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Article

Design of Clean Steel Production with Hydrogen: Impact of Electricity System Composition

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Abstract: In Europe, electrification is considered a key option to obtain a cleaner production of steel at the same time as the electricity system production portfolio is expected to consist of an increasing share of varying renewable electricity (VRE) generation, mainly in the form of solar PV and wind power. We investigate cost-efficient designs of hydrogen-based steelmaking in electricity systems dominated by VRE. We develop and apply a linear cost-minimization model with an hourly time resolution, which determines cost-optimal operation and sizing of the units in hydrogen-based steelmaking including an electrolyser, direct reduction shaft, electric arc furnace, as well as storage for hydrogen and hot-briquetted iron pellets. We show that the electricity price following steelmaking leads to savings in running costs but to increased capital cost due to investments in the overcapacity of steel production units and storage units for hydrogen and hot-briquetted iron pellets. For two VRE-dominated regions, we show that the electricity price following steel production reduces the total steel production cost by 23% and 17%, respectively, as compared to continuous steel production at a constant level. We also show that the cost-optimal design of the steelmaking process is dependent upon the electricity system mix.

Keywords: decarbonization; electrification of industry; steel industry; modelling and optimization; renewable energy sources (RESs); hydrogen storage

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1. Introduction

Combating climate change and reducing its impacts are on the agendas of governments worldwide. Nineteen countries have pledged to achieve carbon neutrality by the year 2050 as part of the Carbon Neutrality Coalition [1], and the European Commission has suggested the so-called 'New Green Deal' to the European Union (EU), targeting climate neutrality by the year 2050 [2]. Targeting climate neutrality makes it obvious that all sectors must reach zero emissions (except perhaps for some "hard-to-abate" sectors, which may compensate with caron dioxide removals). The maturity and cost of technologies and measures that are available to contribute to the low-carbon transition vary between sectors. While there is progress in the electricity generation sector with an increasing share of renewable energy (RE) [3], there has been much less implementation of carbon-neutral processes in energy-intensive basic materials industries in general, and in the steel industry in particular [4]. Given that the steel sector accounts for between 7 and 9% of worldwide CO_2 emissions [5,6], it is a critical consideration when addressing the challenge of climate change [7].

1.1. CO_2 Emissions Reduction Options

There are several options to decarbonize the steel industry, each with a different level of technological maturity and potential for CO_2 emissions reduction. The main options for achieving deep cuts in emissions from steel production are: (i) the use of carbon capture and storage (CCS); (ii) the use of biomass as a fuel and a reducing agent to replace coke [8];

and (iii) electrification with carbon-neutral electricity, via either hydrogen-direct reduction (H-DR) or electrowinning [9,10]. Table 1 lists the main decarbonization options for the steel industry together with their CO_2 abatement potential.

Table 1. The main CO_2 emission reduction options in the steel industry together with their abatement potential as obtained from the literature.

CO_2 Emissions Reduction Options	Abatement Potential	Reference
Increased process efficiency [1]	16%	[11]
Material efficiency	approx. 20%	[12]
Steel reuse and recycling	17%	[13]
Top gas recycling blast furnace	5–10% 15%	[14] [15]
CO_2 capture technology [2]	50–75%	[16–18]
CO_2 capture technology + Top gas recycling blast furnace	60%	[15,19]
Biomass [3]	7–15% 23% 20–42% 31–57%	[20] [21] [22,23] [8]
Biomass + CO_2 capture technology + Top gas recycling blast furnace	over 80%	[14,24]
Hydrogen direct reduction (H-DR) [4]	~100% [5]	[25–27]
Electrowinning	~100% [5]	[25]

[1] Blast furnace/basic oxygen furnace production route. [2] Post combustion capture of blast furnace emissions. [3] Fuel substitution in the blast furnace/basic oxygen furnace production route. [4] Shaft furnace. [5] The CO_2 emissions depend on the electricity system composition.

In Europe, electrification seems to be the preferred option to date [28]. The major European steel companies [27,29–31] have hydrogen-based steel production as their main decarbonization strategies.

By applying hydrogen instead of fossil fuel in the steelmaking process, almost complete removal of CO_2 emissions can be achieved if the electricity is supplied from a fully decarbonized electricity system [32]. Moreover, the hydrogen-direct reduction process achieves the goals of sustainable steelmaking defined by Fruehan [33], which are: (i) preservation of natural resources; (ii) decrease of CO_2 emissions; (iii) decrease of other gaseous emissions; (iv) decrease of landfill waste; and (v) decrease of hazardous waste.

1.2. Hydrogen Direct Reduction Steelmaking Process

Figure 1 presents a schematic of the hydrogen-direct reduction process, which can be divided into hydrogen production and two main steps for the steel production from the iron ore: ironmaking and steelmaking. The iron ore pellets are reduced to direct reduced iron (DRI) in a shaft furnace using hydrogen as a reducing agent during the ironmaking process. The reduction process that occurs in the shaft furnace is continuous [34]. Uniform inflow of the iron ore charge and uniform distribution of the gas reductant across the shaft furnace are essential for ensuring uniform metallization of the direct reduced iron pellets [35]. To avoid re-oxidization by ambient oxygen, the direct reduced iron is compacted into hot-briquetted iron (HBI), which can be stored and transported without the need for special precautions [36]. The hydrogen can be produced by electrolysis (this work assumes that hydrogen from renewables but, in principle, so-called blue hydrogen could also be used while avoiding CO_2 emissions (i.e., hydrogen from natural gas where CO_2 has been captured and stored)), which is the process of using electricity to split water into oxygen and hydrogen. In the second step, hot-briquetted iron is further converted to liquid steel in an electric arc furnace (EAF). The storage of hydrogen and hot-briquetted iron allows for flexible temporal distribution of the electricity consumption of the process. Large-scale hydrogen storage in salt caverns offers the most promising storage option due to low investment cost, favourable conditions for getting them tight and low cushion gas requirements. Yet, such storage is limited by geographical availability across Europe [37]. Gas Infrastructure Europe (GIE) has estimated the capacity requirements of hydrogen storage for Europe to 70 TWh in 2030 and around 450 TWh in 2050 [38]. Several research and innovation projects have been funded and initiated in the last decade to investigate the feasibility of hydrogen in terms of production, transportation, storage, and use [39]. The electrolyser and electric arc furnace offer a high level of operational flexibility, which means they can be turned on and off relatively fast and to a low cost. The electrolyser has a low minimum load, short start-time, and high ramp rate [39]. The electric arc furnace is flexible in terms of the changing rate of power consumption [40] and can be stopped and started in response to the prevailing level of demand [41]. The direct reduction shaft can be run within a flexible range without a decrease in efficiency [42].

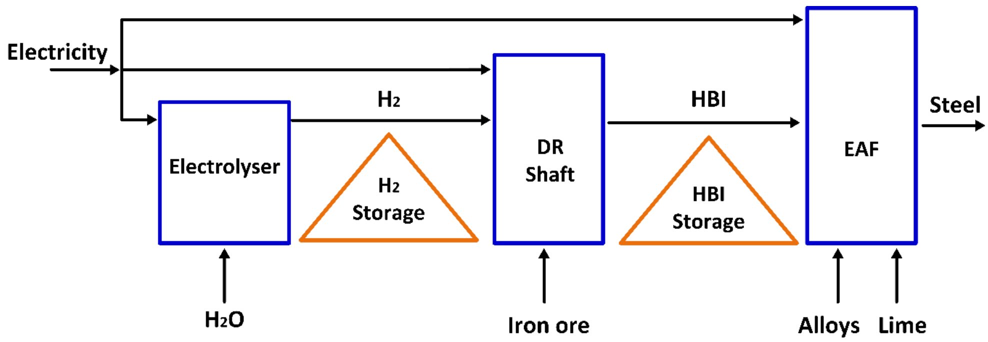


Figure 1. Schematic of the hydrogen-direct reduction (H-DR) process with the three production steps indicated in blue and the two storage options indicated in orange.

