing the traditional coal-based steelmaking route with hydrogen-based steelmaking technologies. From a chemical and energetic point of view, this would mean replacing coal as source of energy and carbon for the iron ore reduction process with hydrogen as reductant and electricity as the main energy input. As a highly energy-intensive industry, the sourcing of energy for its needs greatly affects its overall environmental impacts and its role in a wider energy system. This paper evaluates a possible evolution of energy and material demands in different development stages of a steel plant transitioning towards hydrogen-based steelmaking technologies using a long-term mathematical optimization model. Moving to iron ore reduction by hydrogen from electrolysis with electricity from wind turbines would shift the raw material requirements from large amounts of mined coking coal to smaller amounts of diverse materials for the wind turbines and electrolyzers, including rare earth elements, as well as an increased need for natural gas and recycled steel scrap. While the total quantity of required materials will inarguably be reduced, the impacts of construction of and reliance on increased electricity generation will need to be considered.

Keywords: steel production, hydrogen, integrated systems, decarbonization, optimization

NOMENCLATURE

Abbreviations	
BF	Blast furnace
BOF	Basic oxygen furnace
CC	Continuous casting
CHP	Combined heat and power
CP	Coke plant
DRI	Direct reduced iron
EAF	Electric arc furnace
ELY	Electrolyzer
LT	Ladle treatment
PP	Pellet plant
REF	Reformer
RM	Rolling mill
SF	Shaft furnace
SP	Sinter plant

1. INTRODUCTION

The steel industry is highly energy-intensive, and the most widely used steelmaking route, the BF-BOF route, relies on coal as the main source of energy and carbon for the reduction of iron ores in blast furnaces. As such, the steel industry emits between 7 and 9% of global anthropogenic greenhouse gases[1], giving a clear motivation for developing improvements and alternative steelmaking routes to decrease these emissions.

One promising technology alternative for decarbonizing the steel industry is direct reduction of iron ores in shaft furnaces using hydrogen as a reductant, resulting in direct reduced iron (DRI) that can be further processed in electric arc furnaces[2]. This steelmaking route is referred to as the H_2DR route in this present paper. With direct reduction using hydrogen, the process results in H_2O instead of CO_2, meaning that direct emissions from ironmaking could be greatly reduced. However, low-carbon production of the required amounts of hydrogen would require immense amounts of low-carbon electricity for the electrolysis process. Additionally, the EAF process relies on electricity. The overall primary energy requirements of the BF-BOF and H2-DR routes have been estimated as roughly equal[3].

The discussion of decarbonizing the steel industry can thus for the H_2DR route be seen as part of the wider discussion of a transition from fossil energy to renewables. Both Nijnens et al.[4] and Krane and Idel[5] stress the substantial reduction in overall demand of mined materials that a transition from fossil to renewable energy technologies would entail. They also

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point out that the so-called transition materials can in many cases be recycled, which is not the case with fossil fuels. However, the increased demands of materials for renewable technologies, despite the lower total volumes compared to the coal required for the BF-BOF route, also come with harms that need to be considered [6], especially as several sectors of society simultaneously have similar energy transition plans all contributing to continuous and rapid increase in demand for critical minerals.

This paper aims to analyze quantitatively how the requirements of energy and materials may progress during a transition towards hydrogen-based steelmaking and discuss what this could mean in terms of environmental impacts and system resilience. Section 2 describes the simulation model used for the calculations. Section 3 presents the assumed steel plant configuration and market conditions used in the simulation case. Sections 4 and 5 present and discuss the simulation results and Section 6 finishes the paper with conclusions.

2. METHODOLOGY

Potential steel plant development pathways have previously been analyzed using a long-term mathematical optimization model by Haikarainen et al.[7]. A modified version of this same model was used for the study in this paper. The model was used to simulate a transition from the BF-BOF route to the H_2DR route over the course of 25 years, and the simulation results were analyzed from the perspective of required energy and materials during the simulated time horizon.

