Interaction between electrified steel production and the north European electricity system

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Interaction between electrified steel production and the north European electricity system

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HIGHLIGHTS

- The interactions between a steel industry that applies hydrogen direct reduction (H-DR) and the electricity system are analyzed.
- The availability of low-cost electricity impacts a cost-efficient spatial allocation of the electrified steel production capacity.
- The overcapacity for steel production units and investments in storage systems lead to lower steel production costs.
- The electricity demand from an electrified steel industry in northern Europe is met by wind and solar power.

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ABSTRACT

This study investigates the interactions between a steel industry that applies hydrogen direct reduction (H-DR) and the electricity system of northern Europe. We apply a techno-economic optimization model with the aim of achieving net-zero emissions from the electricity and steel sectors in Year 2050. The model minimizes the investment and running costs of electricity and steel production units, while meeting the demands for electricity and steel. The modeling is carried out for a number of scenarios, which differ in the following parameters: (i) cost of using new sites for steel production; (ii) transport costs; (iii) commodities export; (iv) flexibility in operation of a direct reduction (DR) shaft furnace; and (v) location of steel demand. The results reveal that a cost-efficient spatial allocation of the electrified steel production capacity is impacted by the availability of low-cost electricity and can differ from the present - day allocation of steel plants. The modeling results show that the additional electricity demand from an electrified steel industry is met mainly by increased investments in wind and solar power while natural gas - based production of electricity is reduced. Furthermore, it is found to be cost-efficient to invest in overcapacity for steel production units (electrolyzers, DR shaft furnaces and electric arc furnaces) and to invest in storage systems for hydrogen and hot briquetted iron, so that steel production can follow the variations inherent to wind and solar power.

1. Introduction

In December 2019, the European Commission (EC) presented a new growth strategy – the European Green Deal, the aim of which is to achieve net-zero greenhouse gas (GHG) emissions by Year 2050 in the EU [1]. In response to the Green Deal, the European Steel Association (EUROFER) has published a call for a “Green Deal on steel”, which represents a comprehensive plan of action for the EU steel industry to achieve emissions reductions objectives of 30% by Year 2030 and 80%–95% by Year 2050, while remaining globally competitive. The agreement stresses the importance of establishing a market for ‘green’ steel products [2]. Furthermore, a New Industrial Strategy for Europe was released by the EC in March 2020. This document recognizes the important role of industry in the transformation towards a carbon-neutral economy [3].

The electricity generation sector is generally seen as having the largest potential for low-cost emissions reductions among the energy sectors, as there exists a number of low-carbon electricity generation technologies, such as electricity generation based on Renewable Energy Sources (RES) in the form of wind, solar, and biomass, as well as the option to produce electricity from nuclear power. Currently it seems as the main option – at least in Europe – for cutting emissions from the steel industry is to electrify the sector by switching to hydrogen (H_2)-based processes [4]. The steel and mining company ArcelorMittal S.A. is

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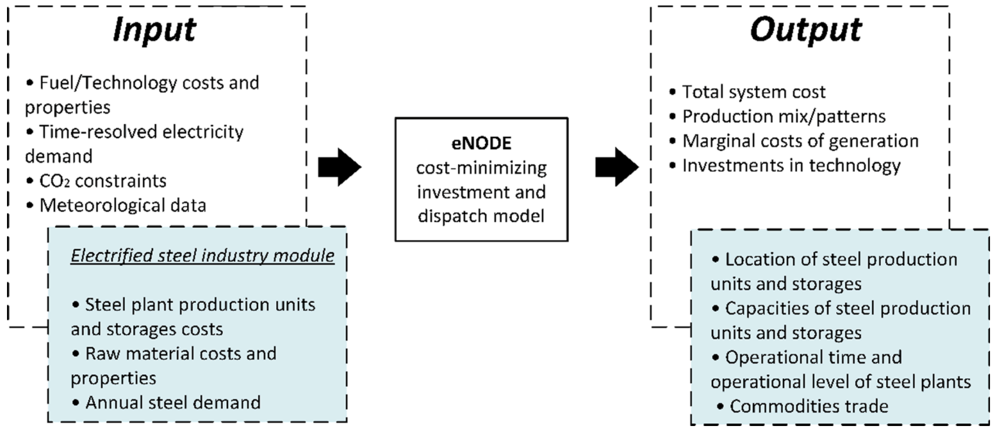

Fig. 1. Schematic overview of the model structure used in this work.

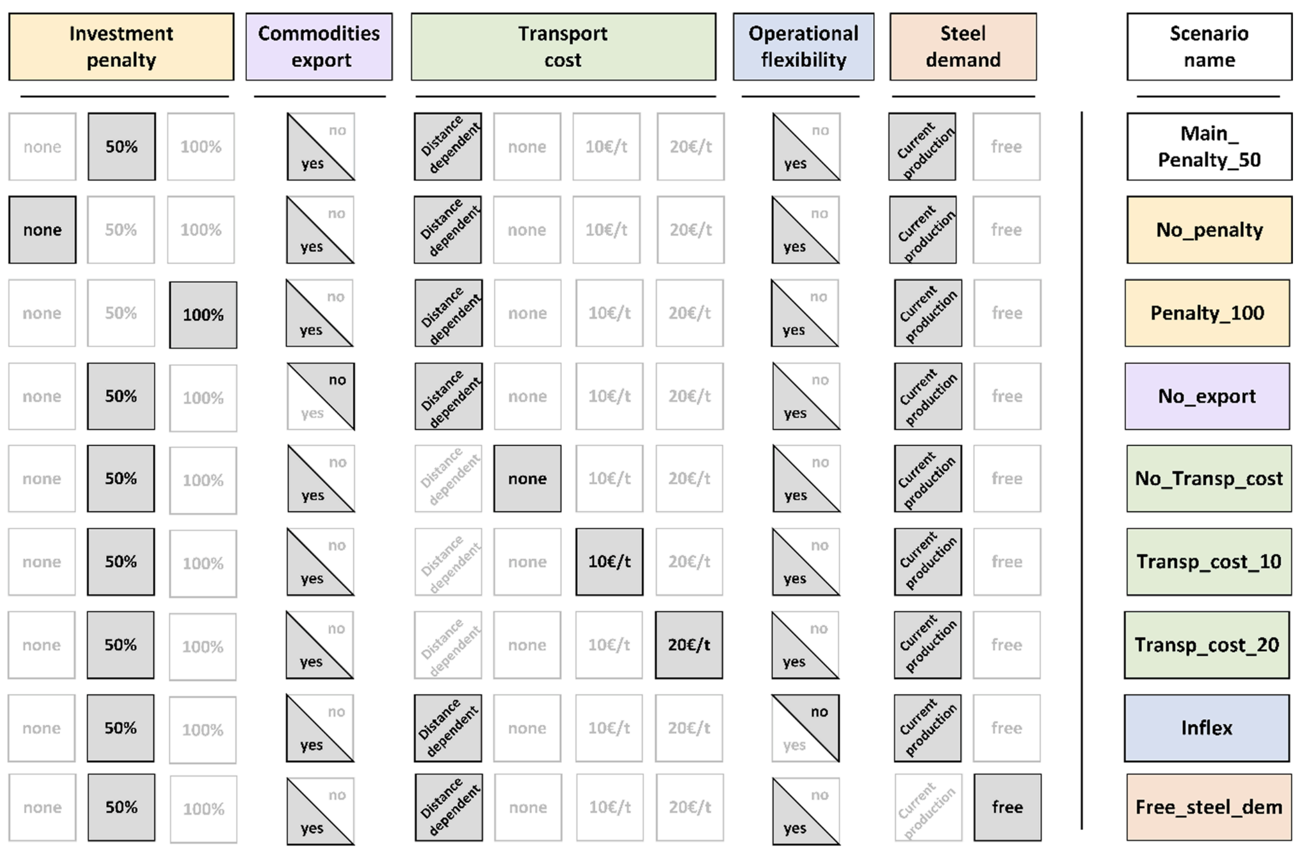

Fig. 2. Schematic overview of the parameters that define the investigated scenarios. The color in which the scenarios name is marked corresponds to the color of the parameter varied in the scenario, as compared to the Main_Penalty_50 scenario.

developing a project that has the aim of using 100% hydrogen as the reduction agent to produce direct reduced iron (DRI) [5]. In Sweden, an alliance has been formed between the iron ore mining company LKAB, the steelmaking company SSAB and the energy company Vattenfall (in the form of a new joint venture called HYBRIT), with the ambition to drive the steel industry transition towards a hydrogen-based direct reduction technology [6]. Salzgitter AG and Tenova signed a memorandum of understanding to pursue the SALzgitter Low CO2 Steelmaking (SALCOS) project [7]. SALCOS plans to move from a pathway of carbon-intensive steel production based on blast furnaces towards a direct reduction and electric arc furnace (EAF) route, which will involve the flexible utilization of hydrogen (Salzgitter AG, 2018). A scenario proposed by the Austrian steelmaker Voestalpine AG for achieving decarbonization of steel production includes the application of hydrogen in the various stages of steel production and the use of hydrogen plasma to reduce iron ore fines [8]. Carbon Capture and Storage (CCS) is an alternative option for reducing carbon emissions from the steel industry, but this option still relies on coal fired blast furnace technology and would actually increase the use of coal to power the extra energy required by the capture process.

According to the EUROFER Low Carbon Roadmap [9], the transition of the European steel industry to low-or zero-carbon emissions will require 400 TWh of CO_2-free electricity in Year 2050. This corresponds to more than seven-times the steel industry's current electricity purchase from the grid and around 13% of Europe's (EU27) current gross electricity production [10]. Using a "what-if" analysis, Lechtenböhmer

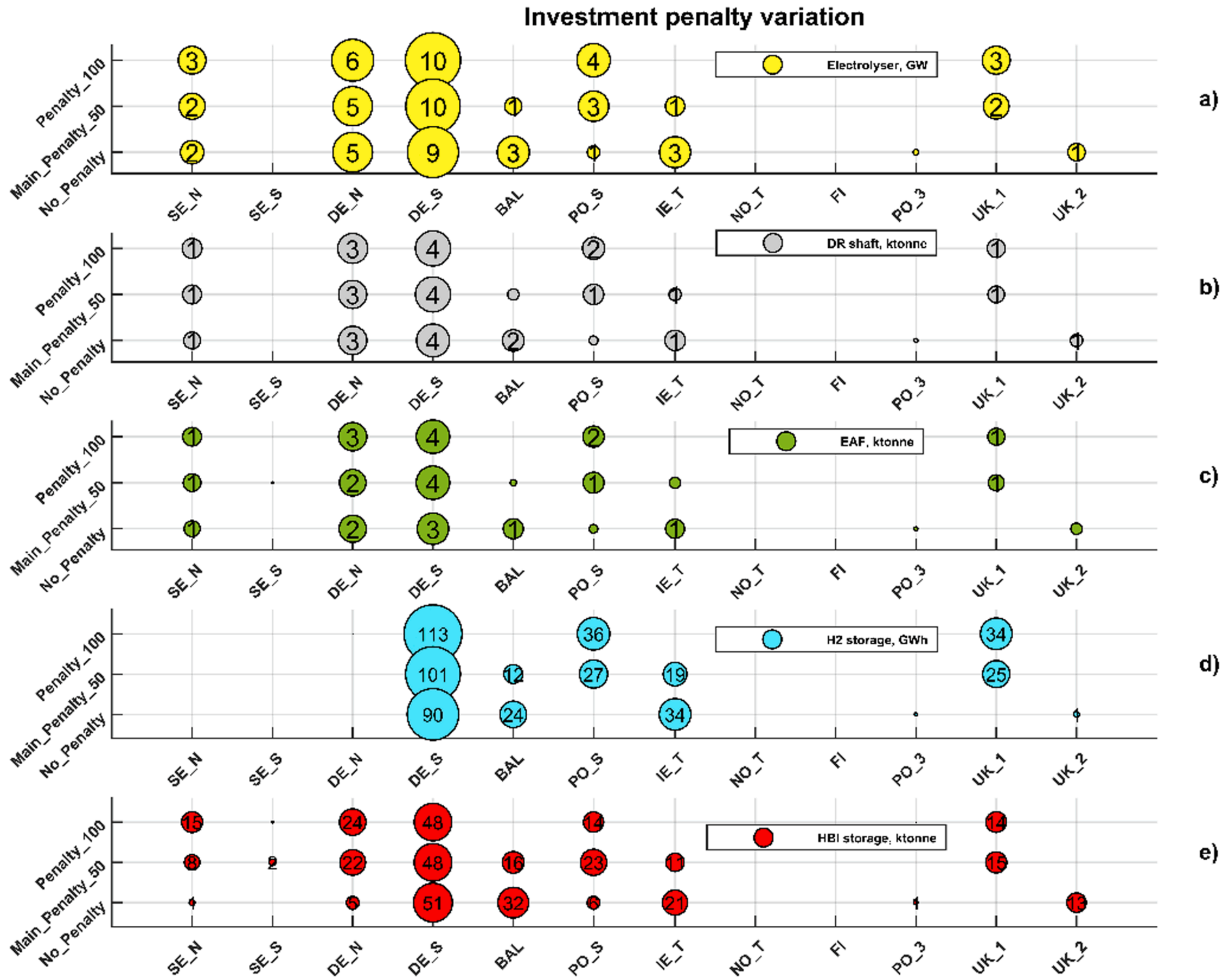

Fig. 3. The modeling results for the scenarios in which the investment penalty imposed on new steel plant locations is varied. The regional allocations of the steel production capacities of the electrified steel plants are given in terms of the electrolyzer in GW (Fig. 3a), DR shaft furnace in ktonne (Fig. 3b), and EAF in ktonne (Fig. 3c); and the two storage possibilities are shown in terms of the H2 storage in GWh (Fig. 3d) and HBI storage in ktonne (Fig. 3e).

et al. [11] have shown that electrification of the energy-intensive basic materials industries (steel, cement, glass, lime, petrochemicals, chlorine and ammonia) in the EU28 is possible from the technology point of view and would result in an additional annual industrial electricity demand of 1,500 TWh, assuming that the demand for these basic materials is maintained at current levels. Massive electrification of steel production will create an additional electric load and necessitate efficient integration of steel production into the electricity system. Electrification will, therefore, strongly influence the investments in electricity generation capacity and the storage options available, as well as the operation of the dispatchable part of the electricity generation system.

Only a few studies have investigated a H_2-based steel industry from an electricity systems perspective. Göransson et al. [12] have analyzed the impacts of electrification of the steel industry, passenger vehicles, and residential heat supply on the north European electricity system using a semi-heuristic, cost-minimizing investment model. They have demonstrated that the strategic, flexible demand for electricity in different sectors would enable a faster transition from fossil fuels in the European electricity system and would reduce overall system costs, as compared to electrification without flexibility provision, given the assumptions in the modeling.

Gielen et al. [13] have assessed the impacts of renewable H_2-based steelmaking in terms of the potential CO_2 emissions reductions and the investments needed in the electricity and steel sectors, by applying a combination of techno-economic assessment and material flow analysis. They have assessed the geographic separation of the energy-intensive iron-making process and the steel-making process for the cases of Australia and China. It is assumed that Australia exports processed iron in the form of direct reduced iron (DRI) rather than raw iron ore to China. Gielen et al. have concluded that the export of DRI instead of iron ore to China could reduce global steel industry CO_2 emissions by nearly one-third, although this would require a 10-fold increase in electricity generation capacity in Australia relative to today's electricity generation capacity of around 48 GW. The method used by Gielen et al. does not include the impacts of an electrified steel industry on the dispatch of electricity generation technologies, including the need for peak power demand. Moreover, the flexibility of H_2-based steel production and its impacts on steel production capacities and storage capacities were not considered by Gielen and coworkers. Vogl et al. [14] have assessed the energy use, CO_2 emission mitigation potential, and economic performance of the H-DR steel-making process, and have discussed that process flexibility, through storage of hydrogen and hot-briquetted iron, or variations in the share of scrap used enables production strategies that react to electricity, scrap and HBI markets.