1.3. Research Gap

The hydrogen-direct reduction process is gaining attention from the industry as well as from the research community. Applying an innovation system approach, Kushnir et al. [43] evaluated the potential barriers to the transition to hydrogen-direct reduction steelmaking, finding the coordination of the technical infrastructure and the cost pressure (cost of capital, cost of energy, potential market) to be the most important barriers. Fischedick et al. [25] presented techno-economic models, which were used to compare three innovative ore-based steelmaking routes, i.e., a blast furnace with carbon capture and storage (BF-CCS), hydrogen-direct reduction, and iron ore electrolysis, to the reference blast furnace route. They demonstrated that steel production via the hydrogen-direct reduction process is economically and environmentally the most attractive way to produce steel, since separating hydrogen production from continuous operation of the steel plant through hydrogen storage gives the opportunity to utilize low-cost renewable electricity.

In many parts of the world, wind and solar power technologies, i.e., variable renewable electricity (VRE) generation, provide carbon-neutral electricity at the lowest cost [44]. In the future, they are expected to supply a large proportion of the demand for electricity. Large shares of VRE will cause significant variations in electricity prices [45]. Growing penetration of variable renewable energy needs to be taken into account by energy-intensive industries. For energy-intensive industries, the flexible operation, which is adjustable to electricity price profiles by varying the load and switching operation modes, can be cost beneficial [46]. Roh et al. [47] analysed the sizing and operation of the chlor-alkali electrolyser employing a bifunctional cathode for different electricity price profiles using a mixed-integer linear optimization model. They concluded that flexible operation of the chlor-alkali electrolysis results in savings in running costs but to raised capital investment due to retrofitting for overcapacity and is only economically viable for the future forecasted electricity price profile (where the average price as well as the deviations from the average price are three times higher than in 2017). As for the hydrogen-direct reduction steelmaking process, it allows for three different flexibility options to meet electricity price variations: 1. hot-briquetted iron (HBI) pellet storage, 2. flexible operation of steel production capacity, and 3. hydrogen storage. Additionally, since the cost of electricity accounts for a significant part of the cost of the hydrogen-direct reduction steelmaking process [48,49], a key question is which the combination of the three flexibility options gives the most cost-efficient steel production system given different electricity price variations.

While previous works on the steelmaking process with hydrogen focused mainly on process modelling for investigating energy use, CO_2 emission abatement potential and economic performance [48], techno-economic analysis [25,50–52], and the impacts of its introduction to the energy system [53–56], there are no studies published on the cost-optimal design and operation of the hydrogen-direct reduction steelmaking process considering its flexibility options. To fill this gap, we develop and apply a linear cost-optimization model to study how electricity price variations influence investments in and the operation of steel production that apply the hydrogen-direct reduction steelmaking process. The developed model is applicable to any country and its application is illustrated using electricity price profiles that correspond to two regions (southern Germany and Scotland) with different conditions for VRE.

The paper is organized as follows. Section 2 outlines the modelling method. In Section 3, the findings from the modelling and sensitivity analysis are presented and discussed. Section 4 summarizes the conclusions drawn from the outcomes of this work.

2. Method

To investigate the effects of the electricity price fluctuations on steel production capacities applying the hydrogen-direct reduction process, a steel process (SP) model was developed with the overall structure shown in Figure 2. The SP model analyses both investment decisions in steel production capacities (in the electrolyser, direct reduction shaft furnace, and electric arc furnace) and storage technologies (hot-briquetted iron pellets storage and hydrogen storage), so as to meet the annual steel demand, as well as the operational times and operational levels of the steel production capacities, including storage utilization. The modelling is performed using different electricity price curves representing two different countries and comparing the current prices (year 2018) and the corresponding prices for a future system (year 2050). The latter prices are for a system that includes high shares of variable renewables (wind and solar power), which are obtained from an electricity systems model ("Hours to Decade"; H2D) [53]. The SP model investigates investments in the new steel production capacity, which means that it does not consider the retrofitting of existing plants. The SP model has an hourly resolution and a temporal scope of 1 year. Since the electricity price is exogenously provided to the model, there is no dependency between the steel production capacity levels and the electricity price. The model assumes there is demand for steel year around, i.e., 8760 h per year and expressed as 1 tonne per hour. Thus, the total annual steel production needed to meet the demand in the model is 8760 tonnes of liquid steel per year (although this amount can be produced in different ways over the year when storage is applied). The model results can be extrapolated to the production level of a steel plant of any capacity.

2.1. Data

The economic data are composed of values for steel production capacities and hydrogen storage, with an assumption of no cost for hot-briquetted iron storage. Data related to the electrolyser and hydrogen storage were acquired from the Danish Energy Agency, Energistyrelsen [57], which provides information about the technological parameters, economics and environment of existing technologies, technologies in development, and technologies still at an experimental stage. The electrolyser costs are based on an estimation for alkaline electrolysis. The hydrogen is assumed to be stored in lined rock caverns [58].

Capital costs for the direct reduction shaft furnace and the electric arc furnace are based on the data from Wörtler et al. [59]. Operating expenses comprise the commodities costs (ore, lime, alloys), electricity cost, and other variable costs (Operations and Maintenance (O&M), graphite electrodes). The O&M costs for the direct reduction shaft furnace and the electric arc furnace were adopted from Fischedick et al. [25]. The cost assumption for iron ore is based on the average market prices reported for the period of 2009–2018 [60]. The steelmaking commodity costs and consumption levels, including for the graphite electrode, are based on previous reports [25,61]. Tables detailing the economic data, with further descriptions of the data provided in the Appendix A.

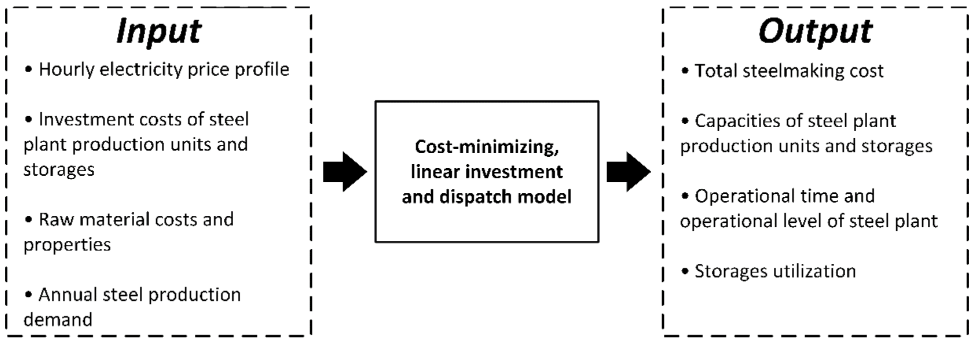


Figure 2. Schematic overview of the model structure applied in this work.

To account for uncertainties in technology costs, a sensitivity analysis was conducted varying (both reducing and increasing) the investment cost of hydrogen storage (the results are given in Table A3).

2.2. Steel Process Model

The main decision variables are the steel production capacity (i_p), production ($g_{p,t}$), and storage charge ($z^{ch}_{p,t}$) and discharge ($z^{dis}_{p,t}$). The set p represents the steel production capacities (electrolyser, direct reduction shaft furnace, electric arc furnace) and storage technologies (hot-briquetted iron pellets storage, hydrogen storage). The overall objective of the SP model is to assess the operational times and operational levels of the steel production capacities, as well as the utilization of storage units so that the steel demand is met to the lowest total cost of steel production (C^{tot}), i.e., the sum of the investment costs (C^{inv}_p), running ($C^{run}_{p,t}$), and cycling ($C^{cycl}_{p,t}$). The objective function of the model, which is a minimization of the total steel production cost, is written as:

$$minC^{tot} = \sum_{p \in P} C^{inv}_p i_p + \sum_{p \in P} \sum_{t \in T} (C^{run}_{p,t} g_{p,t} + C^{cycl}_{p,t}) \quad (1)$$

As the main task is to satisfy the steel demand, the overall steel balance is expressed as:

$$\sum_{t \in T} (g_{p,t} - z^{ch}_{p,t} + z^{dis}_{p,t}) \geq D^{an}_{steel} \quad (2)$$

Equation (2) ensures that the steel production capacity produces a sufficient level of products (hydrogen, HBI), as needed to satisfy the total annual steel demand (D^{an}_{steel}).