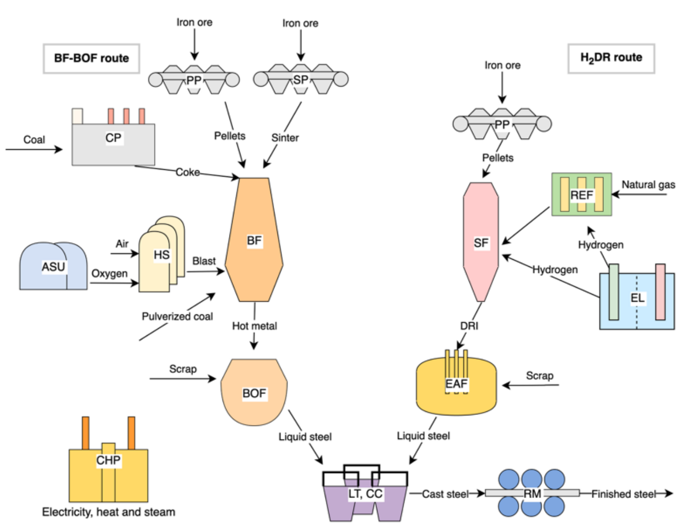

Figure 1. Schematic of main units and material streams in the BF-BOF and H_2DR routes

Modern steel plants are highly integrated, efficiently utilizing process gases and internal energy streams. The main aspects of the transition from the BF-BOF route to the H_2DR route are described in Figure 1. In the BF-BOF route coke and iron carriers (pellets, sinter, lump ore, scrap) are fed to blast furnaces (BF), giving an output of hot metal that is further processed in basic oxygen furnaces (BOF) to remove excess carbon. The molten steel from BOFs then goes through ladle treatment (LT) and continuous casting (CC) processes to finally be shaped into steel products in rolling mills (RM).In the H_2DR route, iron pellets are fed into shaft furnaces (SF) where a reductant gas (usually consisting of mostly H_2 and CO, but also H_2O, CO_2, CH_4 and N_2) through a series of reactions reduces the iron to produce direct reduced iron (DRI) mostly consisting of pure Fe. If the reduction gas is mainly H_2, the exiting top gas will be mainly H_2O and unreacted H_2, which to some extent can be recycled. E.g. in the MIDREX process [8], the recycled top gas partly goes through a reformer to yield new reduction gas, and part is combusted to heat the reformer.

The main modifications to the previous model[7] were the replacement of the shaft furnace model and the addition of a reformer model. For the shaft furnace, a 2D CFD model[9] was used to simulate data points that were in turn used to formulate a surrogate regression model that was implemented in the system optimization model. The same modelling principle was applied for the reformer, with data points simulated with a model in Aspen used to formulate regression equations for the optimization model.

While many studies assume 100% H_2 in the reductant gas, the inclusion of at least CO in the models along with H_2 is relevant for several reasons. Finished steel contains varying degrees of carbon depending on the desired properties, so carbon needs to enter the system at some process stage. The reductant gas composition affects the process conditions and the composition of the DRI product, so it may be desirable to have some CO in the reductant gas to achieve favorable conditions[9]. Flexible adjustment of H_2-CO ratios may also be used to adapt to variable and uncertain energy and hydrogen markets [10].

The optimization model minimizes total accumulated costs or emissions over a selectable time horizon divided into time periods. New investments are possible each time period, so that the system configuration may evolve throughout the time horizon and the operational schemes in each time step are optimized. The structural and operational optimization is formulated as one mixed-integer quadratic programming problem and relies on assumptions regarding future parameter values.

3. CASE DESCRIPTION

This section describes a theoretical steel plant used to analyze a transition to hydrogen-based steelmaking. The initial plant configuration features two blast furnaces and a steady production rate of 456 t_{steel}/h (approx. 4 Mt per year) from the rolling mills is assumed, i.e. the model does not account for dynamics in the production rate or shutdowns during maintenance periods. Initially, an internal CHP plant running on process gases covers the electricity demands of the steel plant. The 25-year time horizon was divided into 5-year time periods, with new investments in electrolyzers, DR shaft furnaces and EAFs possible in each period.

Throughout the time horizon, grid electricity costs were assumed as 85 €/MWh. Grid emissions of 60 kg_{CO2}/MWh were assumed, corresponding to average emissions from the Finnish grid electricity in 2021-2023[11]. This can be compared with the EU average of 210 kg_{CO2}/MWh in 2023[12]. New grid capacity to cover added electricity demands from the steel plant is assumed to be wind energy, but the overall emissions from grid electricity will still not be zero. Assumed material requirements for construction of wind turbines are listed in Table 1[13].