Although the above work shows the potential for CO_2 reductions and the need for expansion of low-carbon, electricity generation technologies, there remains a lack of understanding as to how an electrified steel sector will influence future investments in steel plants and electricity

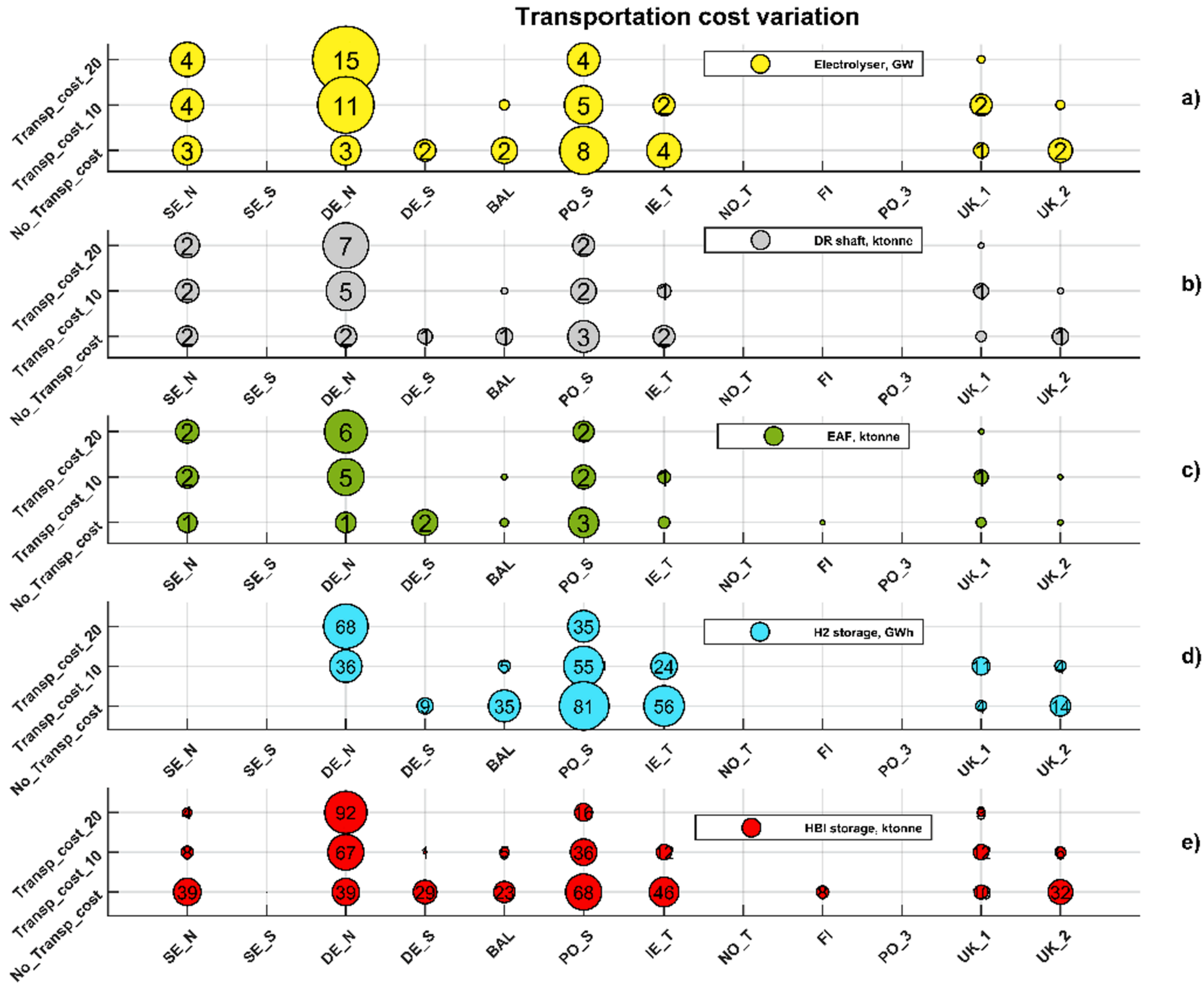

Fig. 4. The modeling results for the scenarios for which the transport cost is varied. The regional allocations of the steel production capacities of the electrified steel plants are given in terms of the electrolyzer in GW (Fig. 4a), DR shaft furnace in ktonne (Fig. 4b), and EAF in ktonne (Fig. 4c); and the two storage possibilities are shown in terms of H2 storage in GWh (Fig. 4d) and HBI storage in ktonne (Fig. 4e).

generation in different regions. Therefore, the present study adds to the previous modeling studies by: (i) studying how electrified steel production can influence the spatial allocation of future steel plants and their sizing; and (ii) analyzing the impacts of an electrified steel industry on investment decisions related to new electricity generation capacity. The study applies a cost-minimizing model (called eNODE) using the north European electricity system, subdivided into 12 regions based on major electricity transmission bottlenecks, as a case study.

1.1. European steel production overview

In 2019, total steel production in the EU corresponded to 16% of global steel output. Most of the steel production in Europe follows two routes: the blast furnace-basic oxygen furnace (BF-BOF) route, and the electric arc furnace (EAF) route. Almost 60% of all EU steel is produced via the BF-BOF production route. In blast furnaces, iron ore is converted to iron, in a step that is referred to as 'ironmaking' [15]. Overall, 26% of the iron ore supply for the European steel industry comes from domestic production, with the remainder being imported [16]. In a second step of the BF-BOF route, termed 'steelmaking', a basic oxygen converter turns iron into steel. The EAF route is currently used mainly to produce steel from scrap collected for recycling. This work focuses on iron ore-based steel production, since ironmaking is associated with extensive CO_2 emissions and decarbonization of ironmaking is expected to increase electricity consumption drastically.

Spatial analysis concerning the localization of steel plants has been the object of academic interest for many decades. Based on the historical data for steel production in the United States and Great Britain, Isard [17] demonstrated that access to coal resources had ceased to influence the locations of iron and steel plants. Due to changes in steelmaking technologies, access to iron ore instead became the dominant factor governing the location of steelmaking plants. Hekman [18] later Beeson and Giarratani [19] observed a locational change in ore-based steel production and concluded that proximity to the steel market, but not raw material prices, contributed significantly to changes in the location patterns of ore-based production. Karlson [20] described the steel industry as transport-oriented, i.e., where minimizing transport cost is decisive with respect to location. Erickson et al. [21], by conducting a simple analysis of availability factors, such as electricity emission factor, natural gas (NG) availability, biomass availability and iron ore reserves, have identified regions that are strategically positioned to become significant future producers of low-GHG steel. They have shown that transposing the annual rate of growth in the steel industry (70 million tonnes of steel produced via BF-BOF and 4 million tonnes of steel produced via NG-DRI-EAF) to regions with low-GHG biomass and renewable electricity could reduce the current GHG emissions of the steel

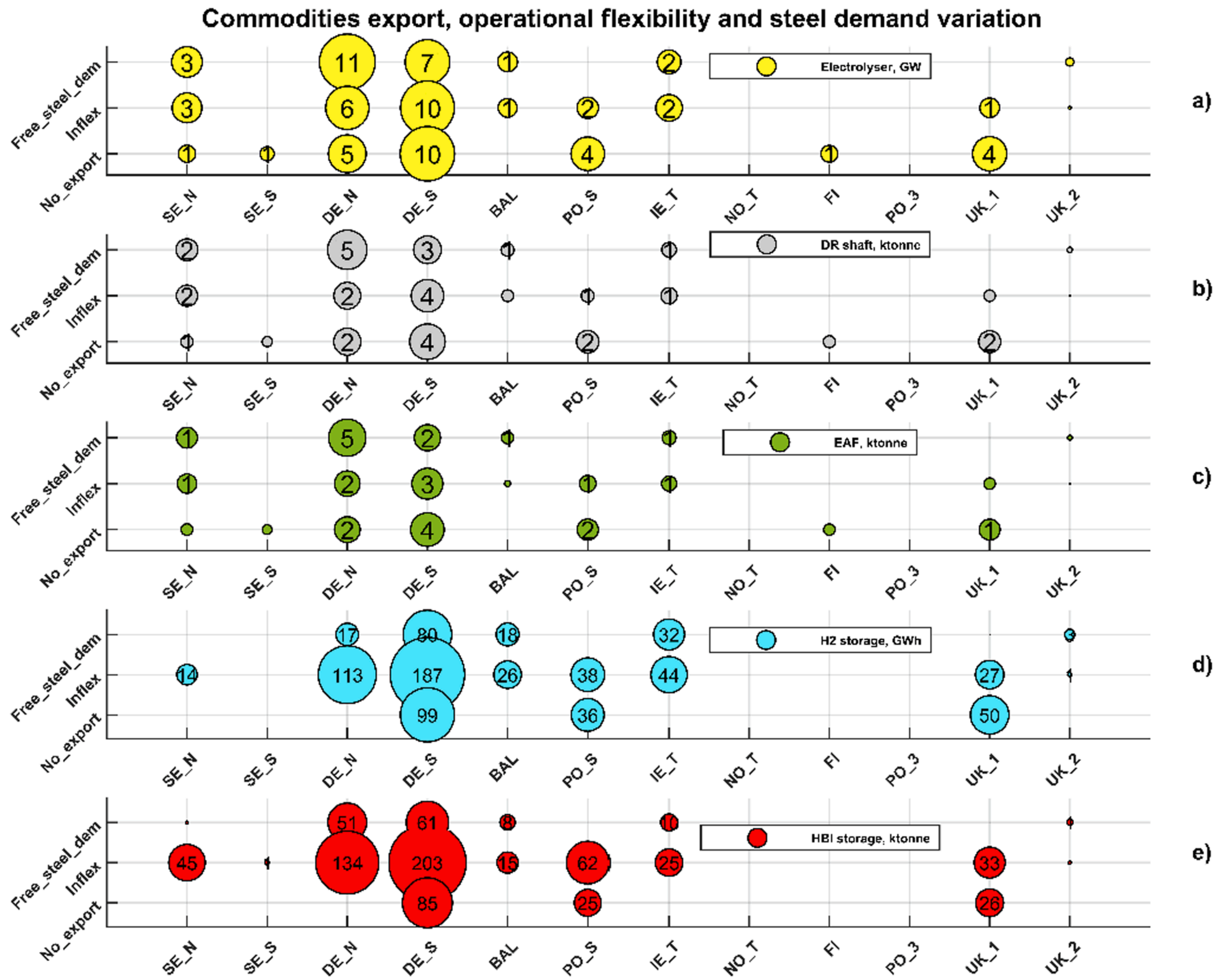

Fig. 5. The modeling results for the scenarios with commodities export, operational flexibility and steel demand variation. The regional allocations of the steel production capacities of the electrified steel plants are given in terms of the electrolyzer in GW (Fig. 5a), DR shaft furnace in ktonne (Fig. 5b), and EAF in ktonne (Fig. 5c); and the two storage possibilities are shown in terms of H2 storage in GWh (Fig. 5d) and HBI storage in ktonne (Fig. 5e).

industry by about 5%. Unfortunately, this is far from what is required to reach the climate targets. This study attempts to elucidate which factors, i.e., proximity to raw material and market, access to low electricity price, transport costs, investments in steel production capacity, will influence the allocation of the new steel plants using the hydrogen direct reduction (H-DR) process.

Electrified steel production via hydrogen direct reduction includes three steel production units (electrolyzers, DR shaft furnaces and EAFs) and two possible systems for commodity storage (H_2 storage and hot briquetted iron storage), see Fig. A1 in Appendix A for a simplified scheme of the process. The H-DR process is an electricity-intensive process, and it will require investments in new electricity generation capacity. However, the amount and time of electricity consumption for an electrified steel industry can be flexible thanks to H_2 and hydrogen and hot briquetted iron (HBI) storage systems. Therefore, it is also of interest to investigate how large-scale implementation of the H-DR process will affect the energy system.

2. Methodology

This paper integrates electrified steel production in a cost-minimizing, electricity system investment model, thereby including the interactions between the electricity system and the electrified steel industry within a single modeling framework. The model allows investigation of the mutual impacts of the electrified steel industry and electricity system, as described below.

2.1. Modeling approach

The impact of H_2-based steelmaking on the north European electricity system is assessed using a linear cost-minimization model (eNODE). The eNODE model minimizes the costs for investments in and operation of an electricity system, while meeting the demand for electricity and, in this work, also the demand for steel. A full mathematical description of the eNODE model (excluding a representation of the steel industry) is given in Walter and Göransson [22]. The year 2050 is used as the modeling year with the assumption of zero CO_2 emissions from the electricity system and steel industry in this year, which is aligned with climate policy objectives. The model is greenfield, which implies that the starting point is an empty system without any electricity or steel production capacity in place. However, existing hydropower and transmission capacity are made available to the model. In addition, there is an investment penalty on steel production capacity in regions without steel production in some scenarios. The eNODE model was originally constructed by Göransson et al [23] and further refined by Johansson and Göransson [24] and Walter and Göransson [22]. The geographic scope considered in this work is limited to Denmark, Estonia, Germany, Ireland, Latvia, Lithuania, the Netherlands, Norway, Poland,

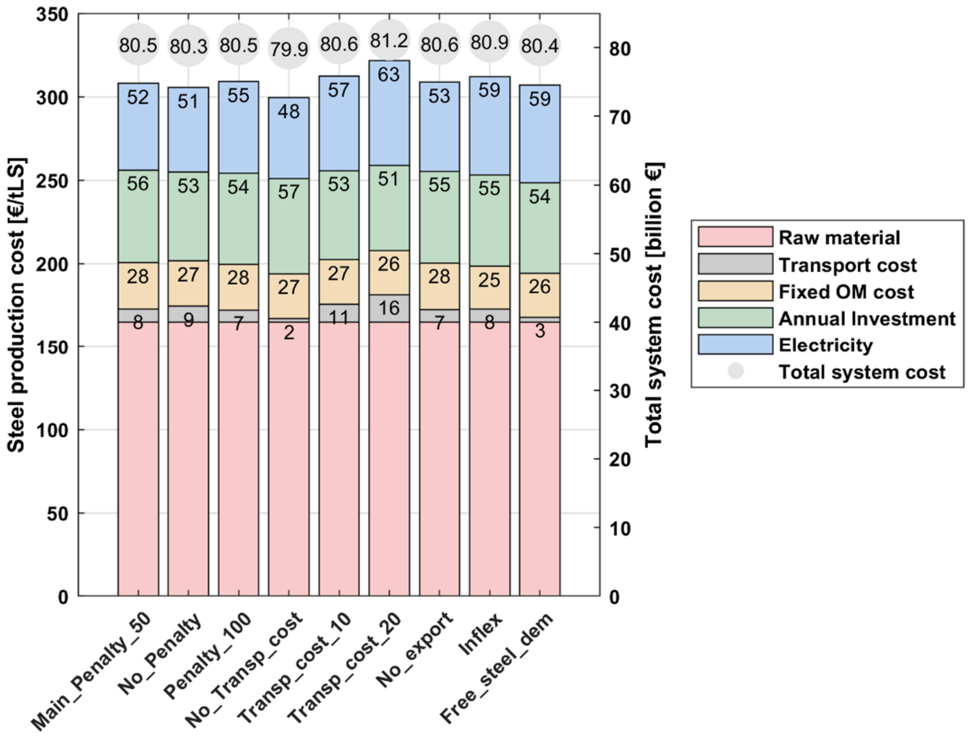

Fig. 6. Breakdown of the modeled steel production cost into the raw material costs, the annualized investment cost, the fixed O&M costs, electricity cost, and transportation costs (left-hand axis). The total system costs are shown (right-hand axis) for the investigated scenarios.