Equation (3) describes the utilization of storage units, i.e., the levels of products (hydrogen, HBI) stored in storage technologies at every time-step ($soc_{p,t}$):

$$soc_{p,t} = soc_{p,t-1} + \eta_p z^{ch}_{p,t} - z^{dis}_{p,t}, \; \forall p \in \; P^{STR}, \forall t \in \; T \quad (3)$$

where $z^{ch}_{p,t}$ represents the amount of products charged to the storage at every hour t, $z^{dis}_{p,t}$ is the amount of products discharged from the storage, and η_p is the efficiency of storage.

In addition, the levels of products (hydrogen, HBI) stored using the storage technologies have to be lower than or equal to the storage capacity (i_p) at all times:

$$soc_{p,t} \geq i_p, \; \forall p \; \in \; P^{STR} \tag{4}$$

In the SP model, it is assumed that the cycling of the direct reduction shaft furnace, i.e., the minimum load level, start-up time, and start-up costs, is associated with additional costs due to thermal stress on the materials and increasing O&M costs. Data regarding cycling costs are difficult to acquire. In this work, the time duration of 12 h is assumed to be the direct reduction shaft furnace start-up time. The start-up cost corresponds to the production cost of hot-briquetted iron pellets during the start-up time. When started, the direct reduction shaft furnace is allowed to vary between 30% and 100% of the installed capacity. The cycling properties of the direct reduction shaft furnace are accounted for according to the method used for inclusion of the cycling properties of thermal generation in the investment models [62].

2.3. Electricity Price Profiles

The hourly electricity price profiles apply the current (year 2018) profiles from Germany and the UK, as obtained from Epexspot [63] and NordPool [64], respectively. Since at present (represented by Year 2018), the countries for which the electricity price profiles are obtained have a single bidding zone defined by national borders (for Germany, the bidding zone is larger and includes Austria and Luxembourg), a uniform electricity price for the entire country is used.

The electricity price profiles for the year 2050 are obtained from the electricity system investment model H2D [53]. The H2D model minimizes the investments and operation costs of an electricity system, while satisfying the demand for electricity for a given time period. This model has a 3-h time resolution and a geographic resolution according to the main bottlenecks in the transmission grid. Northern Europe is divided into 12 regions, and the current configuration (year 2018) of the bidding zones is modified. Therefore, the year 2050 electricity prices deployed in this work do not correspond to those of the entire countries but instead to the regions representing southern Germany and Scotland. These regions are selected to demonstrate a variety of conditions for varying renewable electricity generation. In order for them to be applied in the steel process model developed for this work, the price profiles are modified to an hourly resolution through linear interpolation within each 3-h time segment. Table 2 lists the main characteristics of the electricity systems that give the applied price profiles.

Table 2. The four electricity price profiles used as inputs to the steel process model.

Electricity Price Profile	Region	Year	Solar Power [TWh] (Penetration Level [%])	Wind Power [TWh] (Penetration Level [%])	Average Electricity Price, €/MWh
1	Germany	2018	46 (~8%)	112 (~19%)	45
2	Southern Germany	2050	152 (~22%)	135 (~20%)	61
3	The UK	2018	13 (~4%)	57 (~16%)	65
4	Scotland	2050	0.5 (~1%)	45 (~94%)	49

The year 2050 modelling results reveals that the electricity system of Scotland has 94% wind power in the energy mix (share of annual production). This region is referred to as the "wind-dominated" electricity system. The year 2050 electricity system of southern Germany has high shares of wind power (20%) and solar PV power (22%). However, as solar power generation is concentrated during a few hours of the day, the impact on the electricity price formation of the variability from solar generation is more pronounced, especially during the summertime. The electricity system of southern Germany is referred to as the "solar-rich" electricity system.

Figure 3 compares the electricity price duration curves for the two regions for the year 2018 and the year 2050. In the year 2050, the high shares of renewables result in increases in the duration and number of both the high- and low-electricity price periods, as compared with the year 2018 electricity price profiles. For the electricity system of Scotland, the long low-price electricity periods in the year 2050 lead to an average electricity price that is 20% lower than that of southern Germany in the same time period. The electricity price profiles in the year 2050 are obviously much more volatile than they were in the year 2018.

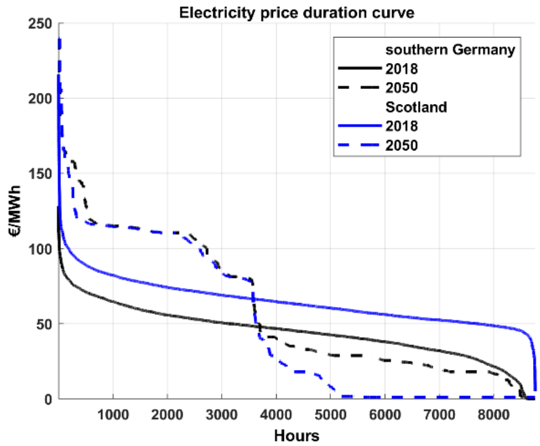
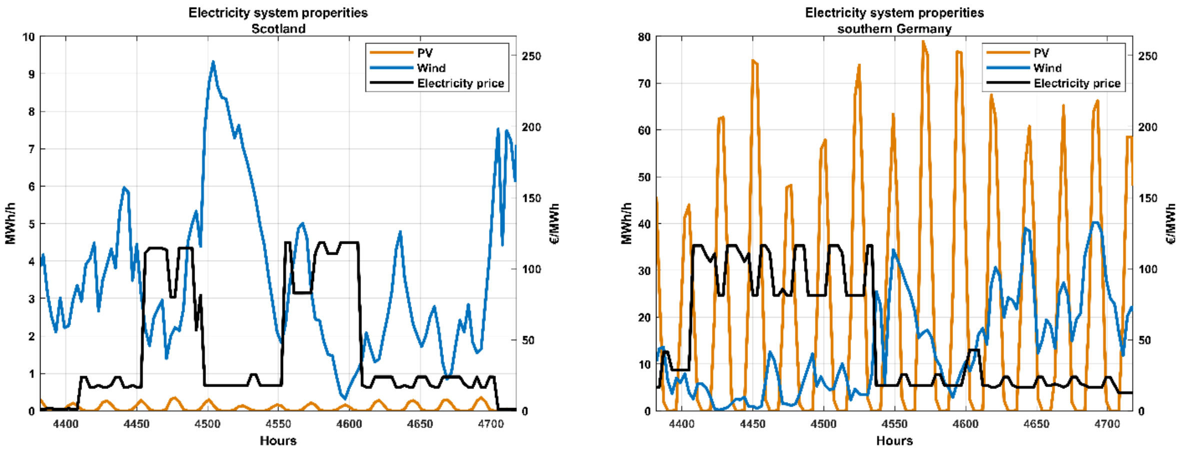


Figure 3. Electricity price duration curves for southern Germany and Scotland in the year 2018 and in the year 2050.

It should be noted that the 2018 electricity prices differ substantially from the electricity prices in 2021 for the regions investigated. In the EU in 2021, gas, coal, and electricity prices have increased to their highest levels in decades [65]. At the same time, the EU ETS price has risen by about €30/tCO_2 from January 2021 to September 2021. The current situation of high energy prices is the result of a combination of supply and demand factors: global economic recovery from the COVID-19 crisis, cold and long winter in the Northern Hemisphere, and a tighter-than-expected supply of electricity. Europe relies on gas imports, and a scarcity of supplies exposes it to price volatility even in the face of minor quantity shocks. The impact of the gas price increase on the electricity price is nine times larger than the impact of the carbon price increase [66]. The current crisis stresses the need to accelerate the transition to clean electricity, in particular in the form of wind and solar.