Table 1. Estimated average material requirements for constructing 1 GW of wind power capacity[13].

Material	Usage [t/GW]
Concrete	345 000
Steel	117 875
Polymers	4 600
Glass/carbon composites	8 075
Aluminum	1 050
Boron	2
Chromium	525
Copper	2 588
Dysprosium	8
Iron	19 750
Manganese	790
Molybdenum	436
Neodymium	68
Nickel	363
Praseodymium	12
Terbium	2
Zinc	5 500

CO_2 permit costs naturally affect the simulation results, as higher costs encourage investments and operational schemes with lower emissions. CO_2 prices were assumed to start from 20 €/t_{CO2} in the initial period, increasing by 40 €/t_{CO2} in each time period. Simulation results are additionally highly dependent on the assumed price of recycled steel scrap. Lower scrap prices favor charging EAFs primarily with scrap. To limit overt reliance on scrap alone, the price of scrap was assumed to increase with increased scrap imports.

In addition to the materials required for construction of added grid electricity capacity, the materials needed for the electrolyzers were accounted for. Assuming alkaline electrolyzer technology, the material requirements for 1 GW of electrolyzer capacity has been reported as 800 t of nickel, 100 t zirconium, 10 000 t steel and 500 t aluminum[14]. Proton exchange membrane (PEM) electrolyzers have also been commercialized, with advantages of modularity, low maintenance and quick response to variable energy source, but requirements of platinum, palladium and iridium[15].

4. SIMULATION RESULTS

Using the optimization model described in the previous section, a potential transition pathway was simulated by first minimizing total accumulated costs for the 25-year time horizon and then repeating the optimization minimizing total accumulated emissions with a limit for the total costs 2% higher than the minimum. This way a feasible nearly cost-optimal solution with significantly lower emissions could be found without going into more rigorous multi-objective optimization. The resulting configurations in each time period are presented in Table 2.

Table 2. Configurations in the simulated transition steps

Time period	Process units and outputs
1	2 BFs: 441 $t_{hot\ metal}$/h BOF: 485 $t_{liquid\ steel}$/h CHP: 154 MW_{el}
2	2 BFs: 388 $t_{hot\ metal}$/h BOF: 426 $t_{liquid\ steel}$/h EAF: 59 $t_{liquid\ steel}$/h CHP: 142 MW_{el}, Grid el.: 23 MW
3	2 BFs: 337 $t_{hot\ metal}$/h BOF: 371 $t_{liquid\ steel}$/h EAF: 59 $t_{liquid\ steel}$/h CHP: 119 MW_{el}, Grid el.: 55 MW
4	ELY: 163 kNm^3/h H_2 2 SFs: 350 t_{DRI}/h 2 EAFs: 485 $t_{liquid\ steel}$/h Grid el.: 1031 MW
5	ELY: 163 kNm^3/h H_2 2 SFs: 350 t_{DRI}/h 2 EAFs: 485 $t_{liquid\ steel}$/h Grid el.: 1031 MW

These transition steps are naturally just one theoretical set of configurations, and the optimization results are completely dependent on assumed simulation parameters and circumstances[7] but represent one possible transition pathway for the sake of this study. Generally, it can be said that the configuration goes from a pure BF-BOF route, via an added EAF charged with scrap in time periods 2 and 3, to an H_2DR configuration with 2 DR shaft furnaces and 2 EAFs in time periods 4 and 5.