Sweden, and the UK. These countries are subdivided into 12 regions based on the current bottlenecks in transmission capacity (*cf.* Fig. C2). The transmission network between regions is modeled based on the existing network and current decisions regarding expansion. It is assumed that electricity can be transmitted without internal congestion within the 12 regions considered. Additional investments in transmission capacity are allowed if they are cost-efficient. The temporal resolution is 12-hourly, where each time-step represents the average of 12 h (day-time 06–17, and night-time 18–05), and the temporal scope is a full year. In terms of energy storage technologies, investments in lithium-ion batteries and H_2 storage are possible in all the regions considered. To account for uncertainties of technology costs, a sensitivity analysis was conducted reducing the cost of nuclear power (fixed operation and maintenance costs were reduced to half compared to the costs applied in the model and given in Appendix B, Table B3).

Fig. 1 shows the main input and output parameters to the model. The hourly electricity load data are from ENTSO-E [25], and the hourly generation profiles for solar and wind are based on weather data from Global Modeling and Assimilation [26] and ECMWF [27]. The additional electricity demand due to electrification of other sectors, such as industry (i.e., cement) and heat and transport, is not considered in this paper. Thus, this work is limited to investigating the general dynamics underlying electrified steel production and the electricity system with implications for the location of steel production capacity.

The present work refines the eNODE model by adding the steel process (SP) module. The inclusion of the SP module provides: (i) the decisions made regarding investment in steel production capacities (electrolyzer, DR shaft furnace and EAF) and storage technologies (H2 storage and HBI pellet storage), i.e., as outlined in Fig. A1; (ii) the operational times and operational levels of the steel production capacities, including storage utilization; (iii) the locations of steel production capacities and storage units; and (iv) the commodity trade flows between the regions investigated. Details on the objective function of the model and the steel process (SP) module are given in Appendix B.

2.2. Investigated scenarios

Based on the previous studies, we identified parameters commonly recognized as steel plant location determinants, which are proximity to raw material [17], steel demand (e.g. proximity to market) [18,19] and transport cost [20]. Parameters which, in addition, are recognized as important when considering the H-DR process are electricity prices [14,28], possibilities for steel commodity export [13] and operational flexibility [29]. The scenarios investigated in this work differ in terms of steel demand, transportation cost, possibilities for steel commodity export and operational flexibility. Fig. 2 gives an overview of the parameters that define the different scenarios applied in the model analysis.

Electricity price and proximity to raw material do not differ between scenarios but differ between the regions considered in this work. The cost of meeting the electricity demand of the H-DR process is included by accounting for necessary investment and generation in electricity production technologies in the modeling of this work. The marginal cost of electricity is often taken as a proxy for the electricity price and is a result of the modeling of this work [i.e., the marginal value of Eq. (2) in Appendix B]. With regards to the proximity of raw material, iron ore is assumed to be mined in northern Sweden and Norway and imported to the port of Rotterdam in all scenarios investigated. The mining in Sweden and Norway is assumed to remain at today's level. Rotterdam is the port through which almost 50% of all iron ore used in northwest Europe currently passes [23].

Investment penalty. The investment costs given in Table B3 in the Appendix B are applied to steel production technologies in regions with existing steel production (see Fig. C1 in Appendix C). However, for regions without existing steel production, an *investment penalty* for investments in new steel production plants (DR shaft furnace and EAF) is assumed, so as to represent some of the material and immaterial values in the current iron and steelmaking regions. Three levels of investment penalties are investigated: *No_penalty*, and penalties for 50% (*Main_Penalty_50*) and 100% (*Penalty_100*) increases in investment cost in steel production capacities in these regions. In the *No_penalty* scenario, the

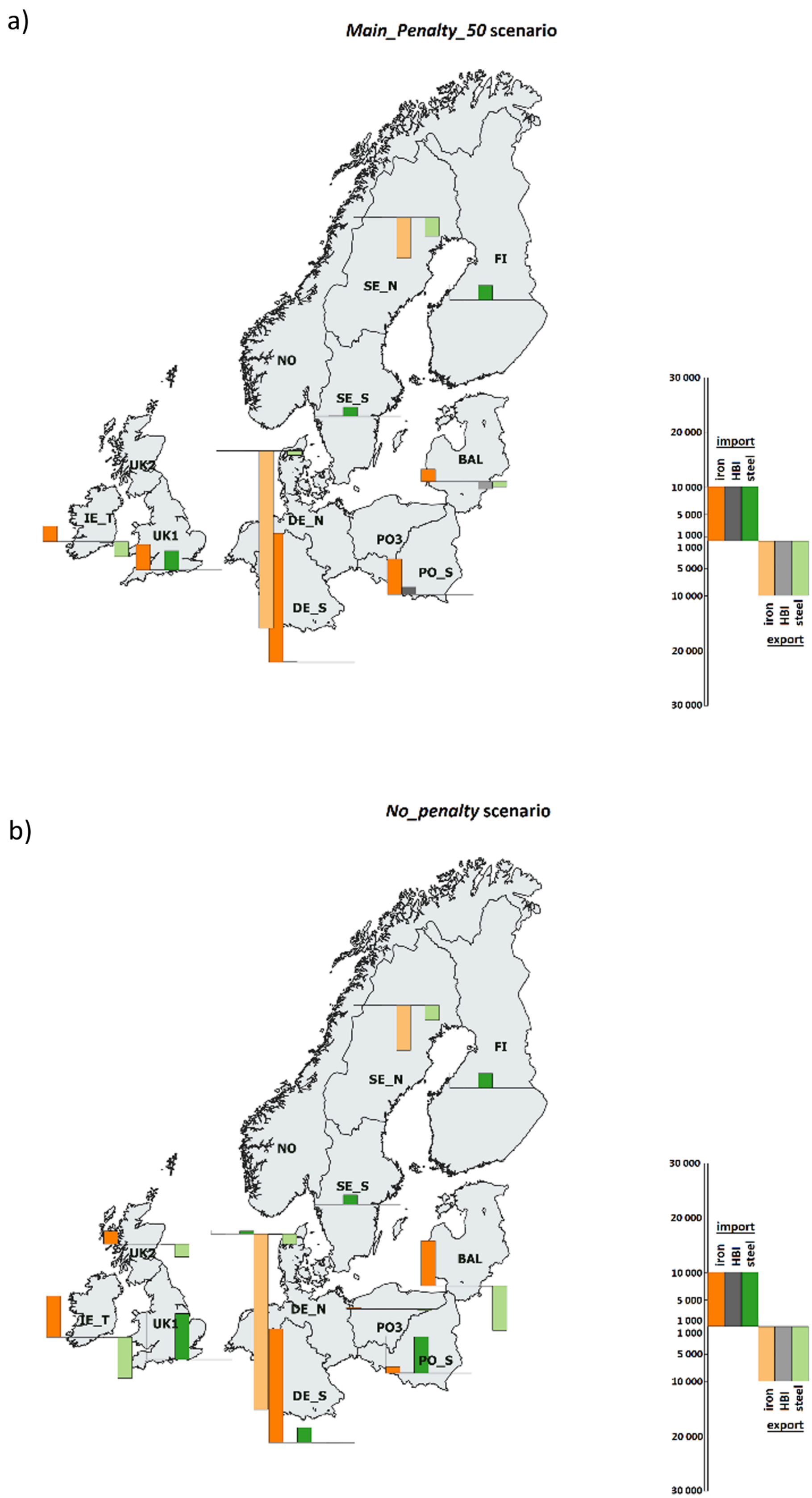

Fig. 7. Maps showing the commodity trade flows across northern Europe for: a) the Main_Penalty_50 scenario; b) the No_penalty scenario; and c) the No_transp_cost scenario. Iron ore and HBI trade flows are presented as equivalent to mass of steel.

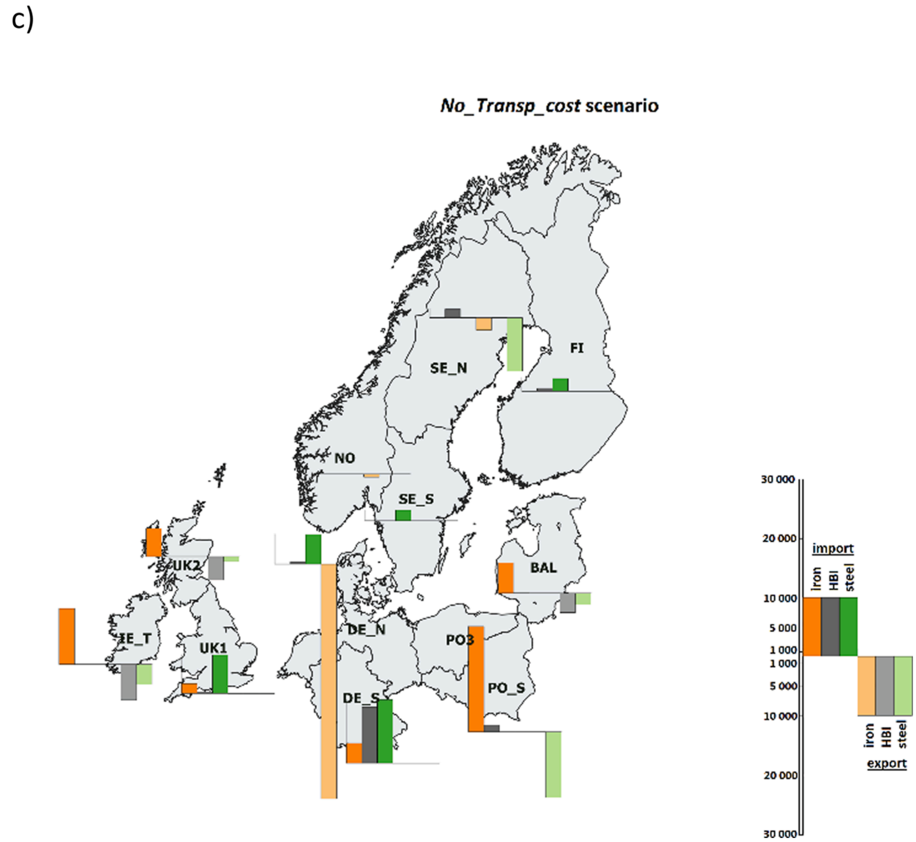

Fig. 7. (*continued*).

cost to invest in iron and steel production capacity is the same for all the regions investigated.

Commodities export. As mentioned above, the export of iron ore is allowed in all the investigated scenarios. As for the *export* of other *commodities*, i.e., HBI and steel, two options are compared: with and without HBI and steel trade. The trade of commodities takes place only within northern Europe.

Transport costs. The scenarios include four representations of the transportation costs (see Fig. 2), as follows:

1. *Distance-dependent transport cost scenario*. Transportation costs for commodities are based on the transport distance between regions and the transported amount of commodity (HBI or steel). Maritime transport mode is assumed for the transportation of commodities between countries. The exception is the transportation mode used between The Netherlands and northern Germany (region DE_N) and southern Germany (region DE_S) and between two regions in Poland (regions PO3 and PO_S), where inland waterway transport is assumed. For regions with no existing steel production (Fig. C1), the nearest seaport is assumed as a delivery point for the commodities to that region. For the regions with steel production in place, the transportation distance is assumed to be equal to the distance between the locations of the steel plants.
2. *No_transp_cost scenario*. No transport costs for HBI and steel trade.

In two of the scenarios (see Fig. 2), uniform transportation costs are assumed, i.e., the distance between regions is neglected and only transported mass is taken into account.

3. *Transp_cost_10 scenario*. Transport costs equal to 10 €/t of the commodity.
4. *Transp_cost_20 scenario*. Transport costs equal to 20 €/t of the commodity.

Operational flexibility. In this study, electrolyzers and EAFs are assumed to have high *operational flexibility* levels, i.e., they can be easily stopped and started. Data regarding the cycling properties, i.e., the minimum load level, start-up time, and start-up costs, of DR shaft furnaces are difficult to acquire. In this study, the impact of the operational flexibility of the DR shaft furnace is tested by applying two different assumptions as to the cycling properties of this unit.

1. It is assumed that the cycling of the DR shaft furnace is associated with additional costs due to thermal stress on the materials which can increase O&M costs. The DR shaft furnace cycling properties are accounted for according to the method used for the inclusion of the cycling properties of thermal generation in investment models (Göransson et al., 2017). The time duration of 12 h is assumed to be needed for the DR shaft furnace to start from the stand-still point to full-load operation, i.e., assumed to be the minimum start-up time. As a start-up cost during these 12 h, the electricity cost for the energy required to heat H_2 and to operate the DR shaft furnace is assumed and included endogenously in the electricity demand in the model. When started, the DR shaft furnace is allowed to vary between 30% and 100% of the installed capacity.
2. The DR shaft furnace has limited flexibility, i.e., it operates constantly without stops and its output can fluctuate within the operational range of full capacity to 30% of full capacity.

Steel demand. Even though higher shares of secondary steel production (in EAFs) may be possible in the long-term, due to embedded material, steel production from virgin materials is estimated to be at least 50% in 2050 to meet global steel demand under the assumption of maintained steel market structure and corresponding lifetimes [30]. In the model we consider only demand for iron ore-based steel. According to World Steel Association data, apparent consumption, which is also referred to as steel demand, correlates with steel production data [16].

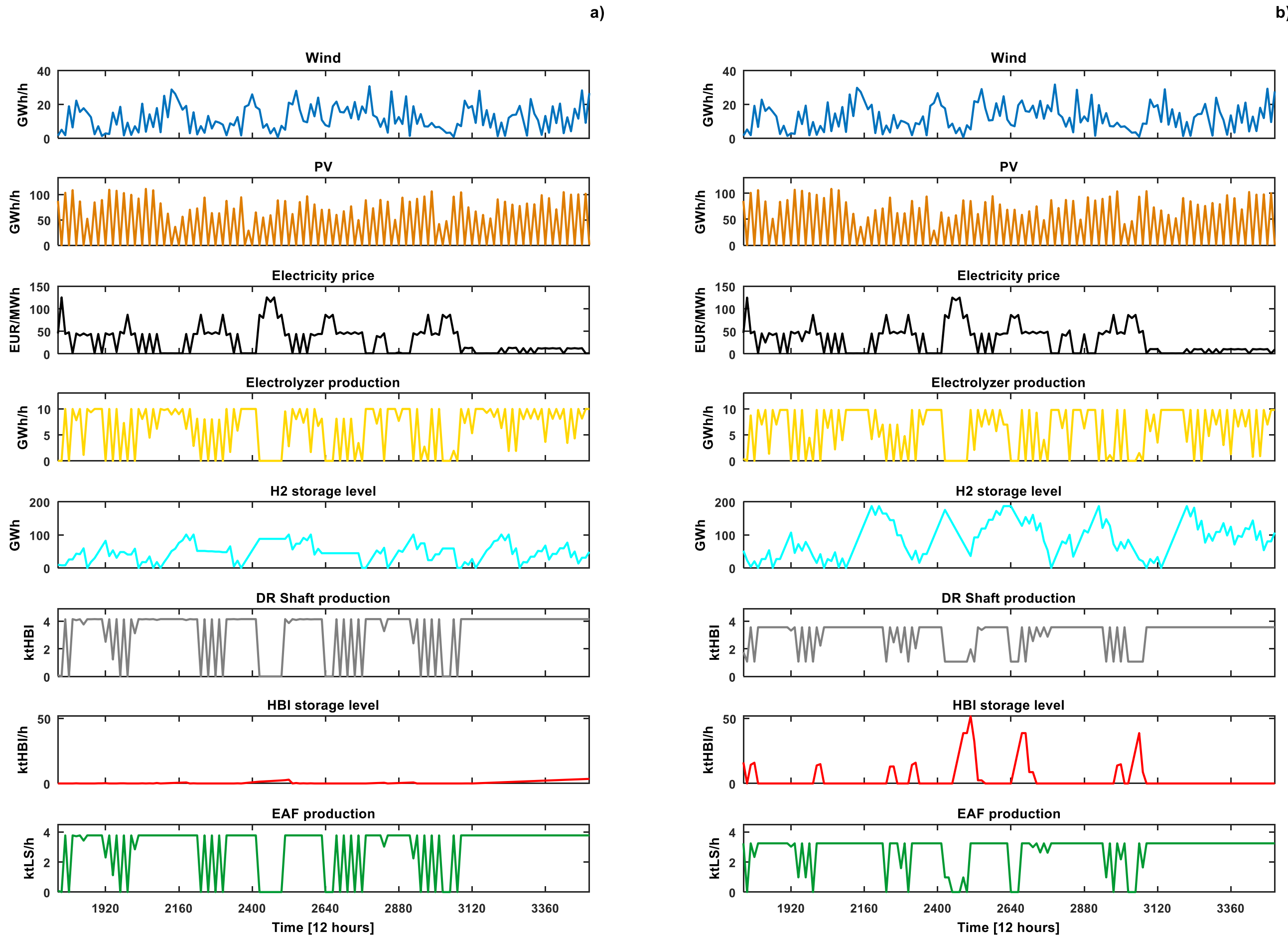

Fig. 8. Electricity generation from solar PV and wind power (in MWh/h) and electricity price profiles (€/MWh) for southern Germany as obtained from the modeling. Zero CO2emissions from the electricity system and steel industry are assumed. Shown are: the production levels from the electrolyzer (in GWh/h) and DR shaft furnace (ktHBI/h), and the state of charge of the H2 storage (GWh); and production levels from the EAF (ktLS/h) and state of charge of the HBI storage (tHBIh), in southern Germany (DE_S) for the Main_Penalty_50 scenario (a) and for the Inflex scenario (b). The temporal resolution is 12-hourly, where each time-step represents the average of 12 h.