The high volatility of the electricity price profiles in 2050 are evident in Figure 4, which shows the electricity prices together with the wind and solar power generation levels for southern Germany and Scotland for 3 weeks in July 2050, as obtained from the modelling. It is clear that solar and wind power influence the electricity price volatility in different ways. Wind power variations lack any cyclic component in their variation. The solar variations are cyclic due to their daytime and night-time dependency. This is seen in the "solar-rich" region of southern Germany as a result of the diurnal variation of solar power, with low prices during the daytime and high prices at night. For the "wind-dominated" system of Scotland, the electricity price variations have durations of several days, albeit with no regular pattern.

Even though solar power generation has a strong impact on the electricity price in southern Germany (year 2050), this impact diminishes during wintertime. However, there are obviously some regions with good solar conditions all year around. To investigate the operation of steel production capacities in such a region, a sensitivity analysis was performed by applying an artificial electricity price profile. The electricity price profile for the artificial sunny region with good conditions for solar power throughout the year was constructed by assigning the available electricity price for the summer of 2050 in Germany to all four seasons.



(**a**) (**b**)

Figure 4. Electricity price curves, together with the levels of wind and solar power generation for: (**a**) Scotland; (**b**) southern Germany, for three weeks in July 2050.

3. Results and Discussion

The results on the implication of the electricity price fluctuations on the investments and operation of hydrogen storage, steel production capacity, and hot-briquetted iron pellets storage are presented in Section 3.1 and on the roles of steel decarbonization in different countries depending on the local characteristics in Section 3.2. In Section 3.3, the results of the sensitivity analysis are given. In Section 3.4, the implications of the current work as well as the importance for different stakeholders are discussed. Finally, in Section 3.5, the limitations of the work are presented.

3.1. Investments in Steel Production and Storage Capacities

Table 3 compares the minimum investment level (i.e., what is required to satisfy the annual steel demand if the steel production units are operated at full capacity all hours of the year) in the steel production capacity (electrolyser, direct reduction shaft furnace, and electric arc furnace) with the modelled steel production capacity and storage size for the regional electricity price profiles (the year 2018 profile and the modelled year 2050 profile). The comparison shows that the variations in the electricity price result in investments in the production capacity that are larger than would be required if the steel production was operated continuously during all hours of the year and if there were no investments in storage. It should be noted that there are no investments in storage units when applying the present (year 2018) price profile. However, due to the high operational flexibility, the electrolyser is sized to take advantage of electricity price fluctuations already at todays' electricity prices. For Scotland in the year 2018, the model invests in the electrolyser capacity, which is 14% higher than required if operated at the rated output. For Germany, an investment in the electrolyser capacity is 18% higher than minimum investment level for the same year. Investments in the direct reduction shaft furnace and electric arc furnace are 18% and 20% is higher, respectively, compared to the minimum investment levels in both regions. Investments in the steel production capacities are increased as the variability of electricity prices is increased from the year 2018 to the year 2050.

From Table 3, it is clear that investments in storage occur as a result of the optimization of the allocation between the three production steps and the two storage options in the process. With the more variable year 2050 prices, large volumes of hot-briquetted iron are stored, as well as some hydrogen. The main difference in the design of the steelmaking process for the two national electricity price profiles relates to the sizing of the storage units. The size of the hot-briquetted iron storage unit correlates with the duration of wind variation (up to several days) for Scotland and with the (diurnal) duration of solar variation for southern Germany. Thus, the level of hot-briquetted iron storage in the steelmaking process in Scotland is almost 10 times higher than that in southern Germany.

Table 3. The minimum investment levels in steel production capacities and for the production capacities and size of storages obtained from the modelling, for the two electricity price profiles and the two regions.

	Production Capacity			Storage Capacity	
	Electrolyser [MW/tLS/h]	**DR Shaft Furnace [tHBI/tLS/h]**	**EAF [tLS/tLS/h]**	**Hydrogen [MWh]**	**HBI Pellets [tHBI]**
Minimum Investment level (MinIn)	2.2	1.1	1.0	0	0
Scotland					
2018	2.5	1.3	1.2	0	0
2050	3.8	2.0	1.7	2.7	108
southern Germany					
2018	2.6	1.3	1.2	0	0
2050	3.7	1.9	1.7	4.4	12

Based on the results of the sensitivity analysis, lowering hydrogen storage investment costs (down to 0.0055 M€/MWh) in Scotland and southern Germany for the electricity price profiles for the year 2050 leads to increased investments in both the electrolyser and hydrogen storage and decreased investments in the direct reduction shaft furnace capacity. This configuration of the steel production process, induced by a low investment cost for hydrogen storage, results in a decrease in the cost of electricity and no change in investment costs. Applying a high investment cost for hydrogen storage (0.0165 M€/MWh) gives no investment in hydrogen storage and decreased investments in the electrolyser, which leads to an increase in the cost of electricity.

The CO_2 emissions from the hydrogen-direct reduction steelmaking process mainly reflect the CO_2 intensity of the electricity system. The electricity price profiles applied in this work are taken from a modelled decarbonized North European electricity system [53]. This means there are no CO_2 emissions from the electricity system. However, CO_2 emissions are still manifested through the extraction and production of iron ore and limestone, lime calcination, and the addition of carbon as a required component of steel.

Figure 5 shows the distribution of the production cost per tonne of steel for the two regions for the year 2018 and year 2050 electricity price profiles. In the case of the year 2050 electricity price profiles, the model results are compared to the production cost when one assumes that the steel production capacities are operating continuously during all hours, i.e., without investments in storage (the "minimum investment level" case). The investment cost, raw material costs, direct reduction shaft furnace start-up cost, electricity cost, and the other O&M costs are summed to calculate the steel production cost, which is expressed per tonne of steel produced (i.e., as €/t). In all cases, a large share of the production cost comes from the cost of raw materials (ore, lime, alloys) (up to 51% for Scotland in the year 2050). Internationally traded commodities, such as iron ore, lime, and graphite electrodes, have fluctuating market prices. Even though these prices are uncertain and will most likely vary in the future, these variations should not have an impact on the operational mode of the steelmaking process within short-term periods (hours, days, weeks), since the short-term variability of the raw material price is significantly lower than that of the electricity price.

Figure 5 also indicates that the electricity cost is a large part of the production cost, except for the case of Scotland in the year 2050, with the latter reflecting abundant wind power generation with a low production cost. In the year 2050, investments in storage for the hydrogen-direct reduction steelmaking process, which provides for flexible electricity consumption, result in a production cost decrease of 23% and 17% in Scotland and southern Germany, respectively, as compared to the "minimum investment level" cost (no storage and production capacity is at maximum 8760 h). This is despite the fact that the annual investment costs almost double compared to the minimum investment level. In Scotland, the steel production cost is lower in the year 2050 than in the year 2018, also in the case of continuous production, which is due to a decrease in the average annual electricity price compared to the year 2018 (large share of wind power with low production cost). In southern Germany, however, the steel production cost is higher in the year 2050 than in the year 2018 unless the hydrogen-direct reduction steelmaking process is designed for flexible electricity consumption.

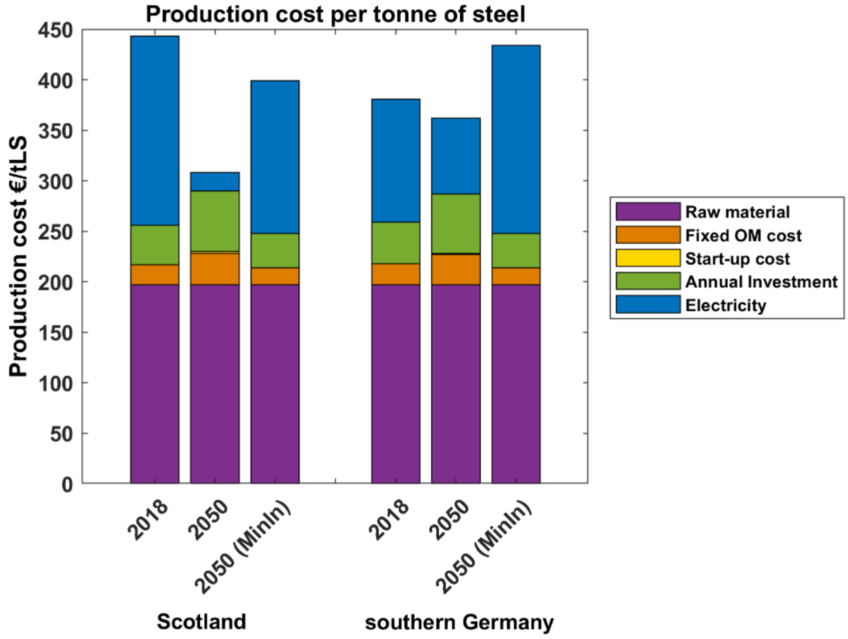


Figure 5. Steel production cost expressed per tonne of steel for the steelmaking process with the minimum investment (MinIn) level in steel production capacity (operation is at full capacity all hours of the year and no storage) in the two regions in the year 2050 (MinIn); for the modelled steelmaking process (Figure 1) for the two regions for the year 2018 and the year 2050 electricity price profiles.