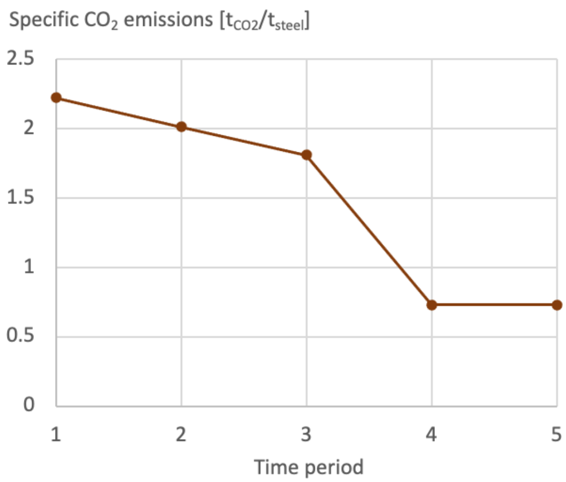

Figure 2. Evolution of specific CO_2 emissions during the simulated time horizon

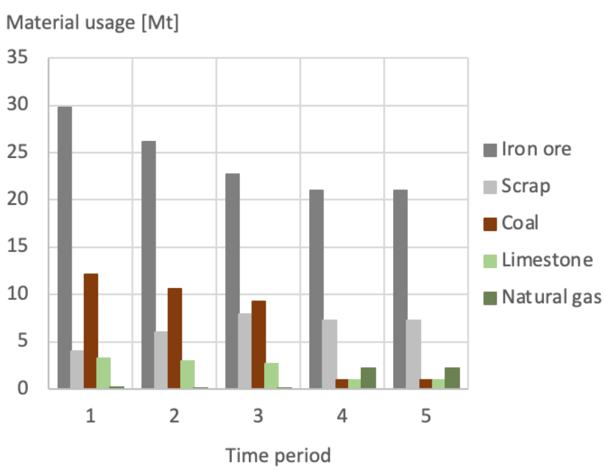

Figure 3. Evolution of continuous material inputs per time period to the steel plant during the simulated time horizon

As seen in Figure 2, CO_2 emissions gradually decrease from the initial 2.2 t_{CO2}/t_{steel} to 0.73 t_{CO2}/t_{steel}. CO_2 emissions of the final configuration greatly depend on the grid emissions, the DRI/scrap ratio in the EAFs and the rates of natural gas fed to the reformer for producing the reduction gas mixture. With the EU average GEI, the emissions of the final configuration would be about 1.1 t_{CO2}/t_{steel}. The main motivation for transitioning to the H_2DR route relies on renewable electricity generation: high grid emissions nullify the proposed environmental gains from hydrogen-based reduction. A previous study indicated that GEI values above about 300 kg_{CO2}/MWh would give higher CO_2 emissions for the H_2DR route than the BF-BOF route [16]. Indirect emissions can also increase if the steelmaking relies on H_2 imports from sources with higher emissions [17].

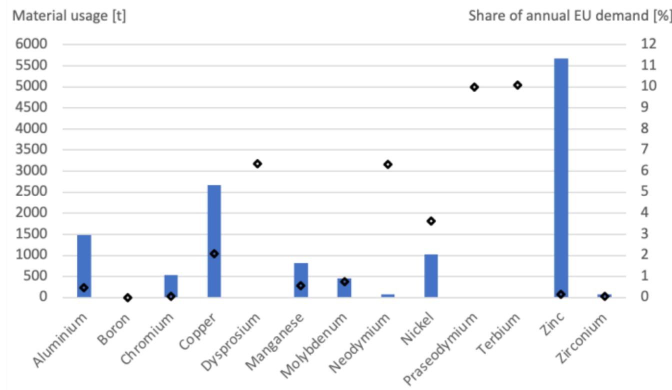

Figure 4. Material usage (bars) and comparison with annual EU demands (markers) for the wind turbines and electrolyzers in the simulated scenario

The largest material demands for the wind turbines and electrolyzers concern concrete and steel. The installations in the simulated transition requires a total of roughly 356 000 t concrete and 130 000 t steel. These values can be compared with, e.g., the annual EU demands: the demand of concrete is about 0.2% of the annual EU demand and the demand of steel about 0.09%. The amount of steel corresponds to 12 days of production from the simulated steel plant. Figure 4 shows the demands of some of the other required materials in the simulated scenario together with a comparison with the annual EU demands. Values for the annual EU demands were assembled from Refs. [18] and [19]. While the need for zinc is relatively large (5 700 t), the need is small compared to EU demands (0.2%). The total demands of dysprosium, neodymium, praseodymium and terbium are small in volume (2 – 70 t) but they all represent 6 – 10% of the annual EU demands.

If these values for material usage (iron carriers, fuels, construction material, etc.) are converted to tons of material per ton steel produced, with an assumed 20-year lifetime for the new investments, the overall mass of required materials can be estimated to decrease from 2.5 t/t_{steel} in the first time period to 1.6 t/t_{steel} in time period 5, by about 34%. As the material use in Figure 4 is measured in tons, while that in Figure 3 is measured in megatons, the largest total material requirement by far is that of iron carriers and it remains largely unchanged, while the reduction in mining requirements practically comes from the reduction in coal use.