In this study, two different assumptions regarding the *steel demand* are applied:

1. The current (2019) ore-based steel production in the investigated regions is used as the regional steel demand [*cf.* Fig. C2 and Eq. (6b) in Appendix C and in Appendix B, respectively]; and
2. The total annual iron-based steel production of northern Europe is used as a collective steel demand, i.e., free allocation of the steel-making step [see Eq. (6a) in Appendix B].

The scenario with the following assumptions is used as the *Main_Penalty_50* scenario. To regions without any existing ore-based steel production, an investment penalty of 50% is applied to the investments cost for steel production plants (DR shaft furnace and EAF). The export of all commodities is allowed, and distance-dependent transportation costs are used. The regional ore-based steel production is applied as the steel demand. The DR shaft furnace can be stopped and restarted. In the rest of the investigated scenarios, one of the parameters (i.e. investment penalty, commodities export, transport cost, operational flexibility, and steel demand) varies as compared to the *Main_Penalty_50* scenario.

The inflexible operation of steel production capacity (i.e., constant operation during all hours in a year) and partially flexible operation (where the flexibility of electrolyser is considered and investments in hydrogen storage allowed) and how these types of operation impact the electricity system have been studied previously [12,31,32]. Therefore, the results (the steel plant locations and their sizes (Fig. D1), the steel production cost and total system cost (Fig. D2), and investments in electricity generation capacities (Fig. D3)) for the inflexible operation of steel production capacity are included in Appendix D.

2.3. Terminology

Good conditions for wind and solar generation, defined by the hourly generation profiles and available land for solar and wind power in the model, can provide low-cost electricity to meet new demands, such as the electrified steel production. The phrase *availability of low-cost electricity generation* is used throughout this study to describe regions with good conditions for wind and solar generation. Hours with no or low-level generation of electricity from renewable sources are referred to as *high-net-load hours*, and hours during which a large share of the load is covered by renewable electricity generation are *low-net-load hours*. The phrase *low-cost access to iron ore* is used for regions that produce or distribute iron or have low costs for iron ore transportation from producer/distributor regions.

3. Results

The results are presented in five parts. The first part shows the steel plant locations and their sizes in the investigated scenarios. The second part illustrates how the steel production cost and total system cost differ

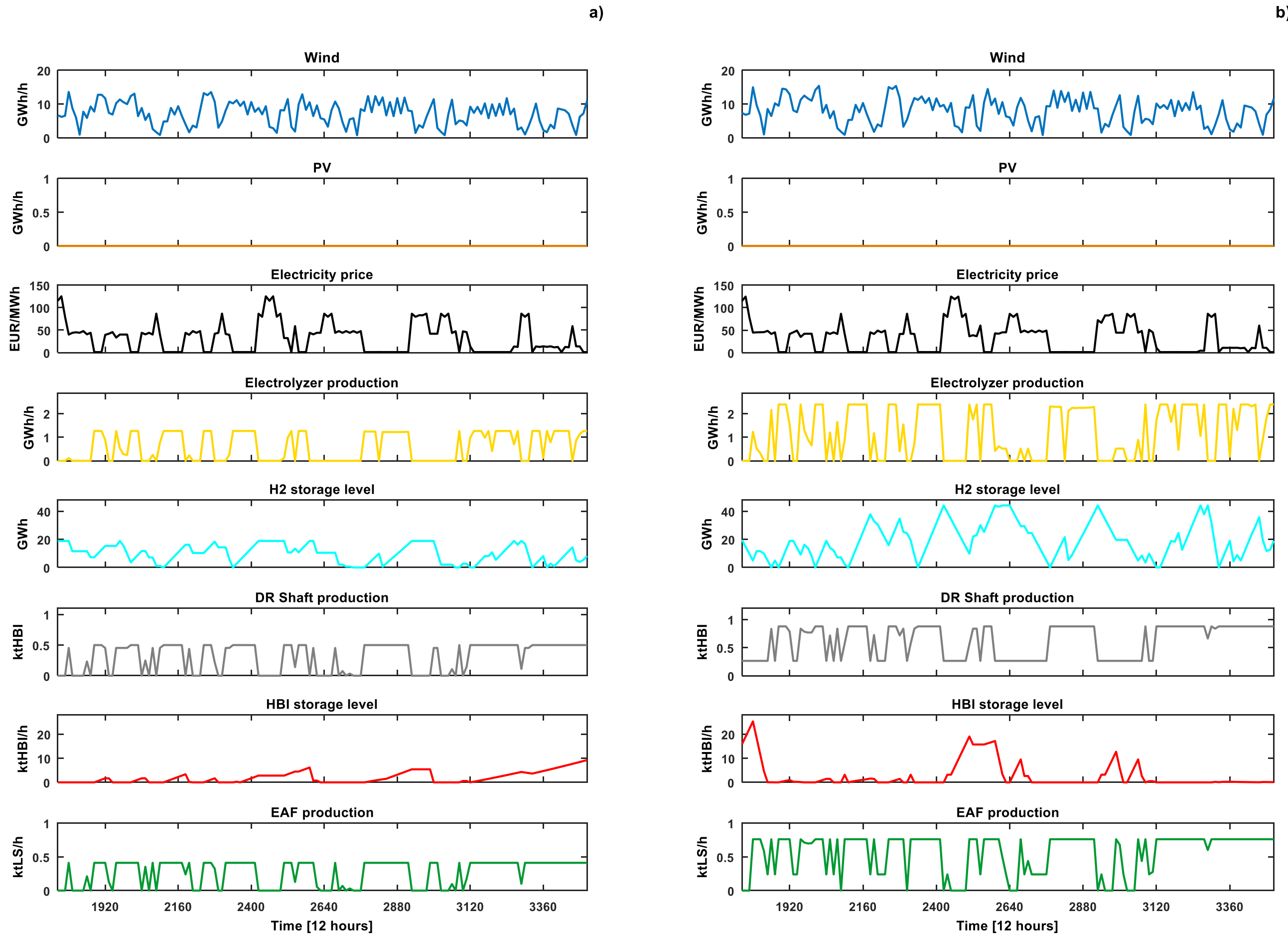

Fig. 9. Electricity generation from solar PV and wind power (in MWh/h) and electricity price profiles (€/MWh) for Ireland as obtained from the modeling. Zero CO2 emissions from the electricity system are assumed. Shown are: the production levels from the electrolyzer (in GWh/h) and DR shaft furnace (ktHBI/h), and the state of charge of the H2 storage (GWh); and the production levels from the EAF (ktLS/h) and state of charge of the HBI storage (tHBIh), in Ireland (IE_T) for the Main_Penalty_50 scenario (a) and for the Inflex scenario (b). The temporal resolution is 12-hourly, where each time-step represents the average of 12 h.

between the scenarios. Commodities export and import patterns are presented in the third part. The fourth part gives the dispatch of the electrified steel production in the different scenarios. Finally, the fifth part covers how the electrified steel industry affects investments in electricity generation capacities.

3.1. Steel plant locations and sizes

The modeling results show that spatial allocation of the electrified steel production capacity will be influenced by the electricity generation mix, resulting in new steel plant sites. It is found to be cost-efficient to invest in overcapacity in steel production units (electrolyser, direct reduction shaft (DR shaft) furnace and EAF) and in storage units for hydrogen and HBI. The total obtained overinvestments for Northern Europe for electrolyser, DR shaft furnace, and EAF varies in the range of 134–153%, 134–152%, and 161–178% for the scenarios investigated as compared to the investments required if steel production units were operated at full capacity all hours of the year without investments in storages. The latter is given in Appendix E (assuming present - day spatial allocation of steel plants in Northern Europe).

Figs. 3–5 show the modeling results for the scenarios, which are presented in three groups based on which parameter is varied: investment penalty (Fig. 3); transport cost (Fig. 4); and commodities export, operational flexibility, and steel demand (Fig. 5). The five subplots in each figure show the location and size of the electrolyzer capacity in GW (Figures 3–5a), DR shaft furnace capacity in ktonne (Figures 3–5b), and EAF capacity in ktonne (Figures 3–5c), together with the H_2 storage capacity in GWh (Figures 3-5d) and HBI storage capacity in ktonne (Figures 3–5e), for each of the investigated scenarios.

Fig. 3, a–c shows that with a high investment penalty in regions that currently lack steel production capacity, i.e., the *Penalty_100* scenario, the steel plants become clustered around those regions with low-cost access to iron ore (i.e., iron ore producer/distributor regions and regions with low costs for commodity transportation) and with existing steel production. With a decrease in the investment penalty, i.e., the *Main_Penalty_50* and *No_penalty* scenarios, steel production capacity starts to be allocated to regions with strong availability of low-cost electricity generation (e.g., Ireland, IE_T and Baltic regions, BAL) or moderate availability of low-cost electricity in combination with low-cost access to iron ore (e.g., northern Germany, DE_N and southern Germany, DE_S) (Fig. 3, a–c).

Fig. 4 shows that with a high, uniform transportation cost, as applied in the *Transp_20_cost* scenario, the electrified steel plants are clustered around countries with low-cost access to iron (iron ore production and distribution) and medium-to-high steel demands, such as northern Germany (DE_N), northern Sweden (SE_N), southern Poland (PO_S), and England (UK1). The allocation of large steel production capacities to northern Germany (DE_N) results in a high additional electricity demand in this region, which makes investment in H_2 storage more cost-efficient, as compared to an increase in thermal electricity generation to support simultaneous production of the electrolyzer and the DR shaft furnace during high-net-load events (Fig. 4, d and e). With decreased

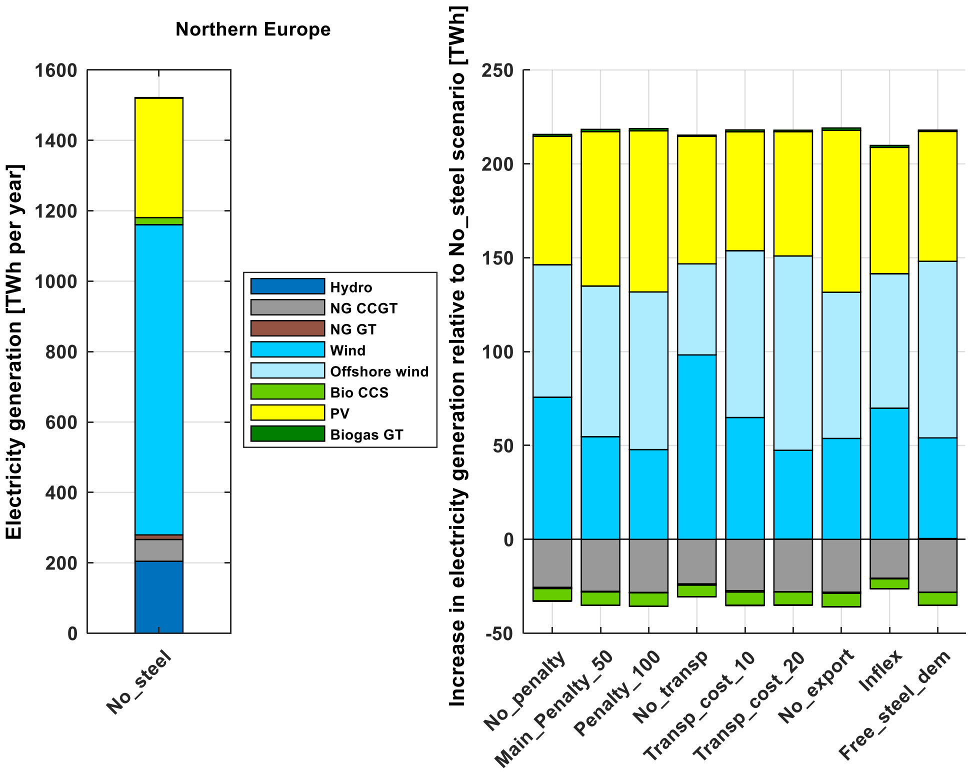

Fig. 10. Total annual electricity generation (in TWh) in Year 2050 for the scenario without electrified steel production (left-hand panels) and the differences (in TWh) in electricity generation between an electricity system without electrified steel production and the scenarios with electrified steel production (see Investigated scenarios) (right-hand panels) for northern Europe. NG, natural gas; CCGT, combined cycle gas turbine; GT, gas turbine; Bio, Biomass; CCS, carbon capture and storage; PV, photovoltaic.

transportation costs, such as those applied in the *Transp_10_cost* and *No_transp_cost* scenarios (Fig. 4, a–c), the availability of low-cost electricity generation from wind and solar becomes a factor that defines the location of the steel plants. Fig. 4, a–c shows that the *No_transp_cost* scenario provides the highest investments in steel production capacities in the regions without existing steel production but with good availability of low-cost electricity generation from both wind and solar, as compared to the other scenarios.

Fig. 5 shows the results for the location and size of the electrified steel production for the *No_export*, *Inflex* and *Free_steel_dem* scenarios. In the *No_export* scenario (Fig. 5, a–c), the locations of the electrified steel plants are the same as the current ones, since the demands for steel in the investigated regions are given by the existing annual ore-based steel production in this work. The steel demand and the number of hours with low-net-load define the levels of investments in steel production capacities and storages in the *No_export* scenario (Fig. 5, a–e), since there is no possibility to reduce the steel production cost through the allocation of the steel production capacity to regions without existing steel production but strong availability of low-cost electricity. Fig. 5, a–c shows that the existence of steel production and availability of low-cost electricity generation determine the location of steel production capacity in the *Inflex* scenario. Moreover, the inflexible operation of the DR shaft furnace is compensated for by large storage sizes (the *Inflex* scenario; Fig. 5, d and e). In the *Free_steel_dem* scenario, the determinants of plant location are low transportation cost and the availability of low-cost electricity generation from wind and solar power (Fig. 5, a–c). The results of the *Free_steel_dem* scenario also show that market proximity (i.e., with assumption as to regional steel demand) has a weak impact on steel plant allocation. The locational determinants for each scenario are given in Appendix F.