As pointed out previously, the steel production cost with the hydrogen-direct reduction process is sensitive to the electricity price as was shown by Vogl et al. [48]. Since the method applied by Vogl et al. does not include the cost of flexible hydrogen-direct reduction process operation (i.e., through additional investments in production capacities and investments in storage technologies) or how these costs should be balanced relative to the benefits (lower electricity price), the steel production costs obtained by Vogl et al. do not reflect differences imposed by different electricity price profiles, as investigated in the present work. The dependence on electricity price profiles is particularly important for the future electricity system, which is expected to have a high share of VRE.

To which extent it is cost-efficient to utilize the potential flexibility in the hydrogen-direct reduction process depending on the electricity price fluctuations and the CAPEX of steel production capacities. A CAPEX cost decline of 10% for the hydrogen-direct reduction technology seems plausible if further research efforts are supported through the year 2030 [25]. As the direct reduction shaft furnace and electric arc furnace are mature technologies, it is reasonable to assume that the capital costs for these furnaces will remain similar up to the year 2050. As for the electrolyser, the CAPEX may be significantly lower owing to increased R&D funding and production scale-up [67,68]. A decrease in the capital cost of the electrolyser is expected to increase investments in the electrolyser and hydrogen storage capacity so that the electricity-intensive electrolyser (cf. Table A2 in Appendix A) can operate more opportunistically without increasing investments in the capital-intensive direct reduction shaft (cf. Table A1 in Appendix A).

3.2. *Operational Time and Operational Level of the Steel Production Capacity*

Figures 6 and 7 show for southern Germany and Scotland, respectively, the levels of electricity generation from solar PV and wind power, together with the electricity price profiles (Figure 6a,d and Figure 7a,d); hydrogen production and hot-briquetted iron pellets production and state of charge of the hydrogen storage (Figure 6b,e and Figure 7b,e); steel production and state of charge hot-briquetted iron storage (Figure 6c,f and Figure 7c,f) in the year 2050 with a design that allows for flexible electricity consumption.

For the case with the German electricity price profile (Figure 6), the operation of the steel production units follows the solar-influenced cyclic electricity price variations as shown for both March (Figure 6a) and July (Figure 6d). The largest consumer of electricity in the steelmaking process, the electrolyser, avoids hydrogen production when the electricity price exceeds 50 €/MWh, as shown in Figure 6b,e. The electrolyser operates at full capacity when the electricity price is less than 50 €/MWh and it produces hydrogen used both for charging the hydrogen storage and for reduction within the direct reduction shaft furnace. However, during long periods of high solar radiation and good wind conditions, such as in July, the electrolyser sometimes operates at reduced capacity to avoid peaks even during low-price hours, i.e., hours 4600–4700 in Figure 6e. The continuous production of the direct reduction shaft furnace during such periods is supported by the discharging of the hydrogen storage. Unlike the electrolyser, the electric arc furnace occasionally operates at full capacity even when the electricity price exceeds 50 €/MWh, i.e., hours 2680–2700 in Figure 6c. The direct reduction shaft furnace operates at reduced capacity when the electricity price fluctuates at levels above 50 €/MWh, and as the level of production from the direct reduction shaft furnace is not sufficient to support electric arc furnace production at full capacity, the hot-briquetted iron storage is discharged (hours 2680–2700 in Figure 6c).