The increase in natural gas use seen in Figure 3 comes to the largest parts from use in the reformers to produce the SF feed gas and as fuel in the rolling mills, since there is no more coke oven gas available after shutting down coke production. Alternative rolling processes could potentially further reduce the energy demands. A smaller amount of natural gas is also used in the EAFs. The increase in annual natural gas use in the simulated scenario corresponds to an increase of 0.2% of the annual EU natural gas demand.

The H_2DR route also competes with simply charging EAFs with recycled scrap. This scrap-EAF route uses less electricity and materials but is restricted by the availability of scrap. Recycling cannot cover the entire current and predicted future steel demand[20], so there is a need to develop the complementary routes, including improvements to the BF-BOF route.

5. DISCUSSION

The required new grid capacity to cover the electricity demands for the steel plant in the simulation case, about 1030 MW, can, e.g., be compared with realized wind turbine investments. According to WindEurope[21], 1015 MW new wind power capacity was installed in Sweden in 2024, so without considering capacity factors, the required capacity for a plant with an annual production of about 4 Mt crude steel could roughly correspond to the annual installed wind power capacity in Sweden. Considering a similar comparison at the EU level, with a total annual crude steel production of approximately 130 Mt in 2023, of which 55% was produced via the BF-BOF route[22], a complete transition from BF-BOF to H_2DR would with the same proportions require about 18.4 GW of added grid capacity. This is about 140% of the new wind power installations in the EU in 2024[21].

These values can be interpreted as both relatively large and small: the required installations are certainly sizeable, especially if they are to be realized within a short timeframe. The new installations may require enhancing the electricity grids and the processes of getting necessary permissions for the investments often take years [23]. Yet, when calculated over the lifetime of the technologies and the potential emission reductions they may achieve, it could be estimated that approximately 20 GW of actual grid capacity (capacity factors and variability of renewable energy technologies would need to be considered) could cover the grid electricity needs of hydrogen-based steel production to reduce emissions from the EU steel industry by almost 70%. Estimating emissions from the EU steel industry as about 5% of total EU emissions[2], the transition could reduce EU total emissions by over 3%.

The dependence of the H_2DR route on high-grade iron ores is a relevant concern, as the availability of ores of sufficient quality may restrict the technology[24]. Efforts are thus made to develop routes and combinations of process units accepting lower grade ores. Generally, a wide adoption of hydrogen in the steel industry involves complex relations with a potential hydrogen economy infrastructure[25]. As Boldrini et al.[17] point out, the question of decarbonizing the steel industry requires collaboration and integration of power, hydrogen and steel sectors to decrease both direct and indirect emissions, but large consumers such as the steel sector also have the potential of stabilizing systems relying on variable renewable energy.

6. CONCLUSIONS

Hydrogen-based steelmaking technologies show potential in decreasing CO_2 emissions from the steel industry, with the simulations in this paper suggesting a gradual decrease from 2.2 t_{CO2}/t_{steel} to 0.73 t_{CO2}/t_{steel} over the course of the transition of an integrated steel plant from the BF-BOF route to the H_2DR route. This transition would come with a decrease in total material use by 34%, as the need for coal diminishes, but also with considerable increases in grid electricity demands. The total volumes of materials required for this grid expansion are small compared to the decrease in required coal mining but still contributes to the general trend of increased need for critical materials for an overall energy system decarbonization. As a large energy-intensive industry, developments in the steel industry need to be considered as coupled with the energy and hydrogen sectors.

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REFERENCES

[1] World Steel Association (2025, May 23) *#steelfacts*. Retrieved from https://worldsteel.org/about-steel/facts/steelfacts/

[2] Li C, Zhang L, Wang Q, Zhou D. Towards low-carbon steel: System dynamics simulation of policies impact on green hydrogen steelmaking in China and the European Union. Energy Policy 2024;188:114073

[3] Vogl V, Åhman M, Nilsson LJ. Assessment of hydrogen direct reduction for fossil-free steelmaking. J Cleaner Prod 2018;203:736-745

[4] Nijnens J, Behrens P, Kraan O, Sprecher B, Kleijn R. Energy transition will require substantially less mining than the current fossil system. Joule 2023;7:2403-2413