3.2. Steel production cost and total system cost

Fig. 6 (left-hand axis) shows the breakdown of the steel production cost into the raw material costs, the annualized investment cost, the fixed operation and maintenance costs (O&M) costs, the cost of electricity, and the transportation costs, together with the total system cost, which includes the investment and running costs for the electricity system and the electrified steel industry (right-hand axis) for nine scenarios as given by the model. All parts of the production cost are expressed per tonne of steel produced (i.e., €/t). The cost for raw materials (iron ore) is the same in all scenarios, since the total annual steel demand of northern Europe doesn't change in the investigated scenarios and constitutes a large share (more than 50%) of the production cost in all the cases.

The modeling results given in Fig. 6 yield a steel production cost range of 300–322 €/t for the investigated scenarios. As indicated in Fig. 6, among the parameters investigated, the transportation cost has the greatest impact on the cost of steel. Decreasing the uniform transportation costs progressively from 20 €/t of the commodity to 0 €/t (no cost), as reflected in the *Transp_20_cost*, *Transp_10_cost* and *No_transp_cost* scenarios, leads to an increase in the investment costs and a decrease in the electricity cost. This shift in costs occur because a reduction in transportation cost leads to an allocation of steel production to the regions with strong availability of low-cost electricity generation from solar and wind power. The *Transp_20_cost* scenario gives the highest steel production cost and the highest total system cost among the investigated scenarios.

Decreasing the investment penalty progressively from 100% to 0% (no penalty) for investments in new steel production capacities for regions without existing steel production, as applied in the *Penalty_100*, *Main_Penalty_50* and *No_penalty* scenarios, results in a decrease in electricity costs for steel production and an increase in the transportation cost. The reduction of the investment penalty stimulates the allocation of steel production to regions that lack existing steel production but that have low-cost electricity generation from wind power. This results in an increase in the commodity flow in terms of iron ore to these regions and in terms of steel and HBI from these regions, i.e., transportation costs increase. The *No_penalty* scenario shows the second-lowest cost for electricity among all the scenarios. However, the cost is higher compared to the *No_transp_cost* scenario, as the commodities transportation costs reduce the incentive to reallocate steel production to

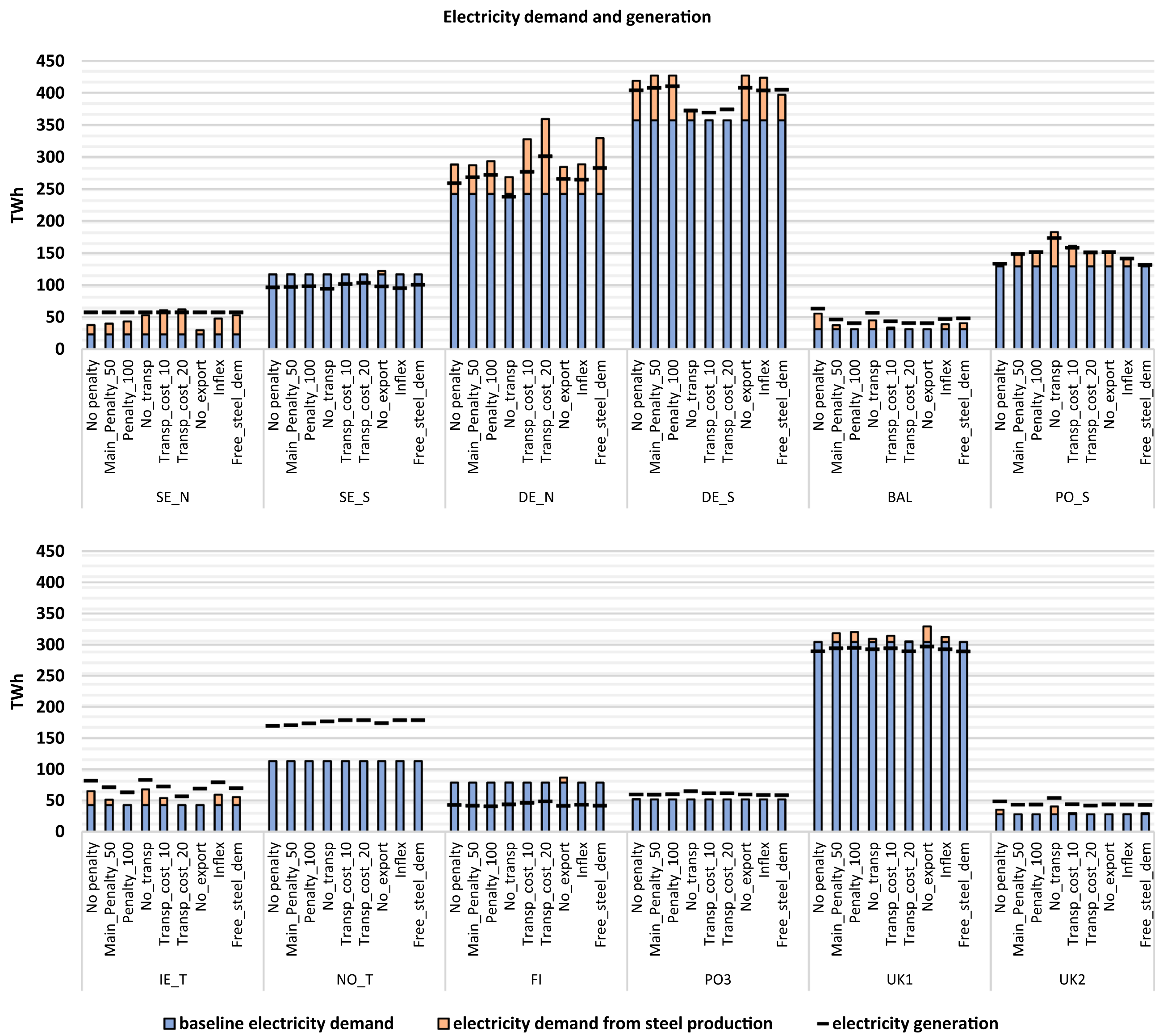

Fig. 11. Total annual electricity generation, baseline electricity demand and electricity demand from steel production (in TWh) for the scenarios with electrified steel production (see Investigated scenarios) for each modelled region.

regions that have good availability of low-cost electricity generation. In the *Free_steel_dem* scenario, the steel production cost is low compared to the other scenarios due to a lack of steel trade flows and, consequently, there is a low transportation cost. The inflexible operation of the DR shaft furnace in the *Inflex* scenario results in the second-highest total cost for steel (i.e 81 billion €). However, from the steelmaking perspective, inflexible DR shaft furnace operation entails a lower cost for steel production than the scenarios with uniform transportation costs, i.e., the *Transp_cost_20* and *Transp_cost_10* scenarios.

3.3. Commodities export and import

Fig. 7 shows the commodity trade flows between the investigated regions for the *Main_Penalty_50* scenario (Fig. 7a), the *No_penalty* scenario (Fig. 7b) and the *No_transp_cost* scenario (Fig. 7c).

In the *Main_Penalty_50* scenario, the steel plants are clustered around the regions with low-cost access to iron ore and high availability of low-cost electricity generation. Fig. 7a shows that in the *Main_Penalty_50* scenario, regions that have high availability of low-cost electricity generation from wind power and an investment penalty of 50% imposed on the cost of investment in steel production plants (DR shaft furnace and EAF) import iron ore and export HBI or steel (i.e., IE and BAL). Iron ore is exported to the Baltic region, even though it costs less to transport iron ore from northern Sweden (the region with existing iron ore production) to Finland and southern Sweden (the regions with the existing steel production plants) than to the Baltic region, due to the availability of low-cost electricity generation in the Baltic region. The penalty placed on investments in steel production capacity prevent expansion of the steelmaking step in terms of EAF in the Baltic region (BAL), which results in the export of HBI from the Baltic region (BAL) to southern Poland (PO_S).

The *No_Penalty* and *No_transp_cost* scenarios have the most-widely distributed locations of steel plants among the investigated scenarios. This makes commodity trade flow patterns less predictable. The commodity trade flow of the *No_penalty* scenario is shown in Fig. 7b. With no penalty imposed on investments in steel production capacity in regions without existing steel production, the import of iron ore and export of steel for regions that have good availability of low-cost electricity generation from wind power increase, as compared to the results for the *Main_Penalty_50* scenario. Furthermore, there is no HBI trade flow, as the cost of investment in EAF capacity is the same in all the regions in the *No_Penalty* scenario.

Fig. 7c reveals the main characteristics of the *No_transp_cost* scenario. The lack of transportation costs causes an increase in HBI exports. Regions that have good availability of low-cost electricity generation from wind power and an investment penalty of 50% for steel production capacities import iron and export HBI and steel to regions with high demands for steel and existing steel production. In regions with strong availability of low-cost electricity generation from wind power (IE_T, UK2, BAL), HBI exports (as equivalent to mass of steel) are greater than steel exports, so as to take advantage of the low-cost electricity to produce HBI, while avoiding the penalty placed on investment in EAF.

3.4. Operational time and operational level of the steel production capacity

Figs. 8 and 9 show the modeling results for southern Germany (DE_S) (Fig. 8) and Ireland (IE_T) (Fig. 9) for the *Main_Penalty_50* scenario (a) and for the *Inflex* scenario (b) together with the levels of electricity generation from solar PV and wind power and the marginal electricity price profiles. Shown also are the levels of H_2 production and HBI production and the state of charge of the H_2 storage, and the level of steel production and state of charge of the HBI storage. Each time-step represents a 12 h average.

To analyze the dispatch of the steel production capacity, the modeling results from the *Main_Penalty_50* scenario and the *Inflex* scenario are compared. The *Inflex* scenario differs from the other investigated scenarios (see Fig. 2) by the limited cycling properties of the DR shaft furnace, i.e., the shaft furnace operates continuously, with the output varying between 30% and 100% of the installed capacity. The region of southern Germany (DE_S), in which electricity is mainly supplied by solar power (see Fig. C4b in the Appendix C), and Ireland (IE_T), a wind power dominated region (Fig. C4d in the Appendix C) are used as examples.

Due to the high share of solar power in the electricity mix of southern Germany, the electricity price follows the diurnal variation of solar generation (Fig. 8, a and b). In the *Main_Penalty_50* scenario, the steel production capacities (electrolyzer, DR shaft furnace and EAF) adapt to the levels of availability of low-cost solar power in several ways. All steel production capacities avoid production during hours with a net load that is sufficiently high to result in electricity prices of $\geq$ 50 €/MWh (Fig. 8a, Hours 2,400–2,520). When the net load is moderate, resulting in an electricity price that varies in the range of 15–50 €/MWh, steel production capacities operate in an electricity price-following mode (Fig. 8a, Hours 2,880–3,120). The electrolyzer follows the peaks in low-net-load events, i.e. corresponding to periods with low electricity prices, unlike the DR shaft furnace and EAF, which produce continuously during such events (Fig. 8a, Hours 3,240–3,360). The continuous production of the DR shaft furnace when the electrolyzer runs at part capacity is supported by the discharging of the H_2 storage. If the level of production from the DR shaft furnace is not sufficient to support EAF production at full capacity, the HBI storage starts to discharge.

The wind-influenced electricity price for Ireland shows longer durations of both the low and high electricity price events and no regular variation pattern (Fig. 9, a and b), as compared to the electricity prices for southern Germany. The electricity price variation in Ireland consists of long periods of high- and low-net-loads, which result in the long periods of idleness respectively of long periods of steel production (Fig. 9, a and b, Hours 2,760–2,820 and Hours 3,120–3,360). As can be seen from Fig. 9a, the electrolyzer mostly operates in electricity price-following mode. During short-duration high-net-load events, illustrated by periods of high electricity prices, the DR shaft furnace and EAF work at part capacity in Ireland in the *Main_Penalty_50* scenario. The storage utilization pattern in the wind-dominated region is the same as that in the solar-dominated region for the *Main_Penalty_50* scenario.

Continuous DR shaft furnace operation, as in the *Inflex* scenario, implies larger storage units in both countries presented in this analysis, as compared to the *Main_Penalty_50* scenario. Large storage units substitute the operational flexibility of the DR shaft furnace. The utilization pattern of the H_2 storage in the *Inflex* scenario (Figs. 8 and 9 b) is similar to that of the *Main_Penalty_50* scenario in both countries (Figs. 8 and 9 a). The electrolyzer produces H_2, that is used both for charging the H_2 storage and for reduction within the DR shaft furnace, and the level of H_2 production varies in response to electricity price fluctuations. The fluctuation of the electrolyzer production at part capacity is higher in the *Inflex* scenario than in the *Main_Penalty_50* scenario, so as to support continuous DR shaft furnace operation. The HBI storage absorbs the DR shaft furnace production, thereby permitting continuous operation of the DR shaft furnace while avoiding operation of the EAF in the *Inflex* scenario in both countries (Figs. 8 and 9 b).

3.5. New investments in electricity generation

Fig. 10 shows the electricity generation (in TWh) for Year 2050 in the absence of electrified steel production (left-hand panels), and how this generation differs (in TWh) for the different scenarios (see Fig. 2) with electrified steel production (right-hand panels) for northern Europe.

The left-hand panel in Fig. 10 gives the total annual generation in Year 2050 for all modeled regions. For the scenarios investigated in this work, wind power and solar power dominate the electricity supply-side in northern Europe. The varying renewable generation is complemented by flexible thermal generation based on NG and biogas. The CO_2 emissions from the combustion of NG are compensated for by the capturing and storing of CO_2 from biomass-based electricity generation. The additional electricity demand from the steel industry is mainly covered by increased production from wind and solar power, while it reduces the production of electricity from NG-based generation technologies. Since electrified steel production results in a decrease in electricity generation from NG-based electricity generation technologies, electricity generation from the bio-CCS technology, which provides negative emissions to compensate for the fossil-related emissions, is also reduced.

The modeled results for electricity generation and electricity demand from steel production, as well as, baseline electricity demand which is taken from ENTSO-E (2017) for the different scenarios with electrified steel production (see Fig. 2) for each region investigated are given in Fig. 11.

Fig. 11 shows that the spatial allocation of steel plants impacts the net export of electricity for the regions investigated, i.e., the difference between electricity generation and electricity demand. In most regions, scenarios with a high total electricity demand also have a high electricity generation. In exporting regions with favorable conditions for wind power generation, such as Ireland, Scotland and the Baltic region, an increase in electricity demand for steel production is met by increased local electricity generation and export remains constant between scenarios. In northern Sweden, the electricity generation is not influenced by the differences in the electricity demand from the different steel production scenarios. In the regions neighboring northern Sweden, such as Norway and Finland, the electricity generation respond to electricity demand for steel production in Northern Sweden. Thus, electricity demand from steel production does not have to be satisfied in the region where the electrified steel production is located. For the scenarios with the uniform transport costs, such as Transp_cost_10 and Transp_cost_20, northern Sweden, which today export electricity, start to import electricity whereas southern Germany, which at present imports electricity, starts to export electricity.

4. Discussion

In the present study, we apply a greenfield approach that entails neglecting the restrictions imposed by the existing electricity supply and steel sectors. In other words, we consider a “green” field in which a new system can be designed from scratch. This approach is motivated by the applied assumption of no net CO_2emissions for the modeled year (2050). Therefore, almost all of the current electricity generation and steel production capacity need to be replaced in the interval between the present time and Year 2050. Results based on this type of greenfield modeling methodology reveal the cost-optimal composition of the electricity system given the conditions of the year investigated rather than the investments expected to be made that year. Thus, the greenfield perspective does not address the question of intermediate development stages of either the electricity system towards high renewable shares or the steel industry towards low-carbon production. The lack of representation of a transition pathway for the system from the present to Year 2050 makes the greenfield model computationally faster and enables multiple sensitivity analyses, which are the core of the present study, since the parameter-related assumptions central to the future of the steel industry are subject to high levels of uncertainty. Thus, the results should not be interpreted as a forecast but rather as a benchmark for an optimized future system.