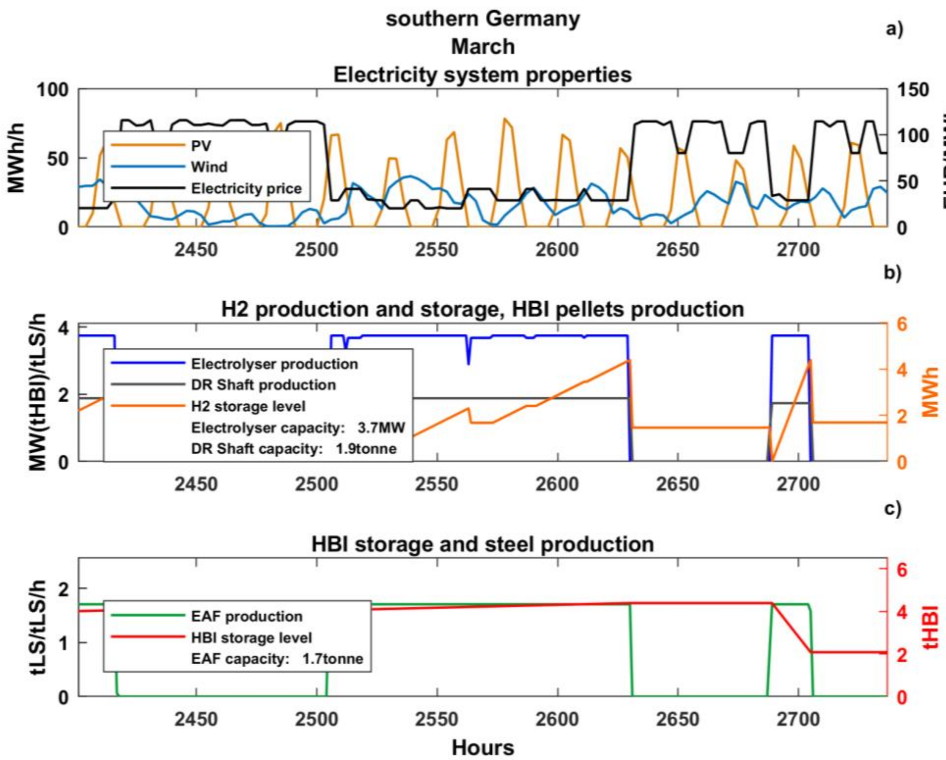


Figure 6. *Cont.*

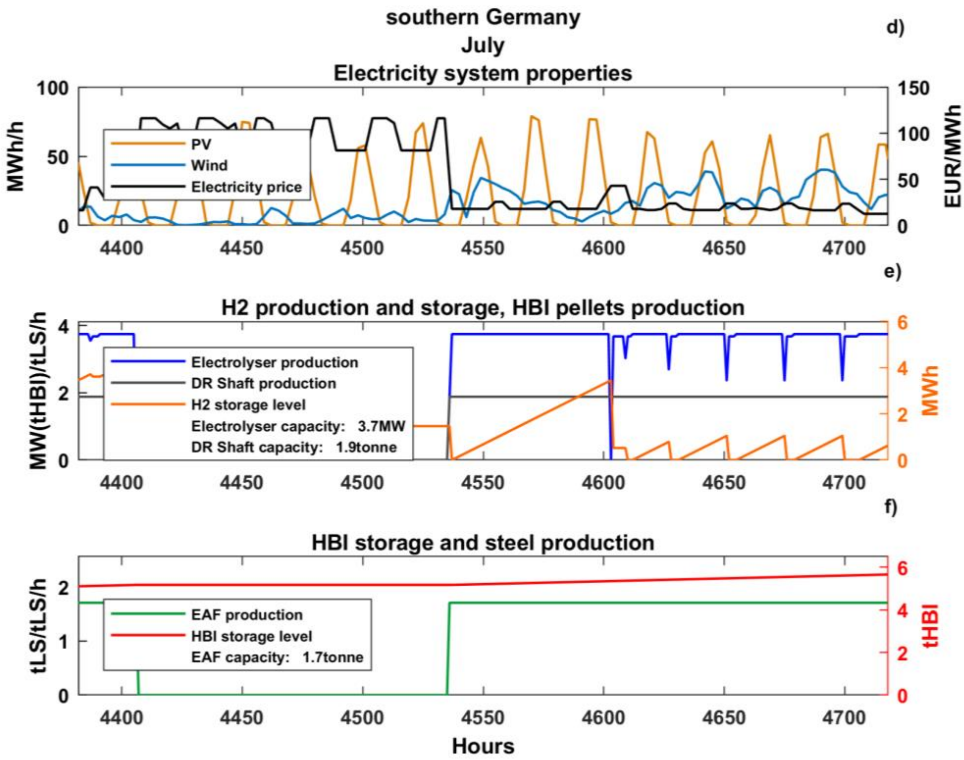


Figure 6. Levels of generation of PV and wind power (MWh/h) and electricity price profiles (EUR/MWh) (**a**,**d**); production levels of the electrolyser and DR shaft furnace (MW(tHBI)/tLS/h), and state of charge of the hydrogen storage (MWh) (**b**,**e**); production levels of the EAF (tLS/tLS/h) and state of charge of the HBI storage (tHBI) (**c**,**f**), in southern Germany for 2 weeks in March (upper plots) and in July (lower plots) in the year 2050.

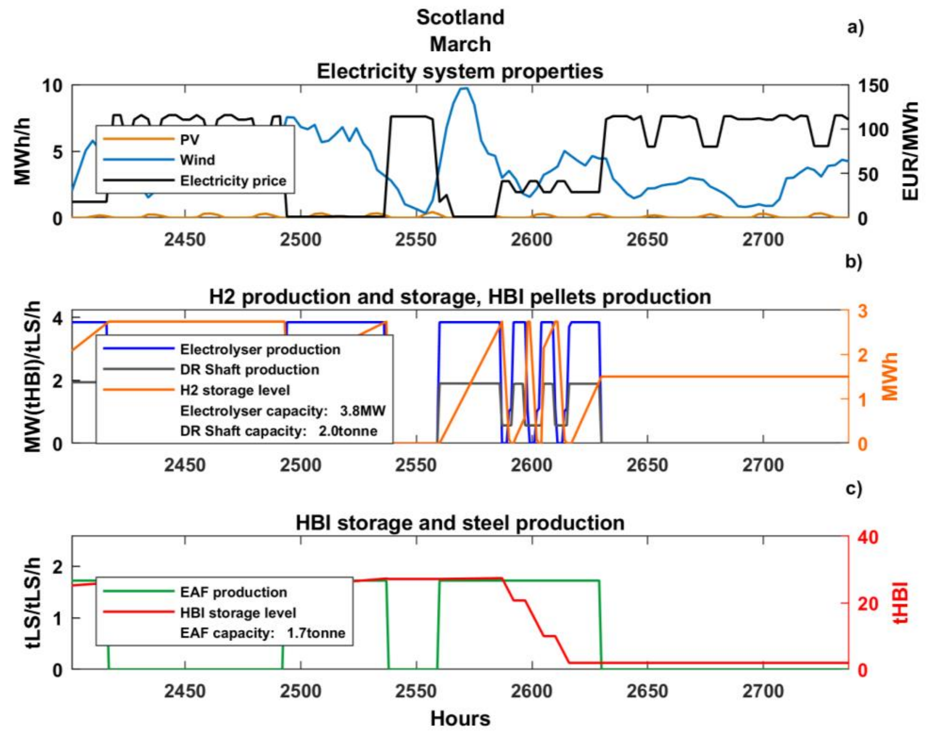


Figure 7. *Cont.*

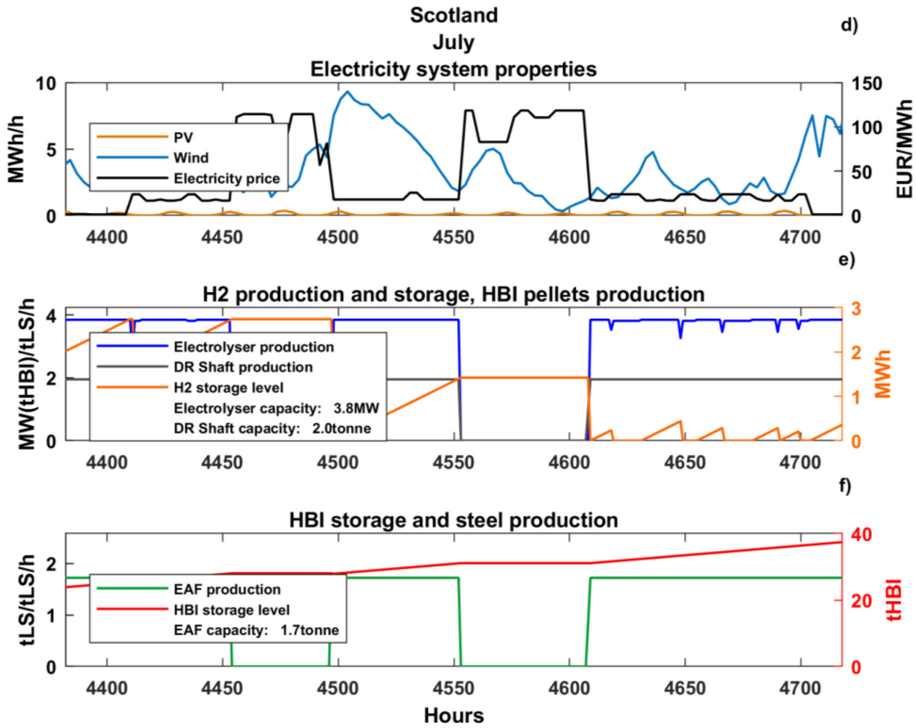


Figure 7. Levels of generation of PV and wind power (MWh/h) and electricity price profiles (EUR/MWh) (**a**,**d**); production levels of the electrolyser and DR shaft furnace (MW (tHBI)/tLS/h), and state of charge of the hydrogen storage (MWh) (**b**,**e**); levels of production of the EAF (tLS/tLS/h) and state of charge of the HBI storage (tHBI) (**c**,**f**), in Scotland for 2 weeks in March (upper plots) and in July (lower plots) in the year 2050.

A comparison of Figures 6 and 7 illustrates that the difference in the electrolyser operation between southern Germany and Scotland is due to the difference in the number of low-price electricity periods. The wind-dominated Scotland region has a larger number of low-price electricity periods than the solar-rich region: southern Germany. In Scotland, the electrolyser stops production during the peaks in the low electricity price (Figure 7b). On the contrary, in southern Germany, the electrolyser constantly operates (Figure 6b). Moreover, in Scotland, the direct reduction shaft furnace does not stop operation during the peaks in low electricity price due to the cost associated with cycling the shaft operation. The electric arc furnace in turn produces at full capacity, taking advantage of the low electricity price (Figure 7f). The continuous production of the electric arc furnace during such periods, when the direct reduction shaft furnace operates at reduced capacity, is supported by the discharging of the hot-briquetted iron storage. The hot-briquetted iron storage capacity is almost 10-times larger in Scotland than in southern Germany since the variability of wind power, with a typical persistence of several days up to a week, dominates the electricity system in Scotland.

3.3. Sensitivity Analysis: Impact of Solar Power

The model results show that the solar-rich region (i.e., southern Germany) has a lower potential to decrease the total steelmaking cost through cost-minimized sizing of the production capacity of the steelmaking process, as compared to the wind-dominated Scotland region. Therefore, to investigate the effects of investments on the operation of steel production and storage capacities in a solar-dominated region, i.e., with good solar conditions all year around, an artificial electricity price profile was created.