[5] Krane J, Idel R. More transitions less risk: How renewable energy reduces risks from mining, trade and political dependence. Energy Res Social Sci 2021;82:102311

[6] Dunlap A, Marin D. Comparing coal and 'transition materials'? Overlooking complexity, flattening reality and ignoring capitalism. Energy Res Social Sci 2022;89:102531

[7] Haikarainen C, Shao L, Pettersson F, Saxén H. Mathematical optimization modeling for scenario analysis of integrated steelworks transitioning towards hydrogen-based reduction. Energy 2024;305:132366

[8] Kazalski P, Koh PY. (2025, May 28) *The Adaptable Midrex® Reformer: A Bridge to the Hydrogen Economy*. Retrieved from https://www.midrex.com/tech-article/the-adaptable-midrex-reformer-a-bridge-to-the-hydrogen-economy/

[9] Zhai Y, Shao L, Zhao C, Zhang X, Saxén H. A Numerical Study of the Thermochemical and Aerodynamic States of H_2-intensive Direct Reduction Shat Furnace. Steel Res Int 2024;2400567

[10] Wu H, Ke D, Song L, Xu J, Liao S, Wang L. Multi-objective and multi-stage capacity planning for low-carbon iron and steel industry empowered by wind-gas-hydrogen energy. Appl Energy 2025;390:125793

[11] Motiva (2025, May 26) *CO2-päästökertoimet* (In Finnish). Retrieved from https://www.motiva.fi/ratkaisut/energiankaytto_suomessa/co2-paastokertoimet

[12] European Environment Agency (2025, May 22) *Greenhouse gas emission intensity of electricity generation in Europe*. Retrieved from https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of-1

[13] Carrara S, Alves Dias P, Plazzotta B, Pavel C. Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system, Publications Office of the European Union, Luxembourg, 2020, doi:10.2760/160859

[14] IEA (2025, May 26) *The Role of Critical Minerals in Clean Energy Transitions*. Retrieved from https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

[15] Teixeira B, Brito MC, Mateus A. Strategic raw material requirements for large-scale hydrogen production in Portugal and European Union. Energy Rep 2024;12:5133-5144

[16] Haikarainen C, Pettersson F, Saxén H. Optimizing the transition pathway of a steel plant towards hydrogen-based steelmaking. Ironmaking Steelmaking 2024;SteelSim Special Issue:1-8

[17] Boldrini A, Koolen D, Crijns-Graus W, van den Broek M. The impact of decarbonizing the iron and steel industry on European power and hydrogen systems. Appl Energy 2024; 361:122902

[18] Carrara S, Bobba S, Blagoeva D, Alves Dias P, Cavalli A, Georgitzikis K, Grohol M, Itul A, Kuzon T, Latunussa C, Lyons L, Malano G, Maury T, Prior Arce Á, Somers J, Telsnig T, Veeh C, Wittmer D, Black C, Pennington D, Christou M. Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/386650

[19] SCRREEN (2025, May 28) *Factsheets - CRMS 2023*. Retrieved from https://scrreen.eu/crms-2023/

[20] Harvey LDD. Iron and steel recycling: Review, conceptual model, irreducible mining requirements, and energy implications. Renewable Sustainable Energy Rev 2021;138:110553

[21] WindEurope (2025, May 21) *Wind energy in Europe: 2024 statistics and the outlook for 2025-2030*. Retrieved from https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2024-statistics-and-the-outlook-for-2025-2030/

[22] Eurofer (2025, May 21) *European Steel in Figures 2024*. Retrieved from https://www.eurofer.eu/publications/brochures-booklets-and-factsheets/european-steel-in-figures-2024

[23] Beyond Fossil Fuels (2025, May 22) *How Europe's grid operators are preparing for the energy transition*. Retrieved from https://beyondfossilfuels.org/wp-content/uploads/2025/05/How-Europes-grid-operators-are-preparing-for-the-energy-transition.pdf

[24] Rahbari A, Shahabuddin M, Sabah S, Brooks G, Pye J. Production of green steel from low-grade ores: An end-to-end techno-economic assessment. Cell Rep Sustainability 2025;2:100301

[25] Schneider C. Steel manufacturing clusters in a hydrogen economy – Simulation of changes in location and vertical integration of steel production in Northwestern Europe. J Cleaner Prod 2022;341:130913