The model results show no investments in nuclear power in the future electricity system of northern Europe in Year 2050. Investments in renewable energy sources are outcompeting the new investments in nuclear power in spite of that we apply investment costs for nuclear power (of 4,124 €/kW) [33], which is in the medium range of available future nuclear cost projections [34]. Based on the results of the sensitivity analysis, lowering nuclear power costs leads to investments in nuclear power. Yet, the steel production overcapacity and storages size are only slightly decreased. Thus, the availability of low-cost electricity generation as a locational determinant for steel plants applying hydrogen direct reduction process still holds as the systems mainly consist of high shares of VRE.

Even though the model results indicate that the largest share of electricity demand in Northern Europe is satisfied by renewable energy such as solar and wind power, the modelled investments in renewable energy capacity can be underestimated in some regions. For instance, in northern Sweden, the modelled wind power capacity is lower than the current wind capacity in this region. This can be explained by the lack of representation of economy of scale and social acceptance of energy infrastructure in the model. On the other hand, the possibilities for implementation of flexibility measures and storage such as in the steel industry investigated in this work, may be more challenging in real life (require new cooperation, new plant siting, smart systems etc.) which would translate to an additional cost.

Currently, severe overcapacity (low capacity utilization) affects steel industry profits in terms of: (i) increased production costs, since plant efficiencies are not maximized; and (ii) decreased revenue per unit, since steel prices are lower during periods of low capacity utilization [35]. The global average nominal capacity utilization rate for the period 2004–2020 was 76% [36], while a capacity utilization rate of around 80% is generally considered necessary for steel plants to remain profitable. The modeling results of this work show that the overcapacity of the units engaged in H_2-based steel production leads to lower production costs, due to the dominant role of variable electricity in electricity-based steel production. Investments in overcapacity in steel production units and in storage units for hydrogen and HBI allow operation of the steel production capacity that follows the variations in electricity price, which leads to operating costs savings higher than the increase in capital investment (see Fig. D2 in the Appendix D). Thus, such a system exploits the overcapacity of steel production to facilitate flexible operation of the steel plant, taking advantage of low-electricity-price hours in an energy system that has a high share of varying renewables.

The introduction of electricity-based steelmaking could have profound impacts on the current logistics and infrastructure for transporting bulk commodities, such as coal, iron ore and DRI/HBI. A decrease in coal consumption might increase the availability of port capacity for other bulk commodities. Transporting HBI instead of iron ore reduces the weight of material transported, which confers additional economic benefits. Steel trade flows might be replaced by DRI/HBI trade flows, as the production of steel can be easily accessed in places where steel is in demand due to low investment and running costs for steelmaking via EAF. In the current study, the capacities of the ports and storage time are neglected, since we assume that the ports are always available to receive and store commodities. Capacity constraints, collection and distribution systems in the port, and specific maritime safety are relevant issues when analyzing access to port services and warrant further investigation.

In the present study, the steel demand is given by the current ore-based steel production in the investigated regions, except in one scenario (the *Free_steel_dem* scenario), where it is given by the total annual iron-based steel production of northern Europe. Steel demand relies on the activity levels of major steel-consuming industries, such as the construction, mechanical engineering and automotive sectors. The general trend in demand for steel grades is towards higher strength, tighter mechanical and geometrical tolerances, and higher surface quality, regardless of the specific sector to be supplied [37]. In Europe, the construction sector is the sector that consumes the most steel, accounting for 35% of total steel consumption, followed by the transport (19%) and mechanical engineering (15%) sectors [38]. However, only part of the produced steel is used in construction (e.g., 4% in Sweden), with the majority of construction steel being imported [39]. This means that the input data for the steel demand used in this work are uncertain. Nevertheless, from the modeling results, it can be concluded that the assumptions made with regards to the steel demand have a relatively low impact on steel plant allocation, as compared to the assumptions made with respect to access to iron ore and availability of low-cost electricity generation. Typically, higher-grade steel products require higher-quality raw material inputs with lower impurities to ensure that they are applicable to the end-product they are used in. Future work could include a more-detailed representation of the steel demand in terms of the demands for different quality levels from steel-using sectors and iron ore supply in terms of quality and availability, which might influence the results presented in this paper.

5. Conclusions

The impacts of the interactions between an electrified steel industry and the future electricity system of northern Europe are assessed using a techno-economic optimization model. The modeling shows that the replacement of conventional primary steel production in northern Europe with steel production based on the H-DR technology can increase the electricity demand by 11% (by 183 TWh). It is found that under the assumptions made, the additional demand for electricity from an electrified steel industry in all the regions investigated, when assuming zero CO2 emissions, is met mainly by increased outputs from wind and solar power, whereas natural gas-based electricity production is reduced, as compared to an electricity system without an electrified steel industry. The high transportation costs of steel commodities impact the electricity trade flows.

Based on the results of the modeling, it is found that availability of low-cost electricity generation and low-cost access to iron ore resources (e.g. regions that produce or distribute iron or have low costs for iron ore transportation) are factors that affect the allocation of electrified steel plants. The allocation of steel production to regions with high availability of low-cost electricity implies expanded transportation of commodities, as compared to the allocation of steel production to regions with low-cost access to iron ore. An allocation to achieve low-cost electricity is, thus, particularly favorable if commodities can be transported at a low cost. Moreover, the modeling results show that the cost-efficiency of trading HBI is highly dependent on the cost of transportation.

From the modeling, it is concluded that for a steel industry that applies H-DR, low costs for H2 and electricity can be achieved by avoiding high-net-load events through operational flexibility of the steel production capacity, in conjunction with the storage of H2 and HBI and the allocation of steel production to regions with good conditions for wind or solar generation. The allocation of the electrified steel production impacts the steel production cost and its cost structure (e.g. the raw material costs, the annualized investment cost, the fixed operation and maintenance costs (O&M) costs, the cost of electricity, and the transportation costs) but has a low impact on the total cost of meeting the electricity demand in northern Europe.

CRediT authorship contribution statement

Alla Toktarova: Writing – original draft, Conceptualization, Methodology, Formal analysis, Visualization. **Viktor Walter:** Writing – review & editing, Methodology, Formal analysis. **Lisa Göransson:** Writing – review & editing, Supervision, Conceptualization. **Filip Johnsson:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

The current direct reduction processes employ NG or coal for the reduction of iron ore to reduced iron in the solid state [40]. Among the reduction reactors, the shaft furnace is the most widely applied reactor design [41]. In the reduction shaft furnace, the iron ore pellets flow downwards, with the reducing gas flowing upwards. There are two leading technology providers of NG-based DR processes: HYL/Energiron and MIDREX. Due to its high implementation rate, representing about 61% of the total worldwide production of direct reduced iron (DRI), the MIDREX process is selected in this work as the basis for the H-DR process [42]. In the H-DR process, the reduction agent is pure H_2, which is produced through water electrolysis. Unlike the conventional DR process with NG as the reducing agent, there is no need for the reformer in the H-DR process. However, since the reduction of iron ore with H_2 is an endothermic process, additional heating of the reaction, preferably via electric heating, is required [43,44]. The product of the reduction process, direct reduced iron (DRI), has a porous structure, which can lead to oxidation and self-ignition. To prevent this from happening during the handling, storage, and transportation of DRI, hot briquetting is required. HBI can be stored and transported without special precautions under the International Maritime Organization solid bulk cargo code [45]. An EAF is used to convert DRI or HBI to steel. In the EAF, the DRI or HBI is melted using electricity that is fed via graphite electrodes. NG burners and carbon–oxygen injectors are used to increase the energy intensity in the EAF. The utilization of DRI or HBI in the EAF allows easier and cheaper production of high-quality steel owing to its consistent, well-known chemical composition and low content of metallic residuals (Cu, Ni, Cr, Mo, Sn) of DRI [46]. The efficiency of the melting process in the EAF depends on the quality levels of the raw materials used (See Fig. A1).

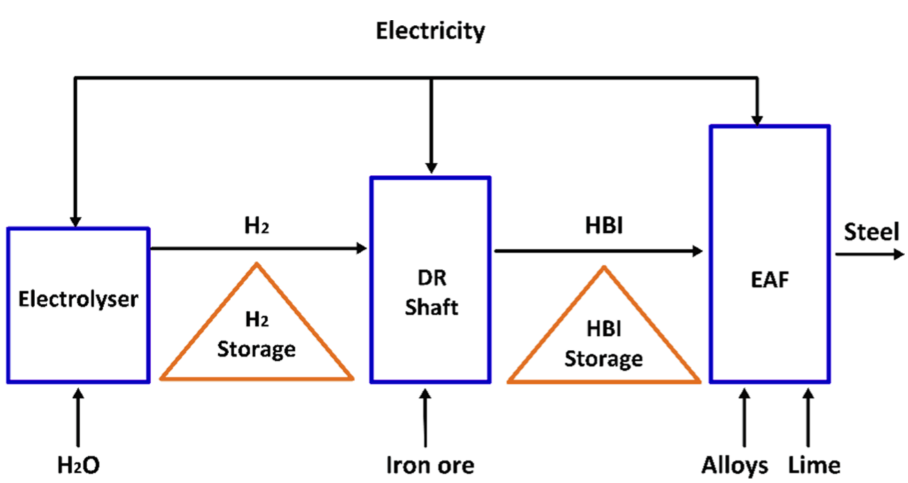

Fig. A1. Schematic representation of primary steel production using the hydrogen direct reduction (H-DR) process.

Appendix B

All the sets, parameters and variables shown in this section are listed in Table B1. Equation (1) describes the model's objective function, which is to minimize the total investments and running costs of both the electricity generation system and the electrified steel industry.

$$minC^{tot} = \sum_{r\in R}((\sum_{p\in P\backslash P^{transm}}(i_{p,r}(C^{inv}_{p,r} + C^{O\&M,fix}_{p,r}) + \sum_{t\in T}(C^{cycl}_{p,t,r} + C^{run}_{p,t,r}g_{p,t,r})) + \sum_{r_2\in R\backslash r}(\sum_{p\in P^{transm}} C^{inv}_{p,r,r_2} i_{p,r,r_2} + \sum_{p\in P^{steel}\cup P^{transm}}\sum_{t\in T} C^{transp}_{r,r_2}(e^{pos}_{p,t,r,r_2} + b_{t,r,r_2})) \tag{1}$$

The electricity demand must be satisfied for each time-step and region, which necessitates Eq. (2). Equation (2) includes the electricity demand from the steel production capacities (electrolyzer, DR shaft furnace and EAF). The free variable e_{p,t,r,r_2} here represents the exported electricity from region r to region r_2, whereas the imported electricity has a negative value.

$$\sum_{p\in P^{el}} g_{p,t,r} + \sum_{p\in P^{STR}\setminus P^{HBI}\cup P^{H_2}} z^{dis}_{p,t,r} \geq D_{r,t} + \sum_{p\in P^{steel}} g_{p,t,r} f_{p,r} + \sum_{p\in P^{STR}\setminus P^{HBI}\cup P^{H_2}} z^{ch}_{p,t,r} + \sum_{p\in P^{transm}} e_{p,t,r,r_2},$$

$$\forall t\in T, \forall r\in R \quad (2)$$

Steel process module

Equations (3)–(6b) describe the mass balance relations between the steel production units. A mass balance for iron ore is given in Eq. (3). Produced iron ore is larger than exported iron ore and iron ore used for HBI production in the DR shaft furnace on annual basis.

$$x_r \geq \sum_{t\in T} \left(g_{P^{DRshaft},t,r} m + \sum_{r_2\in R} b_{t,r,r_2}\right)$$

$$\forall r\in R \quad (3)$$

Equation (4) represents the H_2 balance. Hydrogen is produced in the electrolyzer and used for HBI production in the DR shaft furnace. The balance is given in terms of electricity.

$$g_{P^{Electrolyser},t,r} + \sum_{p\in P^{H_2}} z^{dis}_{p,t,r} \geq g_{P^{DRshaft},t,r} n + \sum_{p\in P^{H_2}} z^{ch}_{p,t,r}$$

$$\forall t\in T, \forall r\in R \quad (4)$$

Equation (5) gives the mass balance for HBI. HBI is produced in the DR shaft furnace and consumed in the EAF. The free variable $e_{P^{DRshaft},t,r,r_2}$ represents export of HBI from region r to region r_2, (a negative value implies HBI import).

$$g_{P^{DRshaft},t,r} + z^{dis}_{P^{HBI},t,r} \geq g_{P^{EAF},t,r} k + z^{ch}_{P^{HBI},t,r} + \sum_{r_2\in R} e_{P^{DRshaft},t,r,r_2}$$

$$\forall t\in T, \forall r\in R \quad (5)$$

Table B1
Notations for the model description.

Sets	
R	is the set of all regions
P	is the set of all technologies
P^{el}	is a subset of P that includes all electricity generation technologies
P^{transm}	is a subset of P that includes transmission lines
P^{STR}	is a subset of P that includes storages
P^{HBI}	is a subset of P that includes HBI storage
P^{H_2}	is a subset of P that includes H_2 storage
P^{steel}	is a subset of P that includes electrolyzer, DR shaft furnace and EAF
$P^{electrolyser}$	is a subset of P that includes electrolyzer
$P^{DRshaft}$	is a subset of P that includes DR shaft furnace
P^{EAF}	is a subset of P that includes EAF
T	is the set of all time-steps
Variables	
C^{tot}	is the total system cost
$C^{inv}_{p,r}$	is the annualized investment cost of technology p in region r
$C^{O\&M,fix}_{p,r}$	is the fixed operations and maintenance costs of technology p in region r
$C^{cycl}_{p,t,r}$	is the cycling cost of technology p at time-step t in region r
$C^{run}_{p,t,r}$	is the running cost of technology p at time-step t in region r
C^{transp}_{r,r_2}	is the transportation cost between regions r and r_2
e_{p,t,r,r_2}	is a free variable representing the export of product that is transmitted/produced by technology $p\in P^{transm}\cup P^{steel}$ between regions r and r_2 at time-step t
e^{pos}_{p,t,r,r_2}	is the positive variable consistent with $e^{pos}_{p,t,r,r_2} \geq e_{p,t,r,r_2}$
b_{t,r,r_2}	is the export of iron ore between regions r and r_2 at time-step t
$g_{p,t,r}$	is the generation of electricity, production of commodities and the state of charge of storage of technology p at time-step t in region r
$i_{p,r}$	is the capacity investment in technology p, in region r
$z^{dis}_{p,t,r}$	is the discharging of storage technology p at time-step t in region r
$z^{ch}_{p,t,r}$	is the charging of storage technology p at time-step t in region r
Parameters	
$f_{p,r}$	is the electricity demand of technology $p\in P^{steel}$ in region r
$D_{r,t}$	is the electricity demand at time-step t in region r
s_r	is the steel demand in region r
s	is the steel demand in northern Europe
m	is the coefficient applied to relate HBI production to iron ore demand in a DR shaft furnace
n	is the coefficient applied to relate HBI production to H_2 demand in a DR shaft furnace
k	is the coefficient applied to relate steel production to HBI demand in an EAF
x_r	is the iron ore production and initial distribution (see *Investigated scenarios*) in region r
$W_{p,t,r}$	is the profile limiting the weather-dependent generation of technology p in time-step t in region r

Table B2
Assumed annual steel demand and iron ore production levels.

Regions	BAL	DE_N	DE_S	FI	IE_T	NO	PO3	PO_S	SE_N	SE_S	UK1	UK2
Steel demand[a], [million tonnes per year]	0	25.3	11.2	2.6	0	0	0	7.6	2.2	1.7	8.1	0
Iron ore production[a], [million tonnes per year]	0	0	0	0	0	1.7	0	0	27.2	0	0	0

[a] The values shown are obtained from the Worldsteel association (2019).

Table B3
Technology investments, operation and maintenance costs (O&M), and lifetimes of electricity generation technologies and steel production technologies.