Figure 8 show the electricity price profile and electricity generation levels from wind and solar PV power (Figure 8a,d), the levels of hydrogen production and direct reduced iron pellets production and the state of charge of the hydrogen storage (Figure 8b,e), and the level of steel production and the state of charge of the hot-briquetted iron storage (Figure 8c,f) in the artificial sunny region in the year 2050 with a design that allows for flexible electricity consumption. Figure 8a,d indicate that the artificial sunny region yields a low electricity price throughout the year, with an average electricity price of 32 €/MWh. The low electricity price of the artificial sunny region increases the operational time of all steel production capacity, which leads to a decrease in steel production capacity investments compared to the results for southern Germany in the year 2050. The electrolyser, which is the production unit with the highest electricity demand relative to its capital cost, continues to operate in an "electricity price-following" mode, as shown in Figure 8b,e. Unlike southern Germany and Scotland, in the artificial sunny region, the dimension of the hydrogen storage is highly influenced by the solar dominated electricity price variation, i.e., frequent variation of high amplitude. The hydrogen storage provides continuous hot-briquetted iron pellets production throughout the year, necessitating minimum investment in the direct reduction shaft furnace and avoiding start-up costs (Figure 8b,e). For the artificial sunny region, the hot-briquetted iron storage size is threefold lower than for southern Germany in the year 2050. This hot-briquetted iron storage utilization allows the electric arc furnace to support continuous production when the direct reduction shaft furnace runs at part capacity (Figure 8c) and supports low-level investments in the electric arc furnace. Even though the artificial sunny region has a low electricity price year round, flexible operation of the steel production capacities due to investments in hot-briquetted iron and hydrogen storage units decreases the steel production cost by 5% compared to the cost of steel production for the "minimum investment level".

The modelling results from this work show that the operational characteristics of the hydrogen-based steelmaking process is system specific, i.e., depends on the electricity system (as represented by an electricity price profile) investigated. However, this work also relates wind and solar power variations to the optimized steel production design. This entails an allocation between the three main production capacities, including two storage options, which is relevant to all regions that expect to have large shares of solar and wind power in the electricity mix.

In addition to the flexibility provision included in this work, the electrolysis can be used to support the grid with intra-hourly balancing and frequency control. The alkaline electrolyser used in this work is the most mature technology, in that it has been producing industrial hydrogen for decades. It has the lowest specific investment and maintenance costs of the electrolyser chemistries currently applied. For the provision of ancillary services, a poly-electrode membrane (PEM) electrolyser is more suitable because it provides more flexible operation within seconds and offers higher efficiencies than alkaline electrolyser [69]. Future work could usefully examine the value of ancillary service provision and the option for the model to choose between different types of electrolyser chemistries.

3.4. Implications

The present study underlines the importance of considering the energy system composition when assessing the investments and running costs of steel production that apply the hydrogen-direct reduction steelmaking process and its associated costs. This work offers insights that could particularly benefit decision-makers from the steel industry for the development of new business models beyond traditional steelmaking. The study by Moreno-Leiva et al. [70] highlights that a better understanding of the energy demand (when, where, in which form, and for which application the energy is needed) for electricity-intense processes is required since it is crucial for accurate design of an electricity system with large shares of renewables, in particular in the form of VRE. In addition, the operational flexibility of the electricity-intensive processes needs to be better assessed and understood. The present paper narrows the knowledge gap on modelling and representation of the industrial demand for the case of electrified steel production. The disclosure of the model equations, parameters, and assumptions allows the developed method to be applied for modelling the energy demand for other energy-intensive industries.

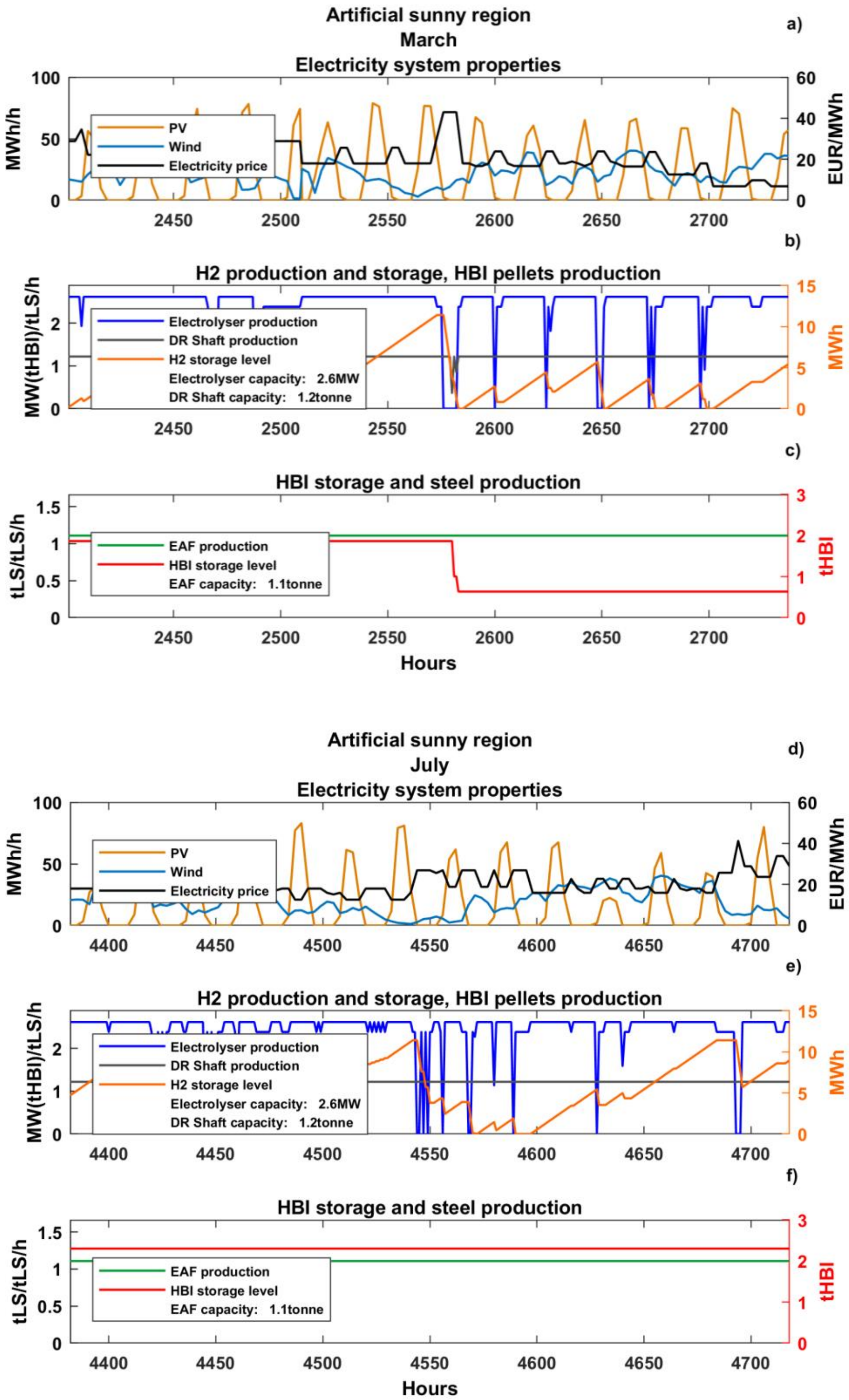


Figure 8. Levels of generation of PV and wind power (MWh/h) and electricity price profiles (EUR/MWh) (**a**,**d**); production levels of the electrolyser and DR shaft furnace (MW (tHBI)/tLS/h) and state of charge of the hydrogen storage (MWh) (**b**,**e**); production levels of the EAF (tLS/tLS/h) and state of charge of the HBI storage (tHBI) (**c**,**f**), in an artificial sunny region for 2 weeks in March (upper plots) and in July (lower plots) in the year 2050.

3.5. Limitations

Large-scale deployment of the steel production based on the hydrogen-direct reduction process will create an additional electricity demand, necessitating efficient integration of steel producers into the electricity system. In this work, the electricity price is applied exogenously in the model, which implies that the response of the electricity system to the new demand for electricity from the steel sector is not taken into account. Göransson et al. [53] deployed a semi-heuristic cost-minimizing electricity system investment model and demonstrated that a flexible demand distribution from the steel industry (investments in hydrogen storage and electrolyser overcapacity are allowed), passenger vehicles, and residential heat sector can decrease the total system cost by 8% and annual electricity prices by up to 20% in northern Europe, as compared to a predefined temporal distribution of the electricity demand from these sectors. The cost of electricity generation depends on the strategies applied to manage variation in generation from non-dispatchable renewables [55].

4. Conclusions

Steel production via the hydrogen-direct reduction process is seen as a key technology option to achieve significant reductions in emissions from steel production. While the electricity price is recognized as an important factor for the competitiveness of hydrogen-direct reduction steelmaking, the impact of electricity price fluctuations on the investments in and the operation of clean steel production have not previously been considered in detail.

We contribute to the field by developing a linear cost-optimization model with a 1-h time resolution to analyse the effects of a varying electricity price on the operation and investments of the units in the hydrogen-direct reduction process including an electrolyser, direct reduction shaft furnace, electric arc furnace, as well as storages for hot-briquetted iron pellets and hydrogen. The model was applied to two regions, which differ in the share of electricity demand produced by solar and wind power (southern Germany and Scotland). Based on the model results, this paper elucidated the interconnection between the energy system composition and the design and operation of the steelmaking process.

Our key findings can be summarized as follow:

- The cost-optimal investments in the steel production capacities of the modelled process are higher compared to investment in a process in which all the production units are operated at full capacity for all hours of the year, i.e., a "minimum investment level" design, for the electricity price profiles applied in this work. Such a process design, enabling a price-following operation, results in a reduction in electricity costs by up to 88% and a reduction in the cost per tonne of steel by up to 23% compared to the "minimum investment level" design.
- The cost-optimal design of the steelmaking process is highly dependent upon the electricity system mix. For example, the hot-briquetted iron storage unit is sized to manage wind variation, of up to several days, for the wind-dominated region and to manage diurnal solar variation for the solar PV-dominated region.
- The benefits of cost-optimal investments in steel-production capacities depend on the electricity system composition. The results indicate that the benefits are greater in wind-dominated Scotland than in solar-dominated southern Germany since the flexibility offered by the steel process is more relevant in the days to week timescale than the seasonal timescale needed to compensate for the low solar PV production in south Germany during wintertime. Based on the findings of the sensitivity analysis, it is found that in a solar PV-dominated electricity system with good conditions for solar PV throughout the year, the potential to decrease the total steelmaking cost through cost-minimized sizing of the production capacity of the steelmaking process is higher, as compared to the wind-dominated electricity system.

Previous studies have observed strong impacts of the energy system composition on the CO_2 emissions reduction potential of the industrial application of hydrogen [50,71]. The novelty of the present study is to understand the influence of the electricity system composition on the process design (investments and operation). Designing the steelmaking process while accounting for electricity price variability is not only expected to decrease the cost of electricity-based steel production, but also to facilitate the integration of varying renewable electricity production.

Author Contributions: Conceptualization, A.T., L.G. and F.J.; methodology: A.T. and L.G.; validation: A.T.; formal analysis, A.T.; investigation, A.T.; data curation: A.T.; writing—original draft preparation, A.T.; writing—review and editing, A.T., L.G. and F.J.; supervision, L.G. and F.J.; project administration, F.J.; funding acquisition, F.J. All authors have read and agreed to the published version of the manuscript.

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Nomenclature

Abbreviations	
approx.	approximately
BF-CCS	blast furnace with carbon capture and storage
CCS	carbon capture and storage
DR	direct reduction
DRI	direct reduced iron
EAF	electric arc furnace
EU	European Union
h	hour
HBI	hot-briquetted iron
H-DR	hydrogen-direct reduction
LS	liquid steel
RE	renewable energy
SP	Steel Process
t	tonne
VRE	variable renewable electricity
Sets	
T	time-steps, [h]
P	steel production capacities (electrolyser, [MW/tLS/h]; DR shaft furnace, [tHBI/tLS/h]; EAF, [tLS/tLS/h])
P^{STR}	storage technologies (hydrogen storage, [MWh]; HBI pellets storage, [tHBI])
Parameters	
D^{an}_{steel}	total annual steel production demand, [t]
η_p	efficiency of the storage technology
Variables	
$C^{cycl}_{p,t}$	cycling cost of the steel production capacity ($P \in DR\ shaft$) in time-step t, [€]
C^{inv}_{p}	investment cost of the production capacity, [€/unit of production capacity (see units of the set P)]
$C^{run}_{p,t}$	running cost of the production capacity in time-step t, [€/unit of production capacity (see units of the set P)]
C^{tot}	total steel production cost, [€]
i_p	investments in production capacity, [unit of production capacity (see units of the set P)]

$g_{p,t}$	yield of the steel production capacity in time-step t, [unit of production capacity (see units of the set P)]
soc_p	products stored in the storage technology at time-step t, [unit of storage technologies (see units of the set P^{STR})]
$z^{ch}_{p,t}$	product with which the storage is charged at time-step t, [unit of storage technologies (see units of the set P^{STR})]
$z^{dis}_{p,t}$	product that is discharged from the storage at time-step t, [unit of storage technologies (see units of the set P^{STR})]]

Superscripts

an	annual
ch	charged
cycl	cycling
dis	discharged
inv	investment
run	running
STR	storage
tot	total

Appendix A

Table A1. Assumed costs and technical data for steel production capacities and hydrogen storage in the H-DR production process.

Production Capacity	Investment Cost	Investment Cost Unit	Technical Lifetime [years]	Fixed O&M Cost [1] [%]	Discount Rate [%]
Production capacity					
Electrolyser	0.50	M€/MW	25	3	5
DR shaft furnace	230	€/tonne per year	40	3	5
EAF	184	€/tonne per year	40	3	5
Storage technology					
Hydrogen storage	0.011	M€/MWh	30	-	5

[1] Percent of the investment cost. Sources: [25,57,59,72].

Table A2. Assumed energy and raw material consumption levels per tonne of liquid steel (tLS) and associated costs for the H-DR production route.

Commodity	Input Level	Input Level Unit	Cost	Cost Unit
Alloys	11	kg/tLS	1777	€/tonne
Electricity EAF	494	kWh/tLS	Var [1]	€/MWh
Electricity electrolyser	2200	kWh/tLS	Var	€/MWh
Electricity DR shaft furnace	322	kWh/tLS	Var	€/MWh
Graphite electrode	2	kg/tLS	4000	€/tonne
Iron ore pellets	1650	tonne/tLS	100	€/tonne
Lime	50	kg/tLS	90	€/tonne

[1] Hourly electricity price profile is implemented in the model. EAF, electric arc furnace; DR shaft furnace, direct reduction shaft furnace; Var, variable. Sources: [25,27,48,60,61,72].

Table A3. The investment levels in steel production capacities and size of storages obtained from the modelling, for the electricity price profiles for the year 2050 and the two regions with high (0.0165 M€/MWh) and low (0.0055 M€/MWh) investment costs of hydrogen storage.

	Low Investment Cost of Hydrogen Storage				
	Production Capacity			**Storage Capacity**	
	Electrolyser [MW/tLS/h]	**DR Shaft Furnace [tHBI/tLS/h]**	**EAF [tLS/tLS/h]**	**Hydrogen [MWh]**	**HBI Pellets [tHBI]**
Scotland 2050	3.9	1.9	1.7	14.6	104
southern Germany 2050	3.9	1.8	1.7	18.4	40
	High Investment Cost of Hydrogen Storage				
	Production Capacity			**Storage Capacity**	
	Electrolyser [MW/tLS/h]	**DR Shaft Furnace [tHBI/tLS/h]**	**EAF [tLS/tLS/h]**	**Hydrogen [MWh]**	**HBI Pellets [tHBI]**
Scotland 2050	3.8	2.0	1.7	0	94
southern Germany 2050	3.7	1.9	1.7	0	13

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