	Lifetime, [years]	Investment cost, [€/kW$_{el}$]	Fixed O&M cost, [€/kW$_{el}$/yr]	Variable O&M cost, [€/kW$_{el}$/yr]	Efficiency, [%]	Minimum load level, [share of rated power]	Start-up time, [h]	Start-up cost, [€/MW]
Biomass[a]								
Condense	40	1935	56	2.1	25	0.35	12	57
CCGT	30	900	12.96	0.8	61	0.20	6	43
GT	30	450	7.92	0.8	42	0.20	0	20
Intermittent[a]								
Solar PV	25	410	10	1.1	–	–	–	–
Offshore wind	25	2115	90	1.1	–	–	–	–
Onshore wind	25	1290	10	1.1	–	–	–	–
Hard Coal/ Lignite[a]								
CCS	40	2925	106	2.1	40	0.35	0	57
CCS + bio cofired	40	3363	127	2.1	39	0.35	12	57
Condense	40	1980	50	2.1	48	0.35	6	57
Natural gas[a]								
CCGT	30	900	12.96	0.8	61	0.20	0	43
CCS	30	1575	35.1	0.8	54	0.35	12	57
GT	30	450	7.92	0.8	42	0.50	0	20
Nuclear[a]								
Nuclear	60	4124	149	–	33	0.90	24	400
Storage[b]								
Fuel cell	30	450	–	3	65	–	–	–
H_2 cave storage[c]	50	11	–	–	100	–	–	–
Li-ion batteries[c]	15	135	0.27	–	95	–	–	–
Steel[d]								
EAF	40	184	5.52	var	100	–	–	–
Electrolyzer[b]	30	500	24	–	79	–	–	–
DR shaft furnace	40	322	9.66	var	100	0.30	12	var

[a] The values for investment costs and the fixed/variable O&M costs for electricity generation technologies are taken from World Energy Outlook assumptions of the IEA from the 2016 edition [33]. Investment costs for CCS technologies are obtained from the Zero Emission Platform [47].
[b] The storage and electrolyzer technology data is obtained from Technology data for energy plants by Danish Energy Agency [48], Brynolf et al. [49] and Nykvist and Nilsson [50].
[c] The units for these are per kWh.
[d] The values for investment costs and the fixed/variable O&M costs for steel production units are taken from Fischedick et al [4], Wörtler et al. [51] and Xylia et al. [52]. The units for these are per tonne-year.

Demand-supply constraints [Eqns. (6a) and (6b)] ensure that the steel production capacity (in terms of the EAF) produces a sufficient level of steel, as needed to satisfy the total annual steel demand for each region or for northern Europe depending on the investigated scenario (see *Investigated scenarios*). The free variable e_{p^{EAF},t,r,r_2} represents steel export from region r to region r_2, whereas steel import is represented by a negative value.

$$\sum_{t\in T}\sum_{r\in R} g_{p^{EAF},t,r} \geq s \tag{6a}$$

$$\sum_{t\in T} g_{p^{EAF},t,r} \geq s_r + \sum_{t\in T}\sum_{r_2\in R} e_{p^{EAF},t,r,r_2}$$

$$\forall r \in R \tag{6b}$$

Equation (7a) ensures that the levels of electricity generation, commodity production, transmission, and stored products do not exceed the installed capacity. For wind and solar power, the installed capacity is weighted by weather-dependent profiles ($W_{p,t,r}$). The $W_{p,t,r}$ equals one in the case of all other technologies.

$$g_{p,t,r} \leq i_{p,r} W_{p,t,r}$$

$$p \in P, \forall t \in T, \forall r \in R \tag{7a}$$

Equation (7b) limits the DR shaft furnace operation, i.e., the shaft furnace operates continuously, with the output varying between 30% and 100% of the installed capacity (see *Investigated scenarios*).

$$g_{p,t,r} \geq 0.3 i_{p,r} W_{p,t,r}$$

$$p \in P^{DRshaft}, \forall t \in T, \forall r \in R \tag{7a}$$

The balance constraints for storage is given in Eq. (8). (See Tables B1-B3)

$$g_{p,t,r} = g_{p,t,r-1} + \eta_p z^{ch}_{p,t,r} - z^{dis}_{p,t,r}$$

$$p \in P^{STR}, \forall t \in T, \forall r \in R \tag{8}$$

Appendix C

(See Figs. C1-C4)

Fig. C1. Map of the 12 geographic regions applied in the modeling. Regions without current (Year 2021) steel production are marked in yellow.

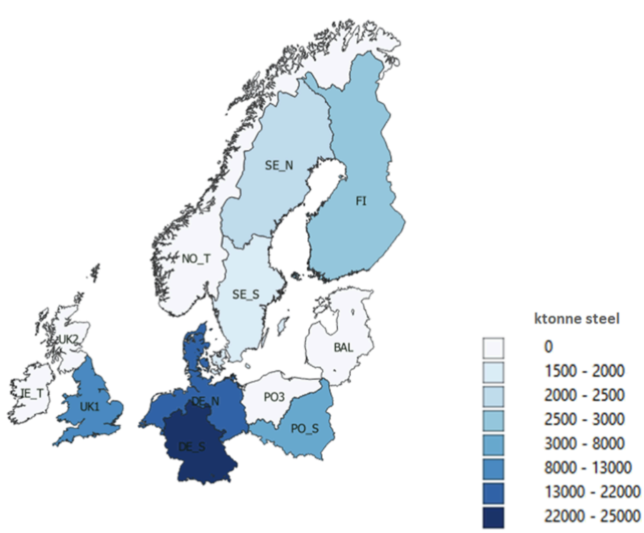

Fig. C2. Primary steel production across the 12 geographic regions applied in the modeling.

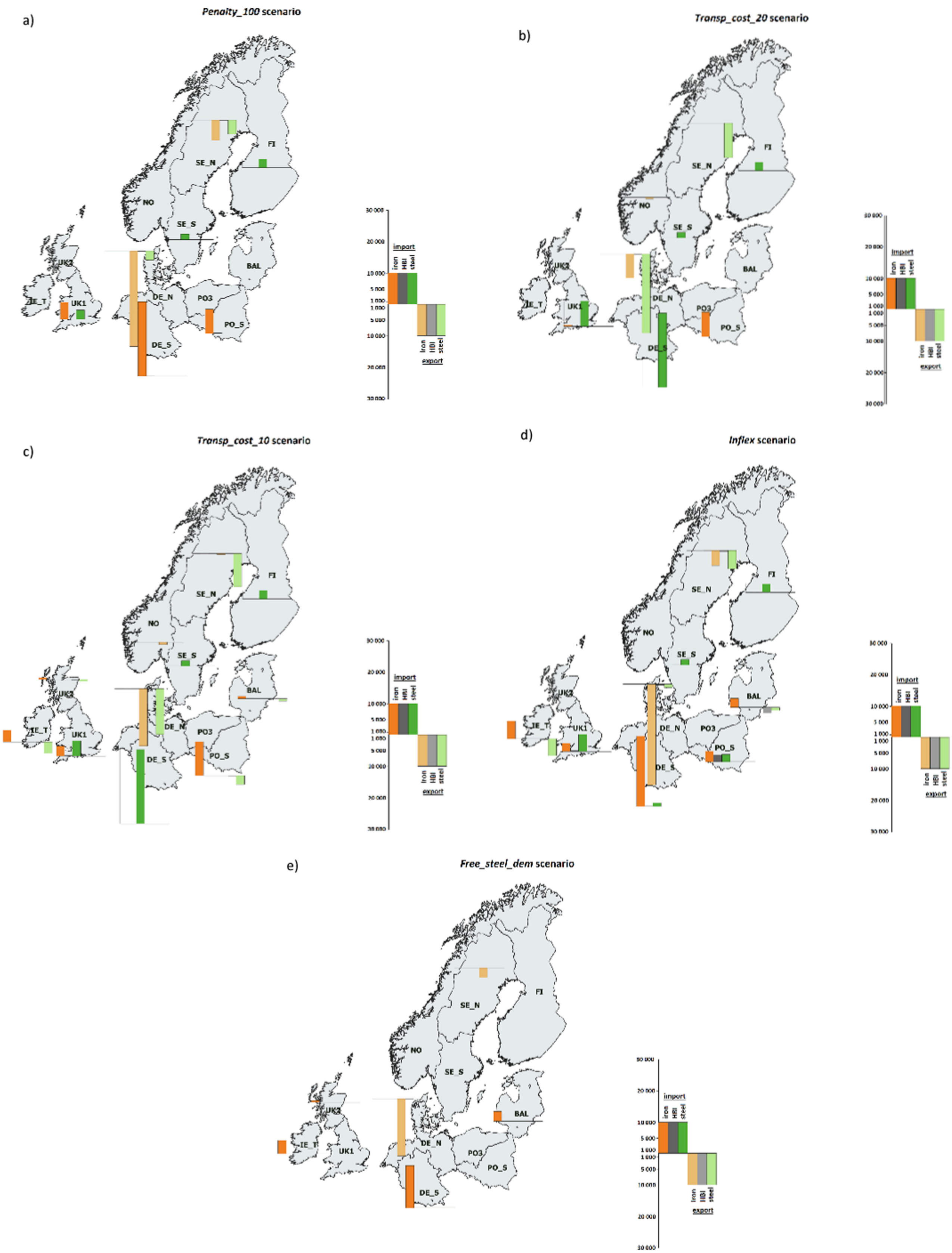

Fig. C3. Maps showing the commodity trade flows across northern Europe for the: a) the *Penalty_100* scenario; b) the *Transp_20_cost* scenario; c) the *Transp_10_cost* scenario; d) the *Inflex* scenario; and (e) the *Free_steel_dem* scenario. Iron ore and HBI trade flows are presented as being equivalent to the mass of steel.

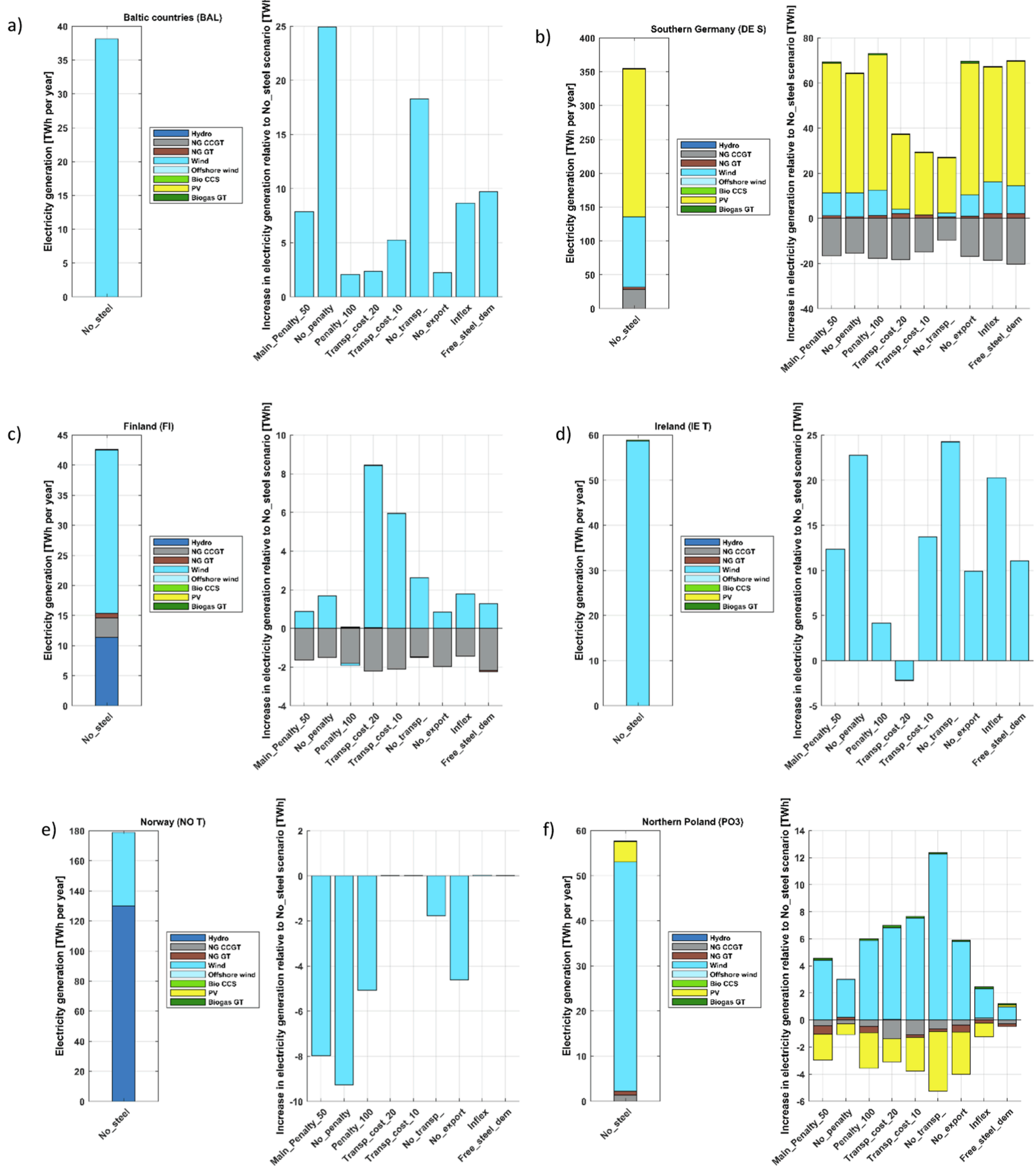

Fig. C4. Total annual electricity generation (in TWh) in Year 2050 for the scenario without electrified steel production (left-hand panels) and the differences (in TWh) in electricity generation between an electricity system without electrified steel production and the scenarios with electrified steel production (see *Investigated scenarios*) for: a) Baltic regions (BAL); b) southern Germany (DE_S); c) Finland (FI); d) Ireland (IE_T); e) Norway (NO_T); f) northern Poland (PO3); g) northern Sweden (SE_N); h) southern Sweden (SE_S); i) Scotland (UK2); j) southern Poland (PO_S); k) England (UK1); and l) northern Germany (DE_N). NG, natural gas; CCGT, combined cycle gas turbine; GT, gas turbine; Bio, Biomass; CCS, carbon capture and storage; PV, photovoltaic.

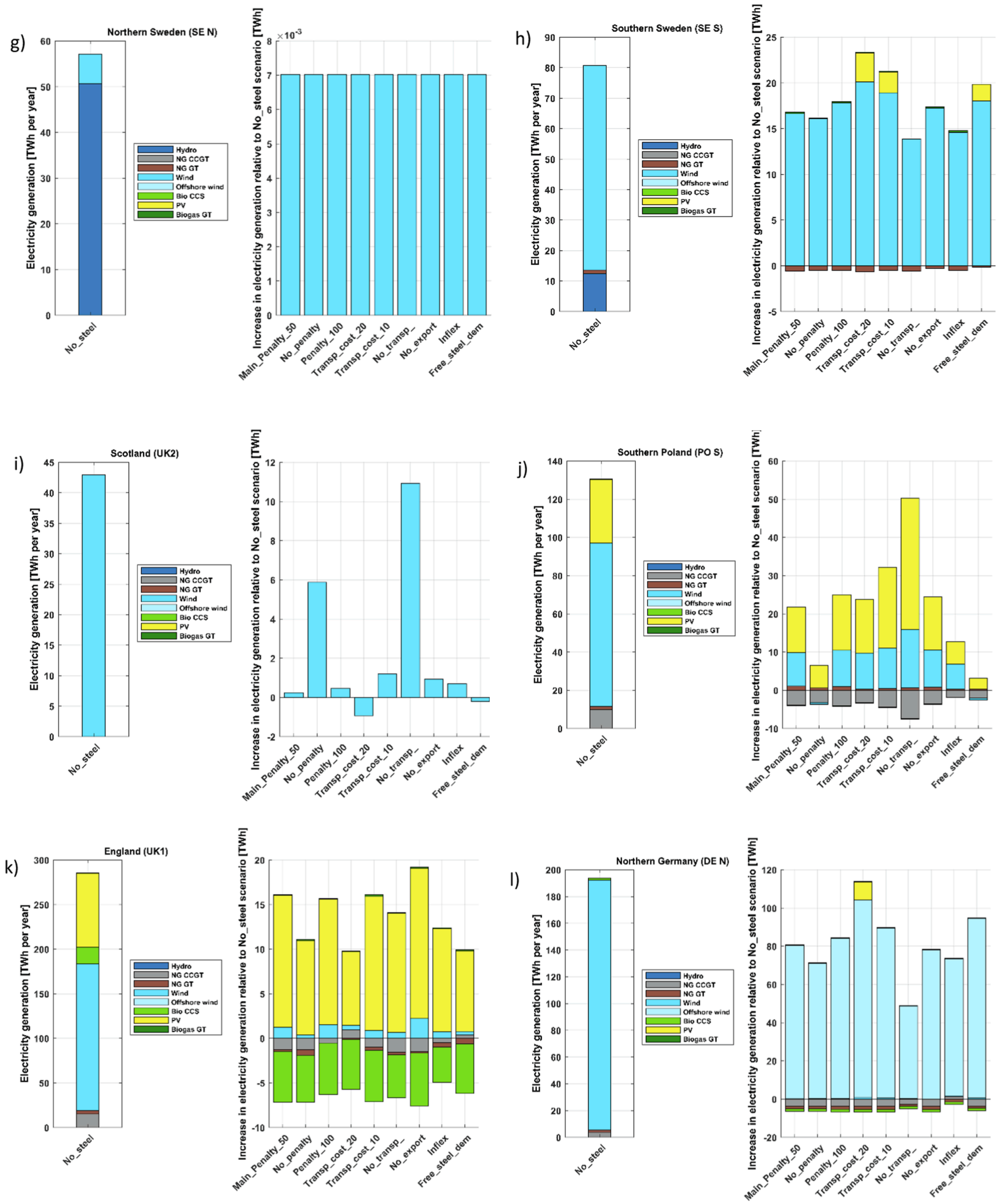

Fig. C4. (*continued*).

Appendix D

(See Figs. D1-D3)

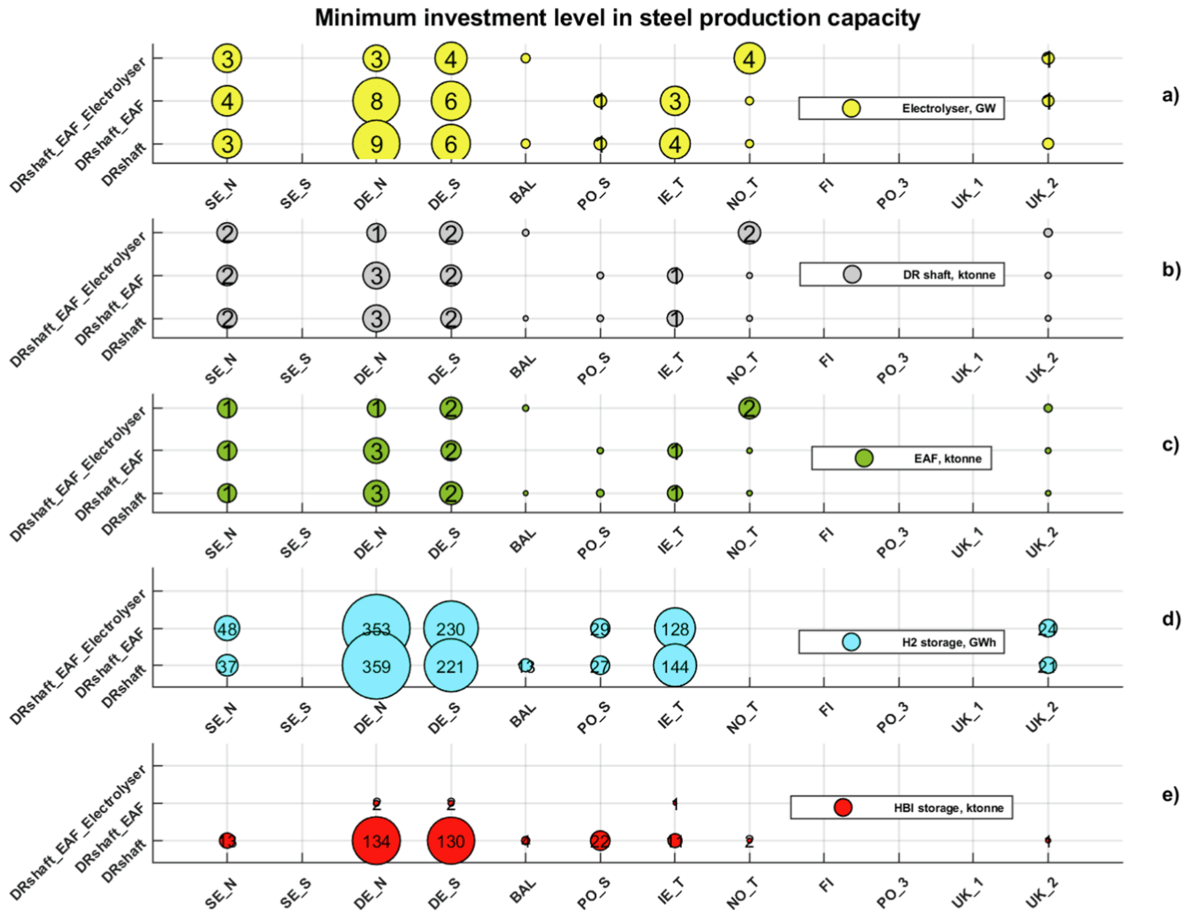

Fig. D1. The modeling results for the scenarios in which the minimum investment level (i.e., constant operation during all hours in a year) applied for steel production capacity. In the *DRshaft_EAF_Electrolyser* scenario all steel production capacities operate at full capacity all hours of the year. In the *DRshaft_EAF* scenario DR shaft furnace and EAF operate at full capacity all hours of the year. In the *DRshaft* scenario only DR shaft furnace operates at full capacity all hours of the year. The regional allocations of the steel production capacities of the electrified steel plants are given in terms of the electrolyzer in GW (Fig. E1a), DR shaft furnace in ktonne (Fig. E1b), and EAF in ktonne (Fig. E1c); and the two storage possibilities are shown in terms of the H storage in GWh (Fig. E1d) and HBI storage in ktonne (Fig. E1e).

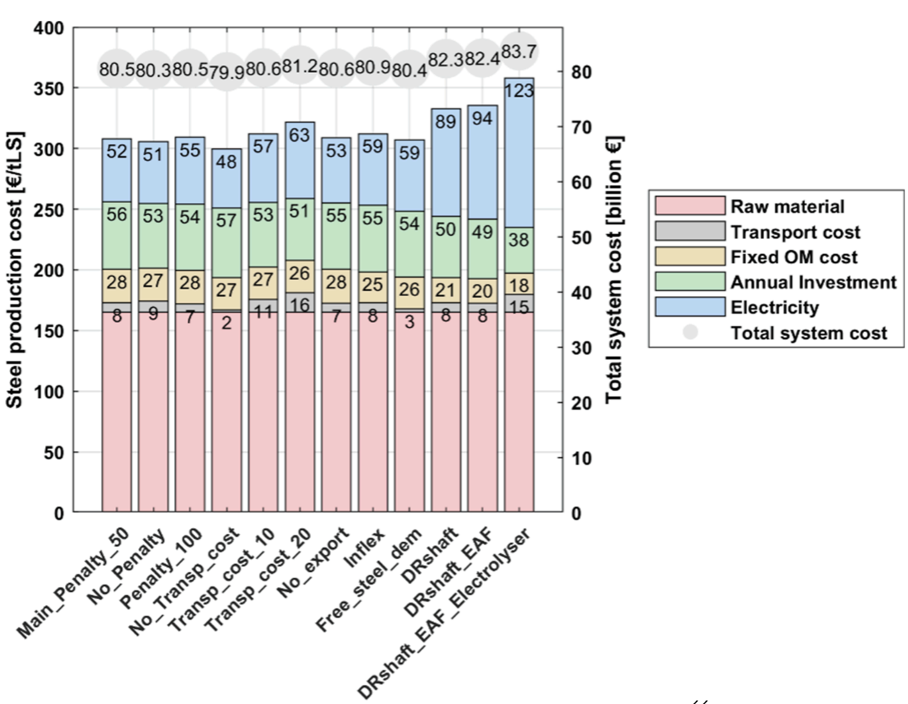

Fig. D2. Breakdown of the modeled steel production cost into the raw material costs, the annualized investment cost, the fixed O&M costs, electricity cost, and transportation costs (left-hand axis). The total system costs are shown (right-hand axis) for the investigated scenarios. The modeling results include scenarios in which the minimum investment level applied for steel production capacity: in the *DRshaft_EAF_Electrolyser* scenario all steel production capacities operate at full capacity all hours of the year; in the *DRshaft_EAF* scenario DR shaft furnace and EAF operate at full capacity all hours of the year; in the *DRshaft* scenario DR shaft furnace operates at full capacity all hours of the year.

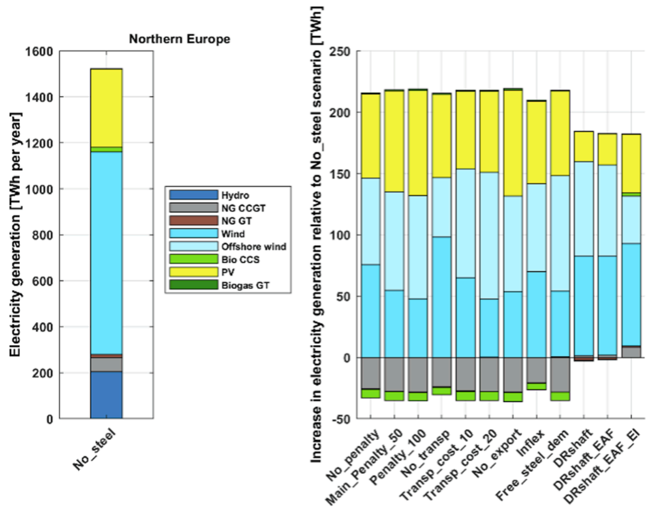

Fig. D3. Total annual electricity generation (in TWh) in Year 2050 for the scenario without electrified steel production (left-hand panels) and the differences (in TWh) in electricity generation between an electricity system without electrified steel production and the scenarios with electrified steel production (see Investigated scenarios) (right-hand panels) for northern Europe. NG, natural gas; CCGT, combined cycle gas turbine; GT, gas turbine; Bio, Biomass; CCS, carbon capture and storage; PV, photovoltaic. The modeling results include scenarios in which the minimum investment level applied for steel production capacity: in the *DRshaft_EAF_Electrolyser* scenario all steel production capacities operate at full capacity all hours of the year; in the *DRshaft_EAF* scenario DR shaft furnace and EAF operate at full capacity all hours of the year; in the *DRshaft* scenario DR shaft furnace operates at full capacity all hours of the year.

Appendix E

(Table 1E)

Table 1E
The minimum possible steel production capacity (i.e., what is required to meet the annual steel demand if the steel production units are operated at full capacity all hours of the year no investments in storages) for the investigated regions and for Northern Europe. The current (2019) ore-based steel production is used as the regional steel demand.

	The ore-based steel production, [ktonne per year]	Minimum capacity EAF, [ktonne of LS per hour]	DR shaft furnace, [ktonne of LS per hour]	Electrolyzer, [GW_{el}]	Minimum electricity demand increase, [TW per year]
SE_N	2200	0.3	0.3	1	7
SE_S	1700	0.2	0.2	0.4	5
DE_N	13,700	2	2	3	42
DE_S	22,760	3	3	6	70
BAL	0	0	0	0	0
PO_S	7600	1	1	2	23
IE_T	0	0	0	0	0
NO_T	0	0	0	0	0
FI	2600	0.3	0.3	1	8
PO3	0	0	0	0	0
UK1	8100	1	1	2	25
UK2	0	0	0	0	7
Northern Europe	58,660	7	7	14	180

Appendix F

(Fig. E1)

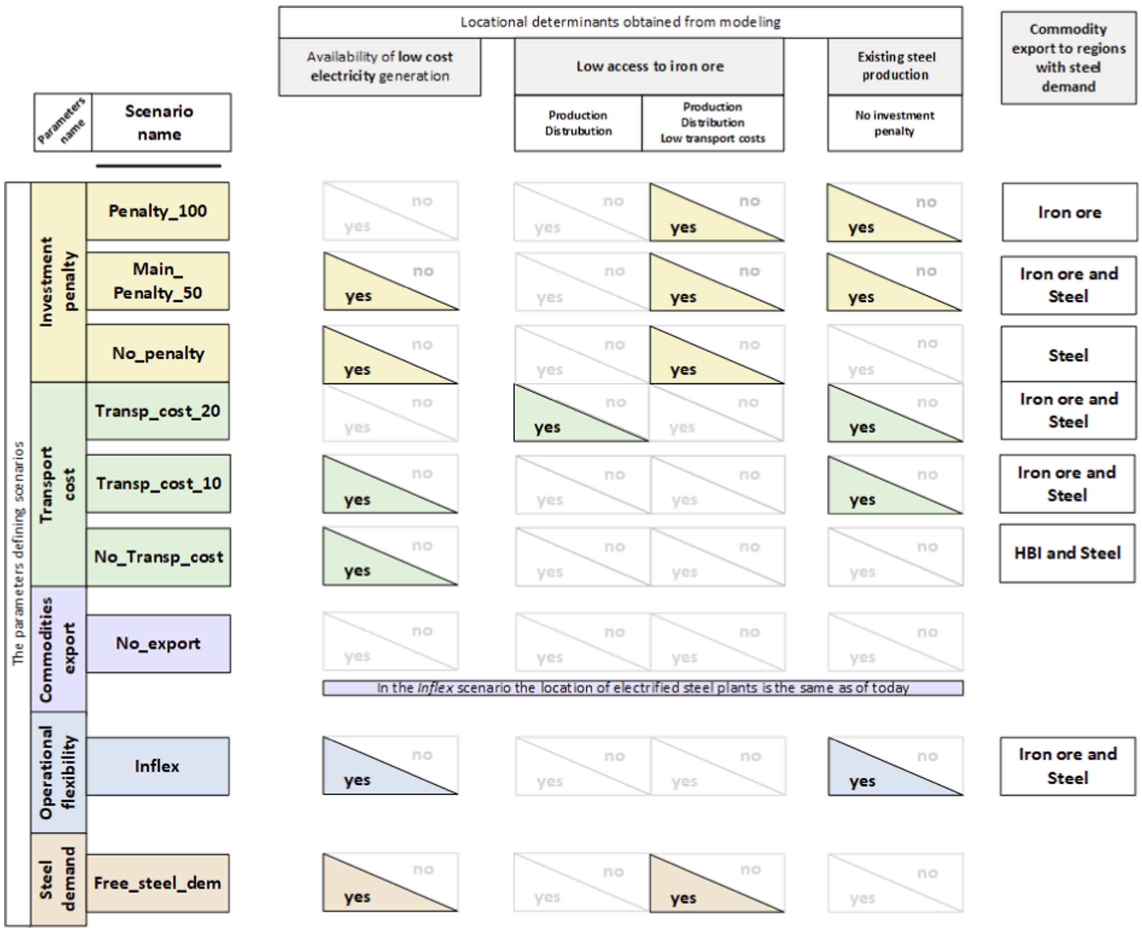

Fig. E1. Summary of the parameters that define: the investigated scenarios and scenarios names; the locational determinants; and commodity exports to regions with steel demand. The colour of the scenario name correlates with the colour of the parameter varied in the scenario and the colour of the locational determinant that impacts the allocation of steel plants.

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